
Morphodynamic Environment in a Semiarid Mouth River Complex Choapa River, Chile

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1. Introduction

The knowledge about mouth systems, estuarine environments and associated processes, seen from the viewpoint of geomorphologic science in Chile, focusing on the contributions of Araya-Vergara [1, 2,3] for the central Chile and Paskoff [4], in the case of semi-arid.

The traditional European and American studies on deltas and estuaries can not address the reality of the most complex estuaries, through evolutionary and taxonomic schemes clear. Such is the case of the mouths on the coast of central Chile, which cannot be studied if it is enriched and modified some molds of the coastal geomorphology as a discipline [4].

According to work done by Pritchard and Caspers [1] indicates that the estuary is a term hydrological and not geomorphological, also provides a definition accepted by the estuarine specialists, defined as a coastal water body that has a free connection with the open sea and from which seawater is measurably diluted with freshwater derived from continental drainage. For its part, Caspers [1] emphasizes the importance of the tidal factor for the classification of the estuary.

Because estuarine delta expression, understood as the accumulation of banks that grow from the inside of the estuary to the sea, is applied to a delta developed into an estuary, it is necessary to seek ways of the land on which was developed estuary, and then pursued a concept of geomorphology. Thus, Araya-Vergara [3] concluded that this form in its most typical commonly is an estuary. Consequently, intends to call delta in *ria* to the internal deltas formed in valleys flooded by the sea.

Notably Davies [3] conceptualizes the estuarine delta as part of a continuum of types of mouth, forming the transitional phase between the estuary and the delta as such (understood as a typically delta marine and distal).

One of the conclusions reached by Araya-Vergara [3, 5] in central Chile, refers to the strong influence morphoclimatic that seems to define the domain of these environments mouth. The author acknowledges the following areas depending on the significance morphoclimatic:

Distal zone of deltas. Corresponds to the Morphoclimatic influence of the desert with summer contributions halogen derivatives of influences height.

Prograded *rias* zone. These coincide with the semi-arid conditions of the Norte Chico, from the Copiapo River (27 ° 20' lat. S) to the Maipo river inclusive (33 ° 47' lat. S). These paleo – *rias* determined by Paskoff [5]. This reflects the higher solid load is attributed to the rivers of arid areas.

Estuarine delta zone. These seem to correspond to the transition area between the semi-arid and humid, from the mouth of the Rapel River (34 ° lat. S) and the Bio-Bio (37 ° lat. S) inclusive, where the river power is important to calibrate wide channel lower course and to provide plenty of substance delta, but also marine energy is sufficient to impede the progress of the progradation into the sea.

***Rias* Zone.** This is connected with the moist and wet conditions in the Región de los Lagos (38° lat. S).

One way to characterize an estuarine system is through the characteristics of its key components. In this context, you can set the forms constituents of estuarine systems, which allows determining a zoning classification of these [3]:

A fluvial or proximal zone, with meandering estuarine.

An interior or media delta zone, with media and distributary banks.

Lagoon or distal zone, with distal lake shore or barrier semiblock by spits or spit outer barrier (Fig. 1).

Proximal zone: indicating the presence of estuarine meanders, they owe their properties to the action of currents ebb and flow, which are related to the action of river and sea action. Estuarine meanders have an essential feature, which is reflected in the way you present: wide at the media and narrow at the ends, also the banks lateral has a shape of cusp.

Media zone: is determined by a change in the pattern of the channel downstream from the area of estuarine meanders. Clearly denoted start means estuarine banks, which have a form characterized by the pointed shape of its ends.

Distal: identify the existence of an estuarine lagoon, which is located between the distal part of the delta area and a spit in the mouth. The spit or barrier are built with the contributions of the littoral drift (in the case of the Chilean coast, it makes sense from south to north), which carries sediment from the existing extension ridge further south coast, the waves push these sediments towards the coast as an arrow, with its free end facing the waves and giving

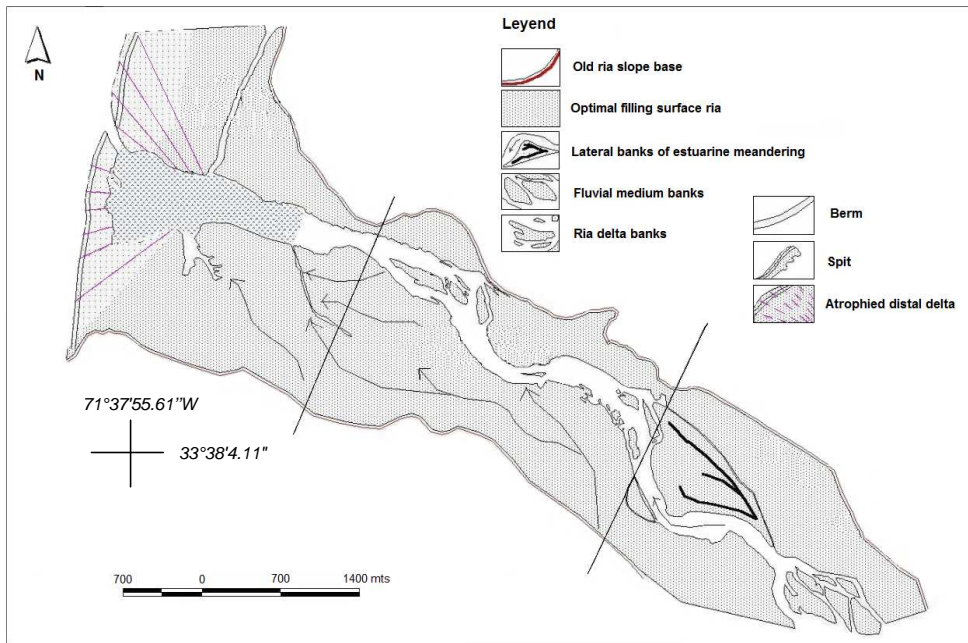


Figure 1. Essential Components, Maipo estuarine system. From: Arriagada [6]

elongated in the same sense that the beach from which the materials. Its curvature, as a *hook*, is explained by the refraction of waves.

This classification has been applied to the case of estuarine systems of the Aconcagua, Maipo, Itata, among others. The case of the Aconcagua, considered by Cortez [7], Martinez and Cortez [8], has provided interesting results in relation to chemical, physical and mixing processes. In applying the model of Cooper [9] the system of Aconcagua river mouth, it was established its status as an estuary dominated by fluvial processes and the waves.

The Maipo River estuarine complex was analyzed by Arriagada [6], work from which it is concluded that estuarine dynamics, associated with changes in the essential forms has been greatly affected by the construction of the San Antonio port, constituting this element of anthropogenic influence in a major evolutionary factor. In this case, according to the analysis developed by applying the model of Cooper [9] concluded that the estuary has a tendency to be dominated by fluvial action. However, there is evidence to indicate the alternation of dominant effects, depending on the season.

Other estuarine systems have been analyzed Rapel, the Itata, the Maule and the Mataquito [3]. In each of them have been identified and characterized the essential forms of estuarine environments, where the presence of banks and spits cuspidate is ubiquitous in them.

Then, the most studied systems from the perspective geodynamics and where the model has been applied, corresponded to central Chile, with few information on systems related to semi-arid mouth.

1.1. Supply and mass transfer

The study of the evolution of coastal systems, must include not only the characterization of the estuaries, but must also incorporate the behavior and evolution of the mass associated dune system. This aspect is relevant because they are indicators of sediment supply and dynamics of coastal environments in general, and estuaries in particular systems [10, 11, 12].

In this aspect, Aqueveque [13] notes the development of three main generations of dunes, ancient and modern means, which are dominated by the degree of evolution and morphology, called *continuum dunaris*. Also, Araya-Vergara [14] adopts the term transmutation for the spatial variation of the dune system, and transmutation, to the change in the morphology of the dune system.

Thus, the mass balance of inner and outer beach is explained by the orientation of the beach, as well as the type of surf zone [14, 15]. This has been found in genetic- evolutionary studies of barjan belts, categories of changes dunes and wave interaction system in large beach coves.

In this situation, one should expect that, in its evolution, the dunes adjacent to estuarine systems present a variation in the mass of dunes, backed by the dynamics and the associated contribution to the estuary.

In addition to the above, we can infer that the dynamic conditions of estuarine systems may be influenced by the processes associated with the basins. Such conditions are of global importance, as they are localized areas where most human settlements, whose impacts are significant morphological [16].

An example of these impacts was what happened at the mouth of the Maipo, where human influence changed the coastline less than 100 years [6]. Other cases have been studied by Federicci and Rodolfi [17, 18], who stated that the rapid retreat of the coastline in Ensenada de Atacama (Ecuador), is due to erosion caused by El Niño events, but also the indirect action of the destruction of wetlands (mangroves).

Araya-Vergara [5] taxonomy points to the classification of estuaries prograded from Copiapo to the Maipo River. These are associated with higher solid load of rivers is attributed to the semi-arid zones.

Consequently, the hypothesis behind this research, notes that in the mouth of Choapa system are recognized morphological traits that account for the evolution of these systems flows into the context of a domain morphoclimatic transitional semi-arid to temperate.

2. Materials and methods

2.1. Study area

In this research, we analyze the mouth of the river system Choapa (Region of Coquimbo) (Fig. 2). The rationale for the study of these systems is based on the differentiation of morphoclimatic domains that support these environments, which highlights the semiarid condition.

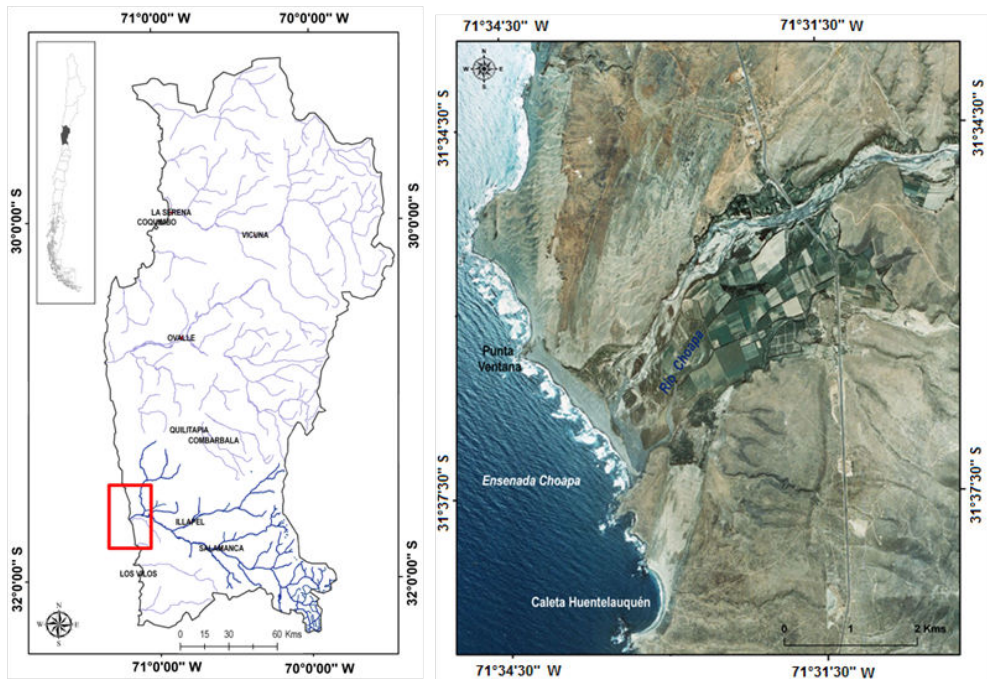


Figure 2. Study Area, Choapa river mouth in the national and regional context.

From the point of view of the climatic characteristics, the study area is located in the steppe climate with abundant cloudiness; geologically the area is inserted into the structural domain premesozoico correspond to the basement, where you can distinguish Choapa Metamorphic Complex [19].

There is also the presence of Huentelauquén formation, interpreted as a deposit of open marine platform [19]. It highlights the unconsolidated Quaternary deposits: aeolian, coastal, alluvial and colluvial. The sand dunes have a transverse component and indicate a contribution of wind SSW-NE direction. These correspond to barjanes and transverse coastal sand dunes.

The geographical context into which you insert the specific problems of the mouth of Choapa, is related to a watershed with land use changes and intensity, but less rapidly than in the case

of the Copiapo and Aconcagua river. For Choapa, recently begun to observe the process of conversion of agriculture and traditional farming to fruit farminggoats [20].

2.2. Methodology

The recognition of the essential systems linked to Choapa and Copiapo river mouths and sustained took place on the following concepts morphological from recognized estuarine systems theory for the domain morphoclimatic semiarid in Chile:

- a. The conceptual basis of the systematization of Araya-Vergara [3]. Among the essential forms to be identified, indicating the estuarine meanders and banks, cuspidate lateral banks, and spit estuarine lagoon, located in the proximal, media and distal, respectively.

The proximal part has meandering estuaries, characterized by fluvial influence that still operates in this area, in the media zone, it means banks are estuarine or cuspidate, due to the influence of river flows, as well as the marine influence. In the distal zone is possible to identify the presence of the spit, as well as estuarine lagoon.

Was realized the identification of the forms cited by photo interpretation of aerial photographs of a period of 30 years, as well as recognition in the field. The final information was mapped by using the software ArcGIS 9.2.

- b. The zoning of each estuarine system was carried out according to the scheme of Araya-Vergara [3], in this way, we use a general conceptual geomorphological model for all estuarine systems, classifying them in the following areas: proximal, media and distal. It included an analysis of the components in each zone.

Analysis of morphodynamics temporal-spatial of estuarine complex through the identification of significant changes that occurred over a period covering the last 30 years, using the topographical maps and photo interpretation of aerial photographs (30 years).

Status of change and evolution of the systems analyzed.

The patterns of change and evolution trend of the morphology surrounding the estuary, was systematized by producing map geomorphology of each system, for the period of time as indicated. Thus, together with analysis of the essential forms of estuarine system, emphasis was placed on the dynamics of the dune systems. The main method of analysis refers to the mapping principle follow the design of dune ridges, which are classified according to the notions of sequence [21] and *continuum dunaris* [14, 22], combining families to determine the dunes (Fig. 3)

Patterns of change and development trends of these estuarine systems, related to the domain morphoclimatic in the context of headland bay beach systems in which they reside.

In the characterization of the near shore environment shows the importance of processes derived from swell. This results in temporal-spatial distribution of the energy of breaking waves. An extensive bibliography on the subject is reviewed by Martínez [23], who delivers new observations to Central Chile. Considered essential advances in active sensing and morphodynamic [24, 25, 26], however working with passive sensors.

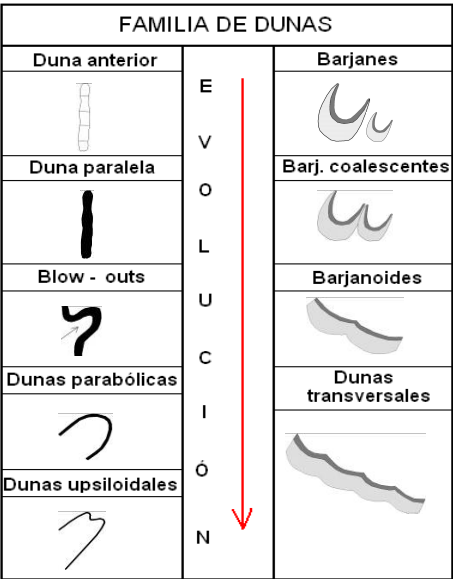


Figure 3. Family of dunes and continuum dunaris. Source: Prepared by the author, from notions of Verstappen [21], Araya-Vergara [14, 22].

Analysis of wave-dominated beaches was performed according to the scheme of Wrihtht & Short [27], as amended by Araya-Vergara [15] for use in aerial photographs. This taxonomy classifies the beach as dissipative, intermediate and reflective. The nomenclature used is summarized in Table 1.

Type of breaker zone	Nomenclature
Reflective	R
Low tide terrace	LTT
Transverse bars and rip	TBR
Rhythmic bars and rip	RBB
Long shore bar and trough	LBT
Dissipative	D

Table 1. Classification of type of wave-dominated beach [28, 29].

To detect change between 1997 and 2008 used three images Landsat 5 Thematic Mapper (TM) (table 2). Landsat TM operate in circular, sun synchronous, near polar orbits at a nominal altitude of 705 km. The inclination of the orbit is 98.2 degrees. The TM sensors view the entire earth every 16 days with a complete cycle of 233 orbits. Full scene products contain 5728 lines of 6120 pixels, corresponding to a ground area of 172 km by 184 km. The TM is a sensor, which

records a continuous strip image of the earth in 7 spectral bands, between 0.45 and 12.5 microns. The satellite images were corrected geometric and atmospheric correction in all the bands required. The spectral water index is a single number derived from an arithmetic operation of two or more spectral bands.

Acquisition Date	Satellite Images	Resolution
1997/06/26	Landsat 5 TM	30 m
2001/06/21	Landsat 5 TM	30 m
2008/09/12	Landsat 5 TM	30 m

Table 2. Used images.

An appropriate threshold of the index is then established to separate water bodies from other land-cover features based on the spectral characteristics. Adopting the format of the normalized difference vegetation index (NDVI), McFeeters [30] and Kuleli et al. [31] developed the normalized difference water index (NDWI), defined as:

$$NDWI = (\rho_{green} + \rho_{NIR}) / (\rho_{green} - \rho_{NIR}) \tag{1}$$

Where ρ_{green} and ρ_{NIR} are the reflectance of green and NIR bands, respectively. The NDWI value ranges from +1 to -1. McFeeters [30] set zero as the threshold. The NDWI data derived from Landsat TM (Thematic Mapper) of the years 1997, 2001 and 2008. They were processed in the software IDRISI Taiga for correcting some of the distortions mentioned by Chuvieco [32] needed in order to obtain a clear index. After the georeferencing, an atmospheric correction using the COST model was used. This model was chosen because his accuracy in semiarid regions, and specially for his accuracy on the Landsat TM blue band. (Fig.4). Moreover, the figure 5 illustrates the flow of this method.

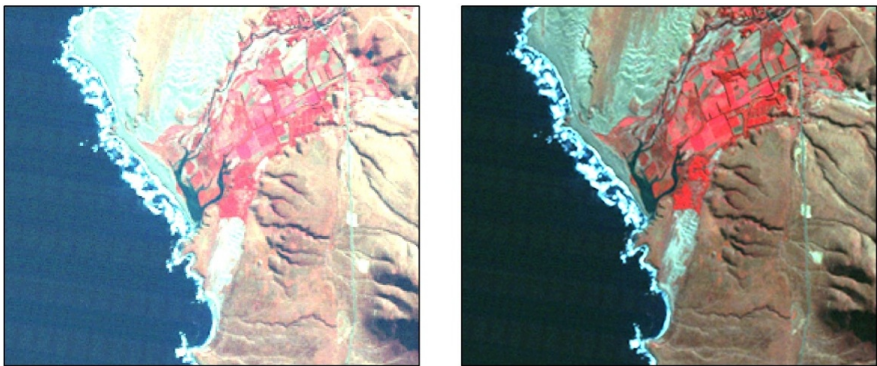


Figure 4. Example of the COST model for atmospheric correction. The left image is a false color composition using the raw bands of the TM image for the mouth of the Choapa River for 2001. The right image is the same composition using the same bands after being corrected by the COST model on the software IDRISI Taiga.

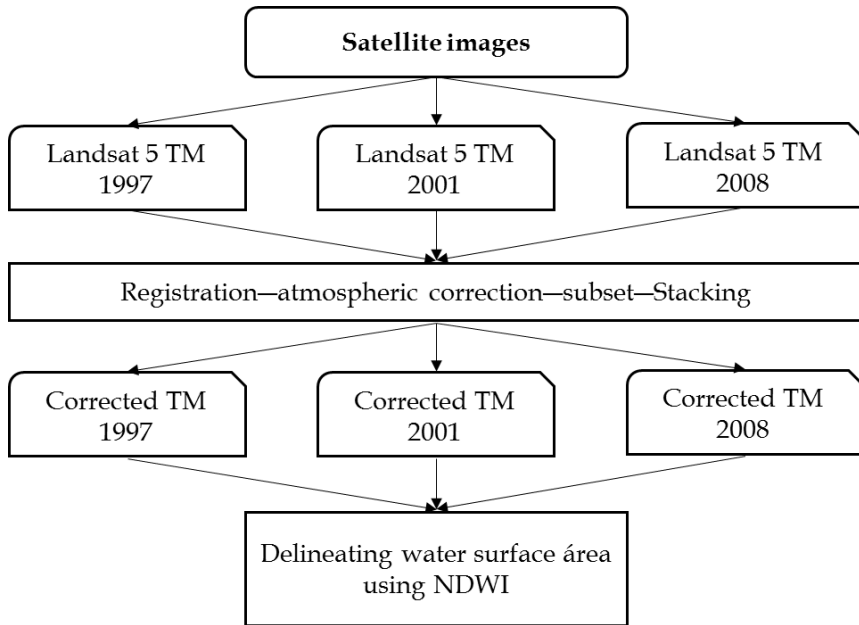


Figure 5. Flow diagram showing the methodology steps

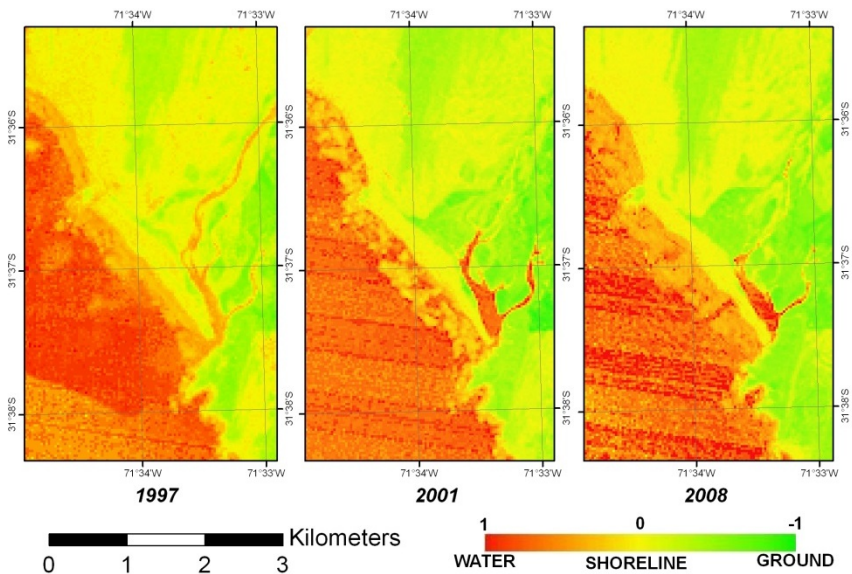


Figure 6. NDWI raw values on the corrected TM images for the years 1997, 2001 and 2008.

The result of the NDWI for each pixel, in which positive values represent water, and negative values represent ground (Fig. 6).

However, this index tend to show wet sand pixels as water due the reflectivity in the band 2, but these values, while positive, are close very close to zero, so a calibration of the water-ground break value was performed though photo interpretation, reaching the breaking value of -0.045 for the 1997 image, 0.053 on the 2001 image, and 0.0048 for 2008. The resulting calibrated water-ground break line is shown on the Figure 7.

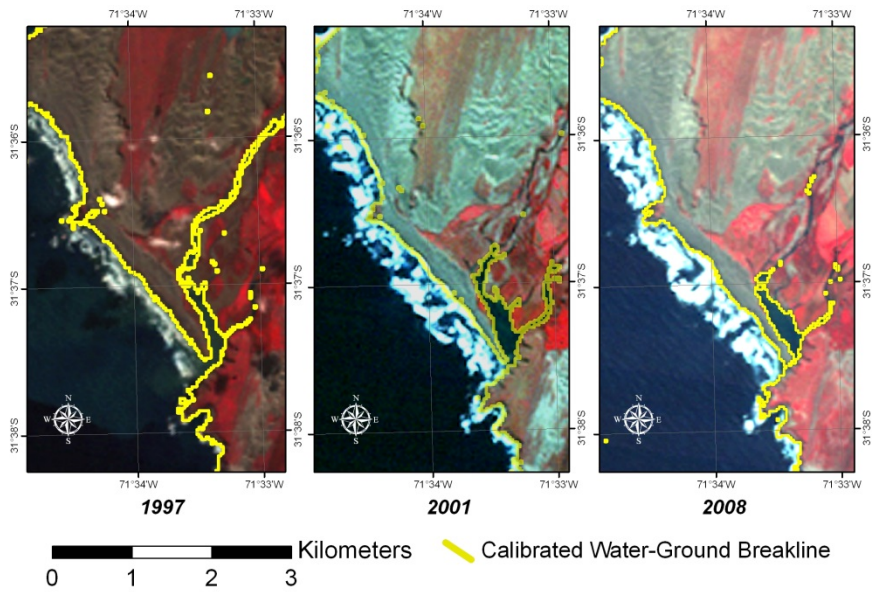


Figure 7. Resulting Water-Ground limit after calibrating the NDWI raw break value.

Finally, a reclassification of these values was made on the software ArcGis 9.2 creating polygons for water and ground categories, allowing a direct comparison for the years used on the images.

3. Results

3.1. Geodynamics of the Choapa mouth system (1978 to 2008)

As shown in Figure 8, for 1978 highlights the presence of a channel in the proximal diffluent, where a glimpse of the river influence that dominates the environment in this sector, where there are large lateral river banks extension. Then in the media part of the system there are the rotation from fluvial media banks and lateral fluvial banks. Note the presence of abandoned

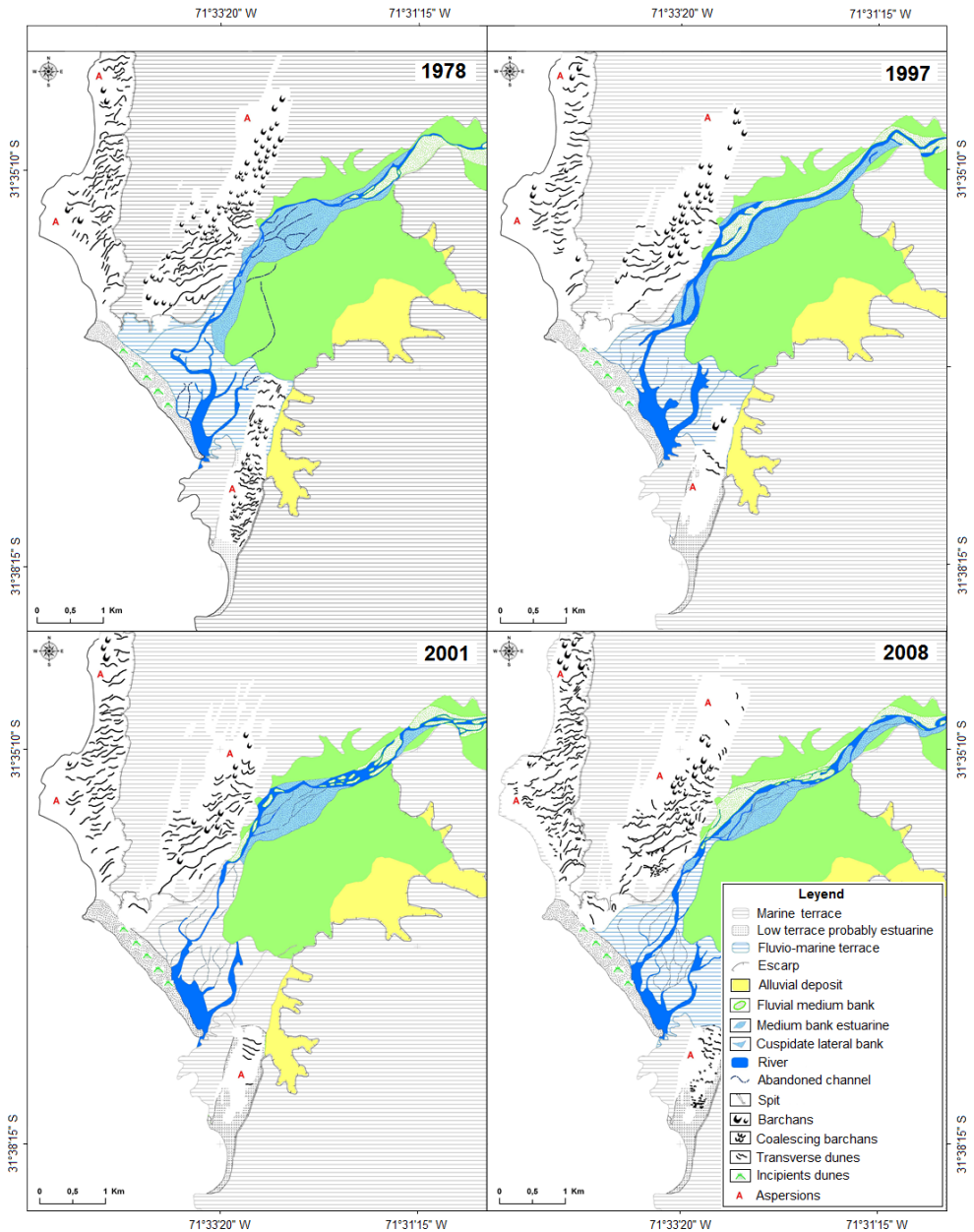


Figure 8. Evolution of the Choapa mouth river, since 1978-2008.

channels on the terrace river banks and in the estuarine side. In the distal part, called attention to the extension of the fluvial-marine terrace, which extends aprox. 2 km.

For 1997, in the proximal part, the estuary has the same type of channel had meandrante to 1978, this continues to the middle of the estuary, where the channel is meandering and winding. Towards the middle, it is possible to clearly distinguish estuarine character means banks, which are detected cuspidate, just before the river course becomes estuarine lagoon. Estuarine lagoon (distal) presents a greater extent compared to 1978. Relative to the sand dune system located south of the estuary include the presence of barjans and certain transverse sand dunes.

For the year 2001 in the distal zone is appreciated the meandering channel, as in previous years. In the middle part, is where the biggest differences you notice it tends to notice a greater number of banks means, indicating a greater sediment load, as a geodynamic behavior like braided channel. This extends to the edge of the middle, where the river channel again becomes meandering. In the distal part, the lagoon estuary is clearly distinguishable. We highlight the presence of abandoned channels, which could be indicators of lower river load.

The situation of 2008 is not much different to the situation of another year. In the proximal part, it shows the meandering course is appreciate where fluvial banks. On the average, banks still appear fluvial as well as the presence of banks estuarine media. The river course is still meandering, reaching its mouth.

The results of the NDWI comparison (Fig. 9), they are completely consistent as they clearly show the variations and some changes on the cannels and banks. However, the most evident change shown by the comparison is the growth of the estuarine lagoon.

3.2. Characterization of Choapa Cove (1978 to 2008)

For the year 1978, in the case of Choapa system, the most striking are the dunes. According to the figure 10, there is a predominance of transverse and barjanes sand dunes. In the coastal sector, there are some cross-sectional and longitudinal patterns less important, these dunes overlie the marine terrace, which is covered. Towards the north-inner estuary, dune field is quite distinguishable, repeating the pattern of tranverse dune, but more remarkable is the barjanic sand fiel, which is considerably large.

The system located to the west, corresponds to the evolution of barjanics sets, so it is assumed to be the oldest, on the contrary, the system located to the east (individual sand dunes barjanic) are recent and are moving in the direction NE.

For 1997, the sand dunes express changes in morphology and in the case of the northern section - coastal estuary, there appears to be an increase in the different dunes, where the cross pattern becomes much more noticeable (Fig 9). Barjan remain, but at lower densities. In the same figure, we see the same patterns and barjanics cross in the north-interior, although it refers to a decrease in the number of barjanic units. In turn, the spray area includes increasing magnitude, so one might infer that the barjan have evolved and in turn, transverse dunes have been dismantled.

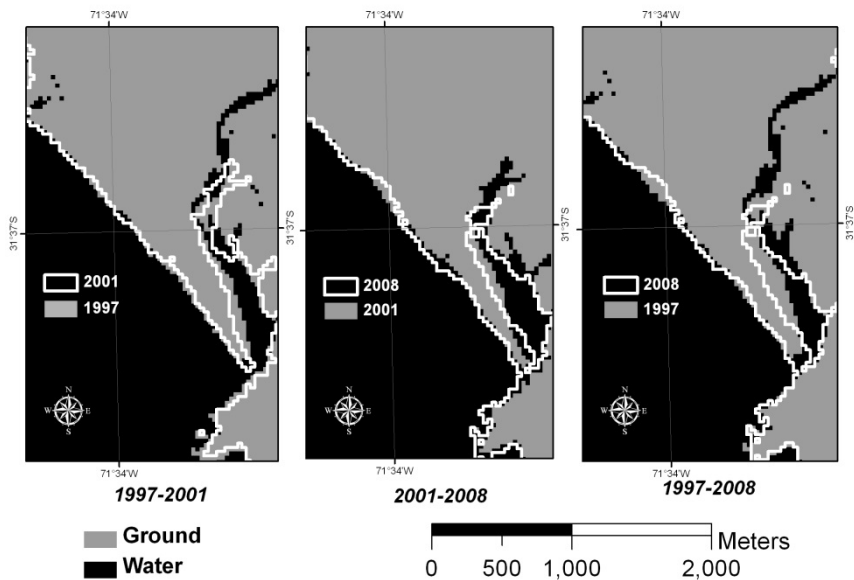


Figure 9. NDWI comparison between 1997, 2001 and 2007. On the 1997-2008 comparison, the estuarine lagoon variation and growth is accurately detected by the NDWI.

In 2001, major changes are in the dunes, as well as for 1978-1996. This year, they become barjanic and transverse barjanoides sand dunes, in the north, we can differentiate the extension of coverage for spraying (Fig. 9). There is a low representation of barjan. In the dune field located south of the estuary, it is noteworthy that the area near the estuary is devoid of mass contribution, and that is clearly seen that there is associated to vegetation, which has no clear traces of individual dunes.

For the year 2008 in the northern part there is a progressive decrease in barjans, reflected in the increased presence of barjanoides, as well as the largest area of spraying, these dune systems (barjanoides, barjans coalescing) cover large areas. Generate distinct forms. There is a continuous supply of material to the marine terrace, which is reflected not only in the designated spray, but also in the genesis and stabilization of dunes.

4. Discussion

4.1. Geodynamic system

In the Choapa mouth river system, the presence of the essential forms differ according to the area to be analyzed, so that in the proximal part, is a clear presence meandering course, while in the middle is not as noticeable presence estuarine banks. The depositional landforms in the

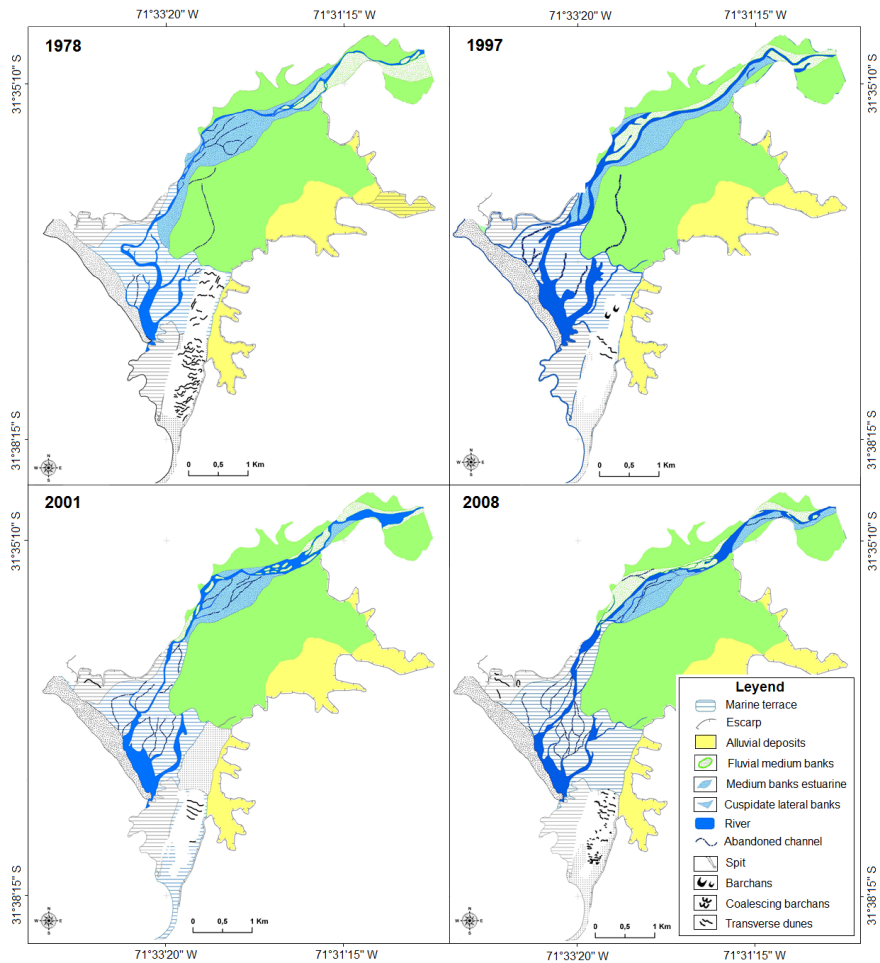


Figure 10. Dynamics Choapa Cove, since 1979 to 2008

middle (banks) have a great dynamic in the study period, varying in shape and location, a situation that hindered the categorization of these banks, in its identification as a river or estuarine. In the distal, zoning Araya-Vergara [3] is quite applicable, because the presence of estuarine lagoon and spit presence of essential forms to correspond to the characterization of this area. This condition is similar to the conditions analyzed in central Chile, as is the case of the Maipo [6], Aconcagua [7], Rapel [1, 3] and Itata [33].

From the point of view of the relative influence of the waves, tide and fluvial component [9, 34] in this estuary river influence seems to prevail, as evidenced by the presence of the spit, it demonstrate a continuous supply of sediment mass, which seems to be more evident in the last year analyzed. This condition is comparable to the situation in the Maipo [6] where the

spit remains almost intact over a long period of time. However, consider the case of the Maipo and Aconcagua morphoclimatic environments are restricted to the case of Choapa different, yet similar conditions exist particularly in the presence of the spit.

4.2. The relationship with the zone surf dynamic

The Choapa Cove present the sand dune complexes identified by Araya-Vergara [13]. There is a predominance sand dunes systems from of genetic barjanic, which also presents transmutation conditions and transmutation [14]. However, Choapa Cove there is a high wave energy because the width of the surf zone is enough. This becomes important as the contribution of mass: in the case of Choapa Cove is possible to see the *continuum* of dunes, led to the sand dunes

These processes are quite notorious during the study period (30 years), indicating a strong dynamics related to sediment this is where the component of the wave and surf zone type is important (Fig. 11), main component is transversal.

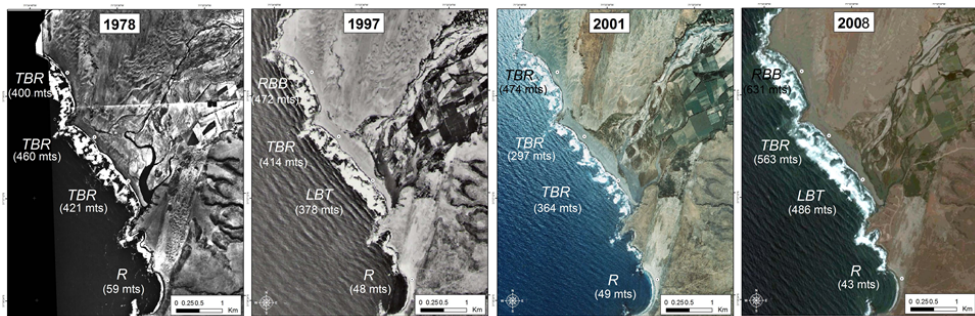


Figure 11. Space-time dynamics of wave-dominated beaches

5. Conclusions

In relation to the Choapa estuarine system, it presents conditions similar to those found in central Chile, mainly in the distal zone. Presents an estuarine lagoon flanked by a spit, which is quite stable in the middle section you can find river banks and estuaries, in alternancy. In the proximal part, the river is clearly a meandering stream.

You could say that the Choapa estuarine system realize greater sediment supply, because the river course change in the distal part in the review period: meandering change to a braided dynamic. So you can say that the system supplies material to the coast on a continuous basis over a period of 30 years.

In the case of Choapa mouth system, evolution has been much more pronounced: by 2007, the sand dunes barjanes change to coalescent barjan and barjanoides, and even become quite

transverse dunes. That is, in this system can be seen in 30 years the *continuum dunaris* from origin barjanic coastal sand dunes.

It is also important to note the change associated with the estuary Choapa, in 1978 is presented as meandering in its distal part, but in 2007, there are differential patterns that denotes a greater amount of sediment, resulting in an barided river in its distal zone. In addition, it adds to the change in the direction of the river. In the Choapa river system there are basic shapes, such as media cuspidate banks, lateral cuspidate banks and spit, which presents constant throughout the period under review.

For this reason, it opens the discussion about the limits proposed by Araya-Vergara [3] regarding the classification of estuaries and the possible conclusion that morphologically mouth system can be termed as estuarine delta and not as part of prograded rias system, by displaying dynamics similar characteristics with the mouths of central Chile, as the Aconcagua and Maipo rivers.

The calculation of the NDWI is a valid method for an automatic delimitation of a shoreline or boundary between ground and water corpses (like the estuarine lagoon) as is shown successful using the presented materials and being consistent with the overall data. However, the accuracy of this index is dependent of the pixel resolution, the preciseness of the geometric and atmospheric corrections, but even more dependent of the calibration phase of the break value between ground and water. This break value differs in every image but is always close to 0. A care photo interpretation can achieve a satisfactory boundary line between ground and water and obtain the data needed for an easy comparison between years.

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