Geogr. Fis. Dinam. Quat.
37 (2014), 51-66, 15 figg., 3 tabb.

DOI 10.4461/GFDQ.2014.37.6

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ASSESSMENT OF GEOMORPHIC PROCESSES AFFECTING THE PALEO-LANDSCAPE OF TONGOY BAY, COQUIMBO REGION, CENTRAL CHILE

Abstract: Soto M.V., Märker M., Rodolfi G., Sepúlveda S.A. & Cabello M., *Assessment of geomorphic processes affecting the paleo-landscape of tongoy bay, Coquimbo region, central Chile*. (IT ISSN 0391-9838, 2014).

The Tongoy bay (30ºS/70º30'W) and the related catchment system in the western fringe of the semiarid Chilean Coastal Cordillera consists of an inherited landscape subject to present-day geomorphic processes. It is an interactive morphological system, formed by coastal range watersheds, marine terraces and sandy beaches. Taking into account the geological setting, a detailed geomorphological survey has shown a particular landscape, which is interpreted as inherited from past tropical climatic conditions. Rock chaos and tors on granitic slopes, as well as the presence of palaeosol horizons on glacis and alluvial terraces, are evidences of this palaeoclimatic heritage. The current average annual rainfall in the area is *ca.* 70 mm; however, during ENSO events, a daily similar rainfall amount is reached. Thus, the area can be considered as affected by rainfall events of low frequency but of high intensity and magnitude. Consequently, the deeply dissected and eroded paleo-landscape system is further shaped during El Niño-related events. Hence, local hazard conditions are generated, especially in slope gullies, alluvial fans and glacis. The geomorphic dynamics related to these events consists of flooding, debris flows and linear/areal erosion processes, occurring especially in micro-catchments situated on the scarps of the highest marine terraces.

Key Words: Geomorphic processes, Geomorphic hazards, Inherited landscape, Semiarid region, Episodic runoff, GIS, Tongoy Bay, Chile.

Resumen: Soto M.V., Märker M., Rodolfi G., Sepúlveda S.A. & Cabello M., *Evaluación de procesos geomorpholÓgicos que influyen el el paleo-paisaje de la bahía de Tongoy, Región de Coquimbo, Chile central.*

La bahía de Tongoy (30ºS/70º30'W) y el sistema de cuencas modeladas en el borde occidental de la cordillera de la costa de Chile semiárido constituye un paisaje heredado pero con actividad geomorfológica actual, caracterizado por los sistemas de cuencas de la Cordillera de la Costa, terrazas marinas y playas arenosas. Los antecedentes geológicos existentes y las evidencias geomorfológicas halladas en terreno dan cuenta de un paisaje heredado de condiciones climáticas tropicales. Los caos de rocas y tors en las laderas graníticas, y los horizontes de paleosuelos en glacis y terrazas aluviales son evidencias de la herencia paleo-climática. Las precipitaciones anuales son del orden de 70 mm, pero aumentan considerablemente y de manera concentrada en relación con el fenómeno El Niño Southern Oscillation (ENSO). Consecuentemente, este sistema semiárido, profundamente disectado y erosionado, se reactiva cuando ocurren eventos de precipitaciones concentradas durante El Niño. Tales circunstancias se traducen en amenazas, de carácter localizado, asociadas a las quebradas torrenciales en las laderas, conos aluviales y glacis. Los procesos activos identificados en el área son inundaciones fluviales, flujos sobresaturados y erosión, sobre todo en las micro cuencas esculpidas en los escarpes de las terrazas marinas más altas.

Palabras Clave: Procesosos geomorfòlogicos, Amenazas, Paisaje herededado, Regiòn semi árida, Escurrimiento superficial episódico, GIS, Bahía de Tongoy, Chile.

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This work is funded by FONDECYT project nr1120234.

INTRODUCTION

The semi-arid coastal landscape of Chile is controlled by complex geomorphic systems. These systems show particular features and landforms inherited from different morpho-climatic domains. Hence, an assessment of the present day landscape must take into account both the inherited landforms and features as well as the present day forming processes. Accordingly, only a complex systems approach allows detecting changes and dynamics in coastal catchments of Central Chile. These driving factors behind the landscape evolution are tectonic activity, climate change, sea level changes and anthropogenic activities such as modifications of land use. The aim of this research is to decipher the landscape evolution dynamics in the Tongoy Bay area by means of a hydro-geomorphological survey and a detailed terrain analysis.

The headwaters of the Tongoy Bay area (30ºS/70º30'W) are located in the Andean highlands (*piso cordillerano*) and are characterized by amphitheatre-like features. The middle and lower catchments consist of deeply incised terrace systems. The area of Tongoy Bay has been already described as «Paleo-Bay of Tongoy» (Le Roux & *alii*, 2006). It has been shaped by processes generating a variety of landforms, varying in age and origin, under a climate different from the present semi-arid one. However, the landscape appears to be now in equilibrium, rather in rhesistatic conditions, than related to the inherited biostatic ones. Correlations among the landforms dated by Emparán & Pineda (2006) indicate a Mio-Pleistocene age. Field observations show that the inherited landform features developed under a humid tropical climate. Araya-Vergara (2000) attributes both deep rock weathering and tor-like forms to both climatic and uplift events that occurred during Miocene along the coastal range of Central Chile. Soto & *alii* (2007) correlate the erosional surfaces and the deep weathering of the coastal range of Santiago (33ºS) to the same period. Strudley & *alii* (2006) confirm the close relationship between the deep rock weathering and the presence of tor-like landforms.

Another group of inherited landforms is composed by marine terraces, belonging to the Coquimbo formation (Miocene to Pleistocene). They are the result of a series of transgressions and regressions related to local and regional tectonic movements, combined with the global variations of sea level (Le Roux & *alii*, 2006). Pfeiffer & *alii* (2011) describe the Pleistocene littoral bars preserved on these marine terraces, which can be correlated to specific sea levels in the past. Saillard & *alii* (2012) have dated the marine terraces in Tongoy Bay. The oldest one, at 200 m.a.s.l. that can be observed only in Altos de Talinay, belongs to MIS 11; other terraces have been dated as MIS 7e, MIS 5c and MIS 1 (see table 1), associated to interglacial periods and evidencing the importance of positive tectonic movements in the study area.

Concerning the endogenous geomorphological processes the study area is inserted in the seismic gap of Coquimbo (Vigny & *alii*, 2009) or Illapel (Pardo & *alii*, 2002). The 1943 Illapel earthquake with a magnitude of 7.9 triggered a tsunami wave of 4 to 5 m (Beck & *alii*, 1998). Other eartquakes were recorded in 1647, 1730 and 1880. The recurrence time of big seismic events is roughly between 60 and 150 years. Thus, the study area can be considered as a highly seismically active area. Recent studies about seismicity and crustal deformation of the Coquimbo area (Vigny & *alii*, 2009) show that tension is increasing for a future interplate event. In this study we have taken the seismic activity into account as a triggering factor of dynamic processes that can affect the inherited landforms.

TABLE 1 - Absolute age of the marine terraces of the Tongoy paleo-bay (source: Pfeiffer, 2011)

Terrace	Elevation at scarp foot	Age (Ka)	Method	References
T II	200 m	412	U-Th (marine fossils)	Saillard (2008)
T III	48 m	225	10 Be (Altos de Talinay	Saillard *et al.* (2009)
T IV	14 m	123	U-Th (marine fossils)	Saillard (2008) Ota *et al.* (1995
T V	9 m	6	10 Be (Altos de Talinay)	Saillard *et al.* (2009) Ota y Paskoff (1993)

However, climate change appears as a factor that may influence more intensively the present day geomorphic processes. As an example, the El Niño/ Southern Oscillation (ENSO) triggers various hydro-geomorphological hazards and thus has an effect on landscape evolution. Mean annual rainfall at Coquimbo is around 75 mm (Diaz, 2005), but it can rapidly increase up to 199 mm, with 104 mm during June, and 34 mm in 24 hours, as recorded for the El Niño event in 1997.

Considering this synergy of factors, the interpretation and reconstruction of the landscape genesis is becoming quite complex, since one has to take into account endogenic (Sepúlveda & *alii*, 2010, 2012) and exogenic process dynamics on different spatio-temporal scales. The features of the actual landscape are consequently not only due to inherited processes and landforms, but also due to exogenous stress, such as extreme rainfalls events (Vargas & *alii*, 2000; Sepúlveda & *alii*, 2006).

The small scale landforms, such as talwegs and micro-catchments, show a dynamic response to present day concentrated rainfall events, as indicated by Sarricolea & Martín-Vide (2012), who pointed out that the La Serena-Coquimbo area is characterized by the highest rainfall Concentration Index (IC) in Chile. Those landforms are inserted into larger ones (terraces, glacis, fault systems or alluvial fans), interpreted as inherited features. The general aim of this research is to decipher the landscape evolution dynamics and the acting hydro-geomorphological processes. Therefore we combine a detailed hydro-geomophological field survey with a quantitative modeling approach. The latter one consists of a detailed terrain analysis and hydrological modeling approach that reveal both: i) the morphological features of the paleolandscape and ii) the present day landscape-shaping processes.

METHODOLOGY

The methodological approach employed in this research is based on the analysis of inherited landforms, now moulded by the present geomorphic processes. These landforms, that are different in genesis and age, are characterizing a particular landscape, composed of coastal watersheds, alluvial plains and marine terraces, that coexist with incised talwegs associated to the tectonic activity (Paskoff, 1970; Le Roux & *alii*, 2006, Saillard & *alii*, 2009, Pfeiffer & *alii*, 2011; Pfeiffer 2011).

Materials and Methods

The geological and geomorphological features were characterized starting with the subdivision of landforms in groups. The classification of slope systems (Araya Vergara, 1985, 1980) was applied in order to characterize the genesis and the dynamics of the fluvial catchments. The lithological information was extracted from Emparán & Pineda (2006), who makes a distinction between volcanic and plutonic systems. Moreover, erosional and depositional landforms that are present at footslopes, as alluvial fans or glacis, were recognized. On the major slope systems, *talwegs* were identified, mapped and classified as semiarid torrential streams (Araya-Vergara, 1985; Soto & *alii*, 2007, 2012).

The hydrology of the stream channels was assessed according to the concept of the fluvial *continuum* (Schumm, 1977). The streams draining the coastal range have a length of up to 35 km. Terraced landform levels T' and T° (*sensu* Tricart) were identified using GIS analysis taking into account as a reference the present day drainage network. Moreover, the drainage density and the longitudinal profiles of the main streams draining into Tongoy Bay were analyzed, and important information on the system's status were obtained.

On the basis of previous works done by Paskoff (1970, 1999), Le Roux & *alii* (2006); Saillard & *alii* (2009), Pfeiffer & *alii* (2011), Pfeiffer (2011) the marine terraces were identified; in particular, the denudational slope processes acting on the marine terraces of Tongoy Paleo-Bay (Le Roux & *alii*, 2006) were studied.

The present day fluvial and slope processes were assessed utilizing topographic indices as proposed by Märker & *alii* (2001, 2008, 2011). The *Stream Power Index* (SPI) is a measure of the erosive power of concentrated water flows or streams. In other words, it constitutes an index of the available energy for detachment and transport of soil particles, often in form of turbulent flows. The *Topographic Wetness Index* (TWI) expresses the potential runoff due to soil saturation. Generally speaking, after long precipitation periods the soil is saturated and produces runoff due to a saturation excess. Additionally, high TWI values on slopes indicate an elevated landslide potential, due to higher weight of the saturated substratum (Montgomery & Dietrich 1998a/b, Tucker & Hancock 2010). The *Transport Capacity Index* (TCI) is used as an indicator of the laminar erosion processes in transport limited conditions. Furthermore, storm flows and flooding areas were assessed with a SCS (Soil Conservation Service) Curve Number approach (CNII) (USDA 1986, Hawkins & *alii*, 2009) implemented in the SAGA GIS (System for Automated Geoscientific Analyses - see Conrad 2006; Olaya & Conrad 2008). This approach yields in a spatially distributed way the maximum runoff for a given precipitation event and certain land use and soil infiltration characteristics. For the GIS-based hydro-geomorphological analysis we utilized an SRTM (Shuttle Radar Topographic Mission, USGS) Digital Elevation Model (DEM) with 25 m resolution. The DEM was preprocessed with low pass filtering to extract artefacts and errors like local noise and artificial terraces (Vogel & Märker 2010). Subsequently, the DEM was hydrologically corrected eliminating sinks using the algorithm proposed by Planchon and Darboux (2001).

By means of this approach the areas subject to both areal/linear erosion processes and landsliding, were identified and the level of their intensity was assessed.

Moreover, information on the inherited landscape features by normalizing the present day topography, given by the DEM were derived, with an interpolated surface of the longitudinal profiles of the mayor drainage systems. Here the third order streams, according to Strahler (1952), to interpolate the base level were utilized. The resulting map represents the Vertical Distance to the River Network. This index yields information about corresponding river terraces and marine terrace levels as well as the distribution of beach ridges, glacis remnants, tor structures, and the general effects of tectonic activity.

Study Area

The study area of Tongoy Bay stretches between the Lengua de Vaca Point (Altos de Talinay) and the Bahía Barnes, starting from the highlands of the Andean Cordillera down to Pacific shoreline (fig. 1). The area consists of small catchments of the coastal sector of the Cordillera, formed by slope systems modeled in the Volcanic Complex Agua Salada and in intrusive Jurassic formations, on the Eastern side. The Western side is dominated by the Altos de Talinay Plutonic Complex (Emparán & Pineda, 2006). The structural pattern of the valleys draining to-

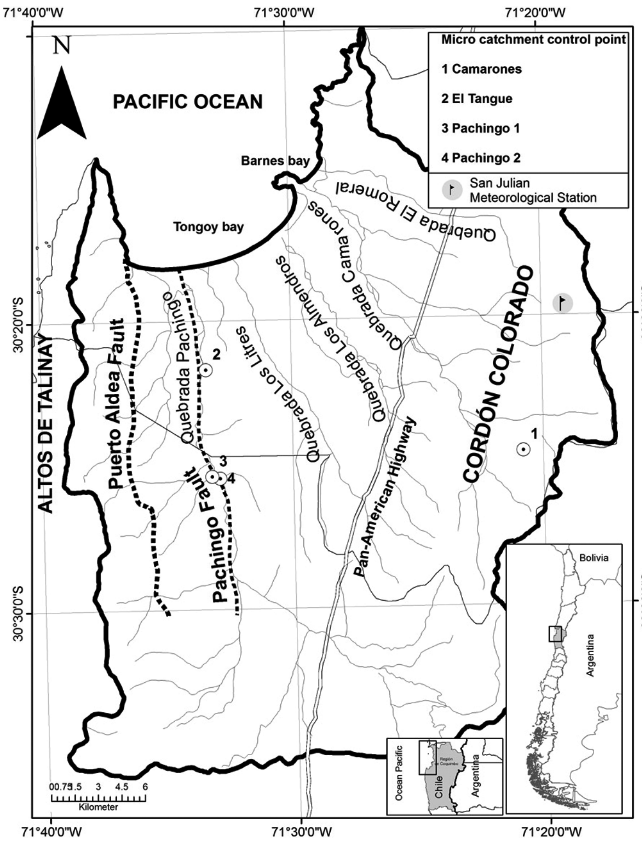


FIG. 1 - Tongoy Bay study area.

wards the Tongoy Bay is characterized by the Puerto Aldea fault and the Pachingo fault (fig. 1). The other dominant landforms are the marine terraces of the Tongoy Paleo-Bay (Le Roux & *alii*, 2006), tectonically raised and incised by the drainage system (fig. 2). There is a sequence of five marine terraces, described by Paskoff (1970), staggered from Holocene to Plio-Pleisocene. The Coquimbo Formation is the most representative, with marine, fossiliferous sedimentary sequences (Emparán & Pineda, 2006). Le Roux & *alii* (2006), Saillard & *alii* (2009), Pfeiffer & *alii* (2011), Pfeiffer (2011) studied the genesis of the marine abrasion terraces in the Tongoy Bay (tab. 1) emphasizing the tectonic uplift and the presence of beach ridges on these terraces.

RESULTS

Geomorphological map and general features of the study area

Two sets of catchments were identified, the granitic and the homoclinal systems over volcanic substratum (fig. 2). In the upper portions of these systems the exposed strata reach their highest gradients, ranging between 30° and 60°. Granitic slope systems are less steep (15°-30°), emphasizing a surface coating consisting of abundant debris mantle also accumulated in the stream network. This material results from weathered granodioritic rocks, that in turn are exposed in form of tors and blocks of various sizes. The presence of torrential streams is an inherited pa-

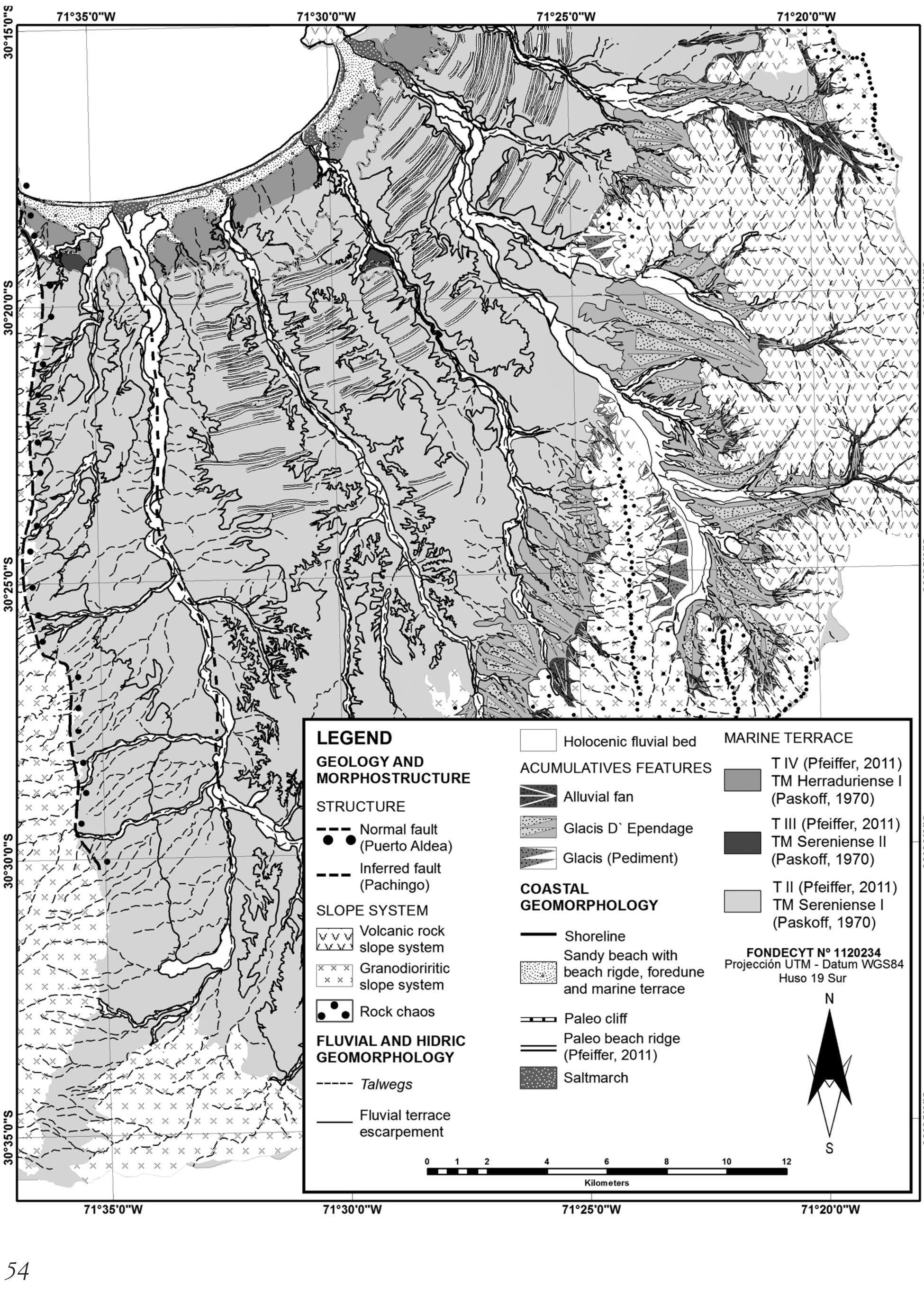


FIG. 2 - Geomorphological map.

leo-environmental condition, but also corresponds to the current landform dynamics, under the prevailing semiarid regime. The incision of the drainage pattern and the freshly transported and deposited materials are an evidence of this dynamics.

The basal landforms correspond to the torrential alluvial fans that characterize all slope systems of Tongoy Bay. The size of these fans depend on the feeding sub-catchments and they are regarded as torrential-like due to the gradient and the convexity of their surface. These fans are often coalescing and their distal parts overlap with glacis-like forms. The alluvial fans described and mapped in fig. 2 are not the result of current morphogenesis; they have to be considered as inherited landforms. However, they show evidence of activity only in the main stream sections that are now dissecting the fan apparatus. This activity is associated with sporadic surface runoff in case of heavy rainfall events.

The glacis landforms found in the Camarones basin are the morphologic key to understand the watershed systems and the inherited correlative forms. They can be described as large expansion glacis, with very gently sloping surfaces, without convexity, no recognizable apex and parallel drainage along the slopes, down to the main drainage system. Figure 3 illustrates these terraced glacis surfaces composed of breccias and conglomerates of Miocene-Pleistocene age, (Emparan & Pineda, 2006). Some pedogenetic features, like abundant iron oxides and deeply weathered profiles on these glacis-terraces, suggest that these landforms are inherited from humid-tropical climate conditions. The inherited dissection can be observed in form of distal and side escarpments with a height of about 20 m. Under the present day conditions the parallel streams draining the area produce linear gully-type erosion landforms on the gently sloping glacis surface (fig. 4). The

FIG. 3 - Camarones expansion glacis (*glacis d'épendage*).

FIG. 4 - Distal part of Camarones expansion glacis. The gullies drain into the present Camarones stream and represent the recent processes in these semiarid coastal catchments.

presence of torrential streams on the slopes, fans and glacis are the geomorphological evidence of the action of water under the current semiarid conditions.

The relative dimension of the coastal mountain front correlates with the size of expansion glacis. The coastal mountain front is characterized by steep slopes on granodioritic and volcanic substrata, from where fans and expansion glacis developed. At least two fan generations can be observed (fig. 5). In this case the presence of soils that allowed wheat cropping until a decade ago is remarkable and related to past anomalies of the pluvial regime at these latitudes.

Torrential beds and channels

The observed drainage system presents a dynamic pattern of entrenched meanders, which evolved in function of discharge and tectonic changes. The talwegs are of epigenic origin and drain the expansion glacis as well as the marine terraces. In these landforms the depth of incision and amplitude of the main valleys, such as Quebrada Pachingo, Quebrada Los Litres, Quebrada Almendros y Quebrada Camarones are remarkable. Quebrada Camarones was estimated to have a maximum depth of 134 m and a width of 719 m of its bottom; Quebrada Pachingo is up to 192 m deep and 353 m wide. The morphometric parameters of the channel-beds of both Camarones and Pachingo ravines, as well as the subcatchments of Pachingo 1, Pachingo 2, El Tangue were analyzed, showing similar patterns. The drainage density of Quebrada Pachingo 1 and 2 are comparable; but this is not the case of El Tangue, which is a very small subcatchment, but showing the highest index of drainage density if compared with Quebrada Camarones, the biggest catchment in the study area (see tab. 2). However, when comparing the drainage hierarchy between the smaller and larger subcatchments, the difference between them is minimal, although presenting a differential response to exogenous dynamics, due mainly to overland flow and associated debris flows: the smaller subcatchments have a faster response to generate high intensity runoff and local debris flows under heavy and short rainfall events. However in the Camarones catchment, the biggest of the study area, such processes need 24-48 hours of heavy rainfall. Another important difference is that the smallest catchment has developed from gully evolution in the fossiliferous terrace scarp, while the Quebrada Camarones catchment corresponds to volcanic and granodioritic rocks belonging to the Coastal Cordillera.

TABLE 2 - Values of some morphometric parameters of selected catchments in the Pachingo and Camarones quebradas

Catchment	Coordinates	Morphology	Drainage density	Catchment area	Perimeter	Basin hierarchy
Camarones	269094.05 E 6638737.48S	Slopes in volcanic and plutonic rocks	1.78	109.33 km^2	64.44 km	4
El Tangue	254195.41E 6638425.19S	Scarp of marine terrace (fosiliferous)	11.45	1.42 km^2	9.59 km	4
Pachingo 1	255142.31E 6631440.79S	Scarp of marine terrace (fosiliferous)	7.00	9.11 km^2	15.56 km	5
Pachingo 2	254619.04E 6631561.49S	Scarp of marine terrace (fosiliferous)	7.14	9.11 km^2	15.56 km	5

FIG. 5 - Glacis on volcanic slopes at the upper Quebrada Camarones. Silt layers with blocks and tors above a terrace are shown. Abandoned wheat field can also be seen.

These smaller catchments are characterized by recent activity of their talwegs, although in Camarones catchment the recent activity, in form of small linear incisions, has been only observed on slopes, fans and glacis surfaces. The strong activity of the smaller subcatchments is proved by the presence of fresh rocky blocks in the talwegs, as a response to heavy rainfall events which happen with low frequency in the coastal semiarid domain.

Within the major river beds Holocene flood activity can be identified, recognizing the T° and T´ terrace levels, which are related to meandering and braided channel pattern. However, these talwegs show a present-day activity as torrential streams, with heterometric alluvial deposits and fresh blocks (fig. 6).

Marine terraces and sandy beaches

Marine terraces and sandy beaches are other characteristic landforms in the Tongoy Bay area, formed by a succession of stepped terraces composed by marine and fluvial sediments of Miocene to Pleistocene age (Emparán & Pineda, 2006). The terraces are tectonically uplifted and deeply incised by the coastal range catchments (fig. 1 and 2, tab. 1). These landforms have been described and dated by the previously referenced authors; nevertheless, some geomorphic and dynamic features can be highlighted. On the marine terraces a series of gullies have developed due to local epigenic processes (fig. 6 and 2); the terrace surface present an introduced vegetation of *Atriplex* and calcrete formations. The presence of pedogenesis in these units is an important feature, as it is related to deep surface dissection and gullying.

On the scarp areas of the subcatchments the intense rainfall-induced erosive action produces activation of the gullies, which dissect Holocene terraces T´ and T° especially in the medium and distal sections. These events also feed the lagoon zones along the shoreline, characterized by shallow waters.

Close to the terrace scarps described by Pfeiffer (2011), that stretch parallel to the present day coastline, beach ridges are present. These beach ridges are accompanied by foredunes, which document the sand supply from the beaches.

Present day geo-hydrological processes

Present day hydro-geomorphological processes identified in the area include floods in the gullies as well as debris flows and flash floods on the slope systems. According to local witnesses, during the 1997 El Niño the Pachingo stream flooded the valley entirely, including the T´ terrace level, located 2-3 m above the stream bed. Small debris flows can also be triggered by these events in lateral gullies (fig. 7). Intense precipitations occur in the coastal semiarid region mainly related with El Niño and Pacific Decadal Oscillation (PDO). The rainfall amount in La Serena is around 75 mm, but increases significantly during El Niño events, when in a few hours the rainfall amount gets close to, or is even higher than the average annual rainfall, as

FIG. 6 - Presently active water course beds in the Quebrada Camarones catchment. Left: river bed, upper part of the basin. Centre: torrential tributary bed. Right: river bed in the distal catchment section of the Quebrada Tongoy; basal dissection is recent and probably due to the last El Niño event, in 1997.

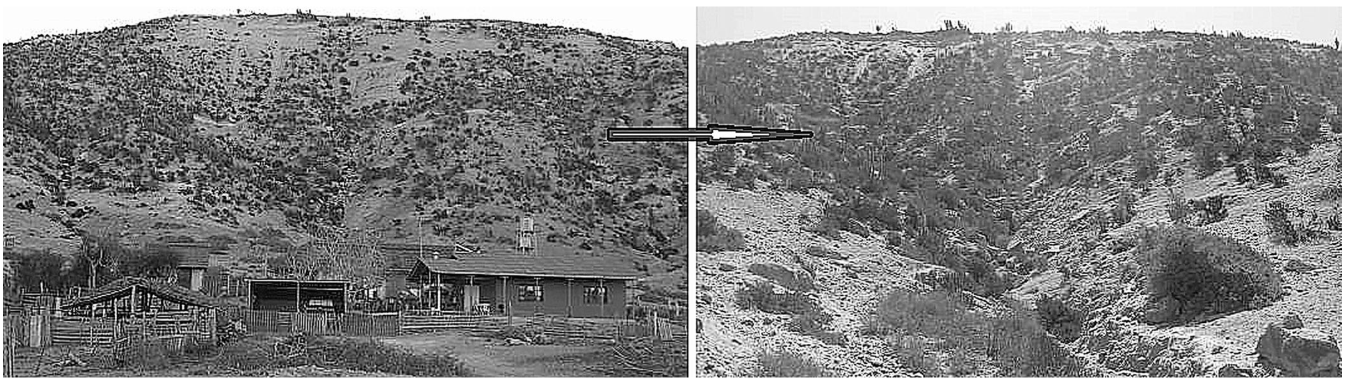


FIG. 7 - Example of active slope on fossiliferous marine terrace. Quebrada Pachingo.

shown in table 3. The intense 2011 rainfall events (tab. 3) can be related to Pacific Decadal Oscillation (PDO) in a La Niña period (Romero & Mendoca, 2011).

Quantitative assessment of landscape dynamics

In order to detect and quantify the present day landscape forming processes as well as the inherited landforms detailed terrain analysis was carried out. Inherited landscape pattern were assessed using the vertical distance to the present day river network. As a threshold value to define the starting point of the river network a critical catchment area of 50 km^2 was utilized. This is corresponding to a third order stream according to Strahler (1952). The longitudinal profiles of the defined drainage network were subsequently interpolated to generate a base level that in turn is then subtracted from the present day DEM. With this analysis three mayor terrace levels were identified, given as elevation above stream network base level at 10-30 m; 60-80 m; and 90-110 m (see figs. 8,

TABLE 3 - Extreme rainfall events registered at San Julián (Tongoy) and La Serena stations

Rainfall during El Niño events	Other rainfall events	
1983: La Serena station	**1984: La Serena station**	
160,1 mm total annual	148,8 mm total annual	
69,5 mm/24hrs (July)	40,0 mm/24 hrs (July)	
1997: La Serena station	**2009-2011: San Julián station, Tongoy.**	
221,8 mm total anual	> 40 mm of cumulated rainfall in 24 hrs	
100,0 mm (July)	**6-6-2011 48,31 mm**	
30,0 mm/24hrs (July 11)	**9-6-2011 63,15 mm**	
30,0 mm/24hrs (July 12)	Cumulated rainfall > 10 mm in 6 hrs.	
40,0 mm/24hrs (August 15)	**28-6-2009 24,34**	
	15-8-2009 11,22	
	14-6-2010 21,98	
	18-6-2010 11,79	
	05-6-2011 11,79	
	06-6-2011 30,15	
	18-6-2011 17,99	La Niña
	19-6-2011 21,57	
	20-6-2011 17,79	
	15-7-2011 11,19	
	2011: La Serena station	
	70mm/13 hrs (June)	La Niña
	96mm/24 hrs (June)	

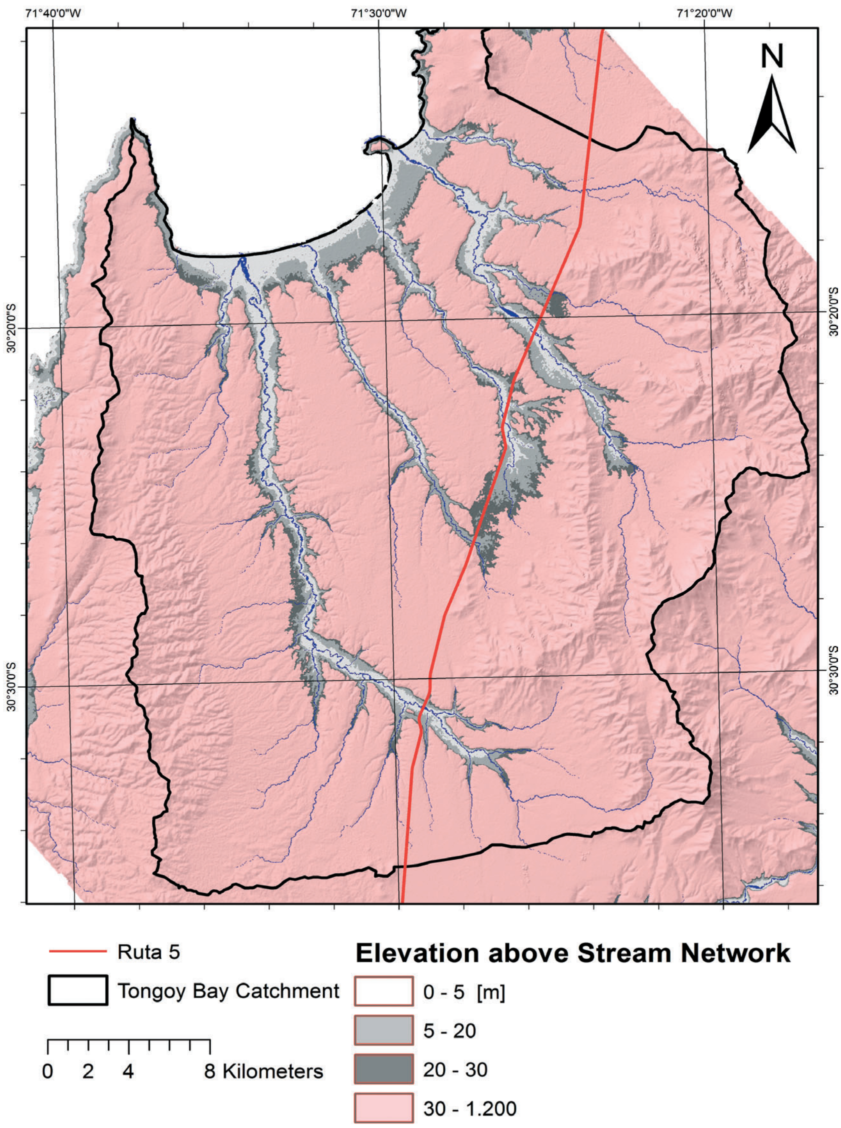


FIG. 8 - 1st terrace level (10-30 m) above channel network (grey below 10 m; red above 30 m).

9, 10). The highest level of 90-120 m seems to be tectonically uplifted and is characterized by conglomerates and fluvial breccias classified by Pfeiffer & *alii* (2011) as T^{II} level. This T^{II} level corresponds to an absolute elevation of ca. 200 m above sea level. The terrace T^{III} level (10-30 m above stream channel base level) corresponds to the basis of the dissected fan and glacis structures According to Pfeiffer & *alii* (2011) absolute elevations of 9-14 m can be attributed to the terrace T^{III} level. Whereas the 60-80 m elevation above stream channel base level marks the basis of the non dissected part of the glacis and fan apparatus. We define this level as an intermediate stage not recognized by Pfeiffer & *alii* (2011). The absolute elevations of this T^{IIa} terrace is about 90-120 m. Figures 9 and 10 show the areas that according to our reconstruction lie below sea level (grey) or remain emerged (red). The analysis highlights the strong correlation of the lower two terraces T^{II} and T^{IIa} with the fluvial terrace levels identified in the field.

In the following hydrogeomorphological results are presented, based on a detailed terrain analysis. The results are calibrated and validated visually by comparing with Google Earth World View data for the soil erosion pattern and by own fieldwork for the fluvial morphology. The discharges and flooding analysis was calibrated with measured stream morphological features like stream width.

Figure 11 highlights detected tor structures (see rectangles). It is clear that the tor structures are related to the local basement. Thus, they represent erosional landforms

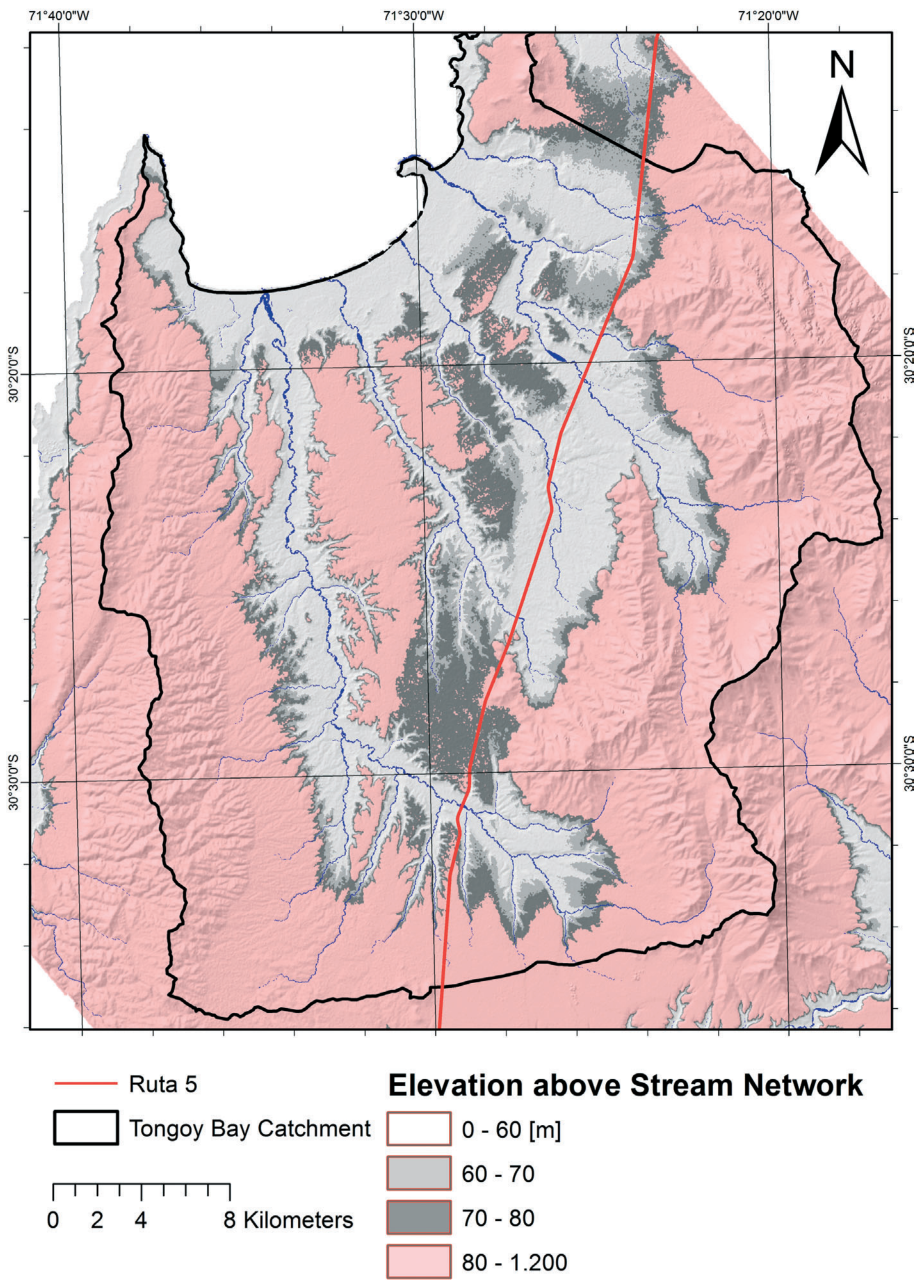


FIG. 9 - 2nd terrace level (60-80 m) above channel network (grey below 60 m; red above 80 m).

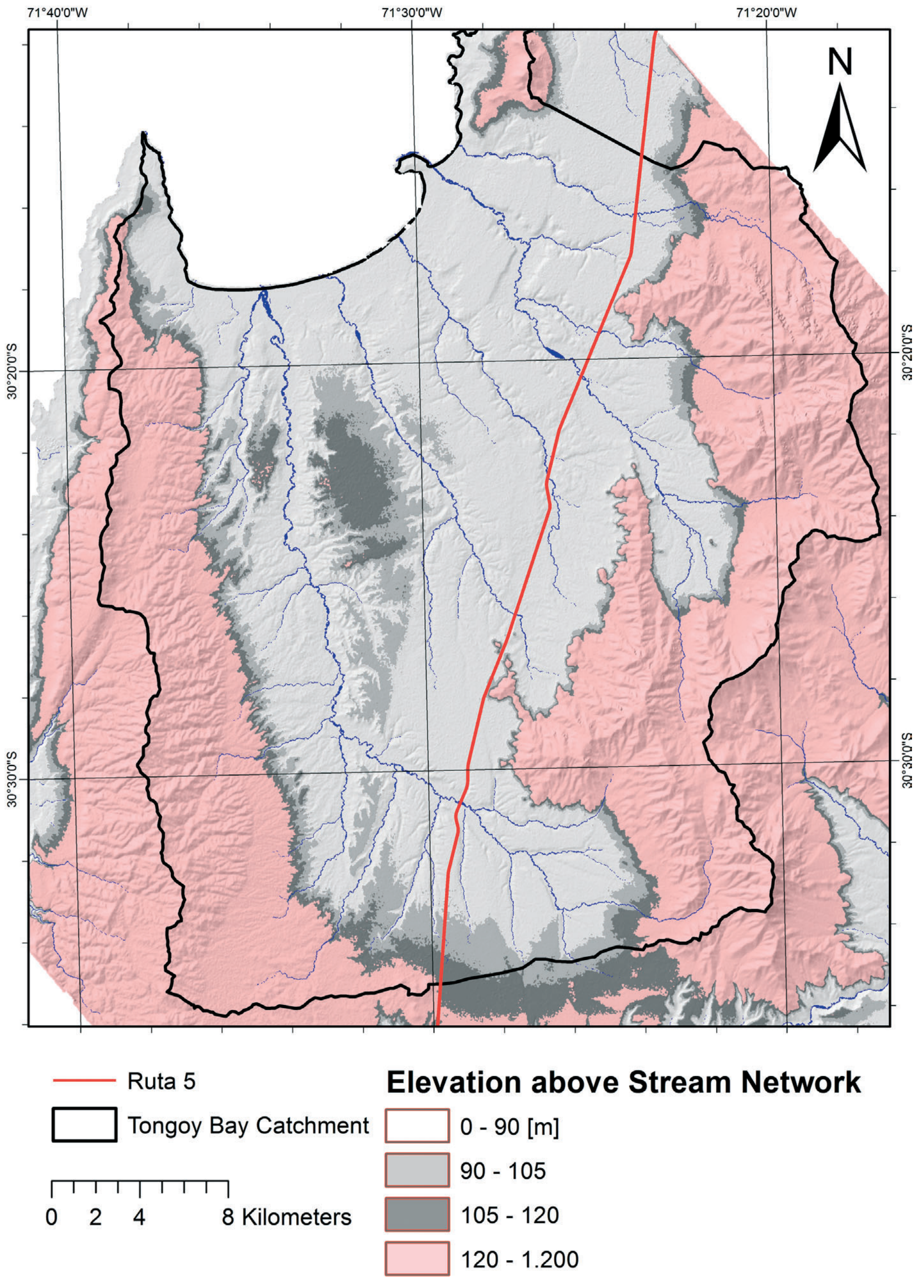


FIG. 10 - 3rd terrace level (90-110 m) above channel network (grey below 90m; red above 110 m).

associated with intensive chemical weathering processes, indicating a different climatic regime during their formation. Moreover, in the central bay area drainage pattern parallel to the coast line and 90° to the main drainage systems indicate the palaeo-beach ridges and marine regression stages. The deposits of these stages are more resistant and are build up by concretions. Consequently, they trigger the drainage pattern in this specific way. Figure 12-14 illustrate the present day process intensities concerning areal, surficial erosion (TCI) (fig. 12), deep linear erosion (SPI) (fig. 13) and areas prone to flooding and ponding of water (TWI) (fig. 14). Soil erosion is mainly concentrating along the escarpments of the incised higher most surface levels (fig. 12). However, also the tectonically induced erosion processes are clearly visible especially in the Quebrada Pachingo. The western slopes are less steep and hence exhibit a lower erosional potential than the steep eastern flanks (see fig. 12). Especially in the convex slope zones and the upper part of terrace incisions high erosion potentials are detected. Nevertheless the western slopes of the Quebrada Pachingo are characterized by a higher drainage density and a wider aerial extent of erosion processes even if they generally show lower intensities. Linear incision processes are exclusively limited to the main drainage network and especially in the upper parts of the catchments as illustrated in fig. 13. Ponding and flooding are primarily associated with the flat valley bottoms and with the very flat terrace surfaces. Figure 15 reveals the energy available

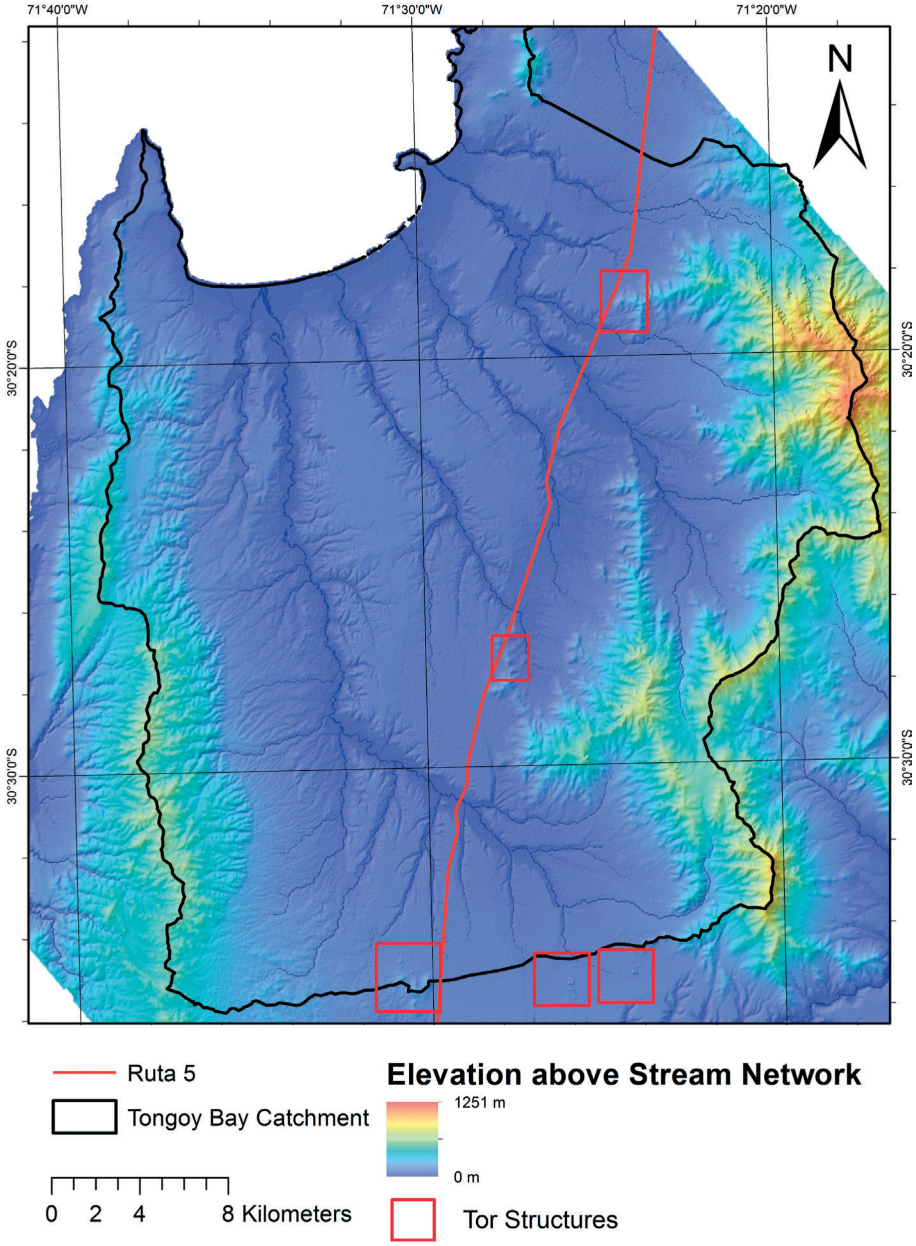


FIG. 11 - Topography normalized by longitudinal profiles of the rivers draining to Tongoy Bay. Vertical distance to channel network in m. Red boxes show tor structures.

for erosion processes and transport of the produced sediments. For a 63 mm/day precipitation event (see tab. 3) we calculated discharges up to 22 m^3/s in the main drainage systems. Even in the smaller tributaries we simulated discharges up to 10 m^3/s. However, the zones at flooding risk are mainly the deeply incised river channels of the Central Bay area.

DISCUSSION

The study area represents a landscape characterized by inherited features. The geomorphology is associated with Miocene-Pleistocene environmental conditions (Paskoff, 1970; Emparán & Pineda, 2006; Le Roux & *alii*, 2006; Pfeiffer & *alii*, 2011; Pfeiffer 2011). The identified geomorphologic systems, such as marine terraces, alluvial fans and glacis, correspond to sedimentologic and pedologic evidences indicating tropical conditions in the past. These conditions can also be documented by the presence of rocks chaos and tors on the granitic slopes, and the evidences of pedogenetic features found in the palaeo-soils developed on the fluvial terraces and glacis.

However, the present day coastal semiarid morphoclimatic regime is dominated by exogenous geomorphological activity whenever intense and concentrated rainfall events occur leading to overland flow, torrential and fluvial processes that follow inherited landforms and further shape and enlarge them. This is also documented by the distribution of present day erosional processes (fig. 12-15).

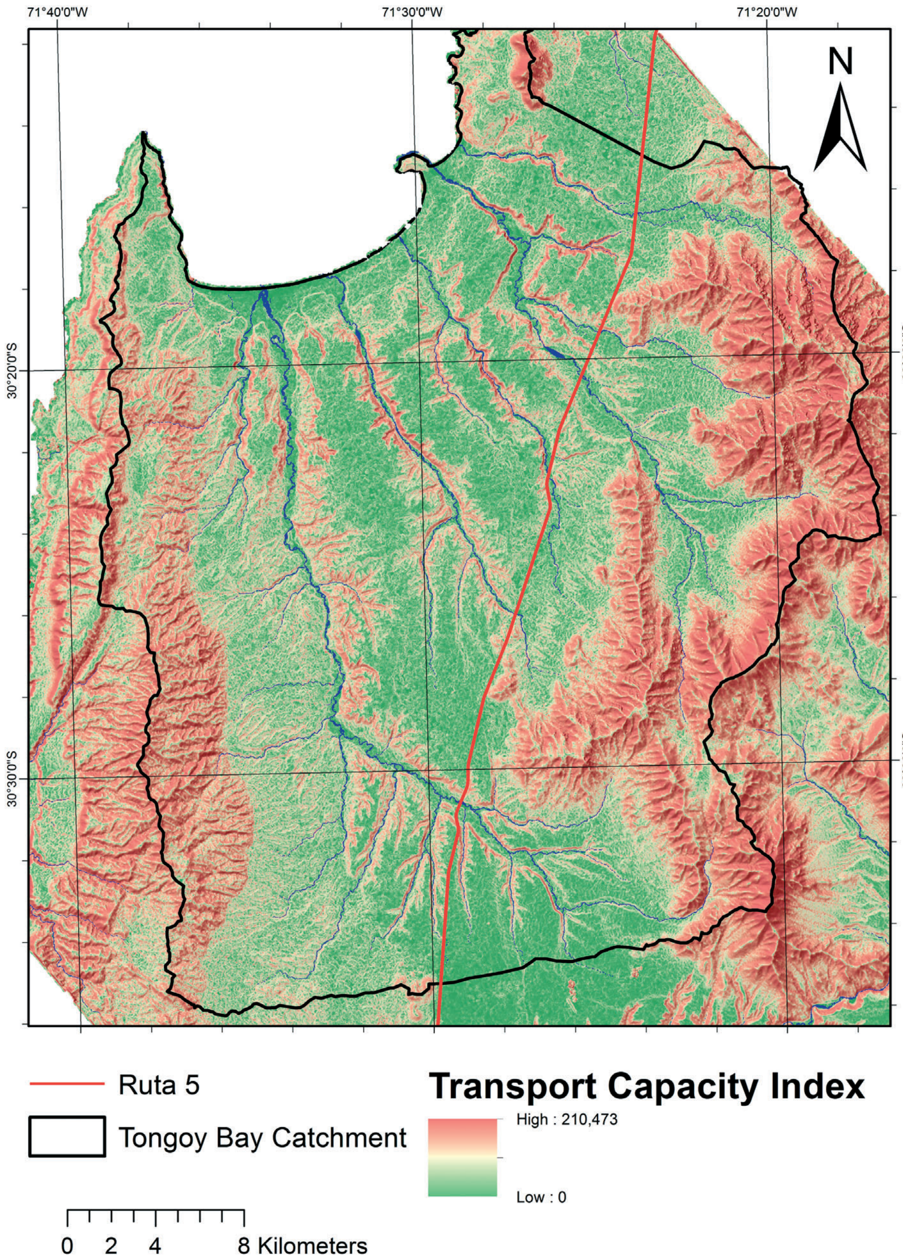


FIG. 12 - Transport Capacity Index of the Tongoy Bay cacthments.

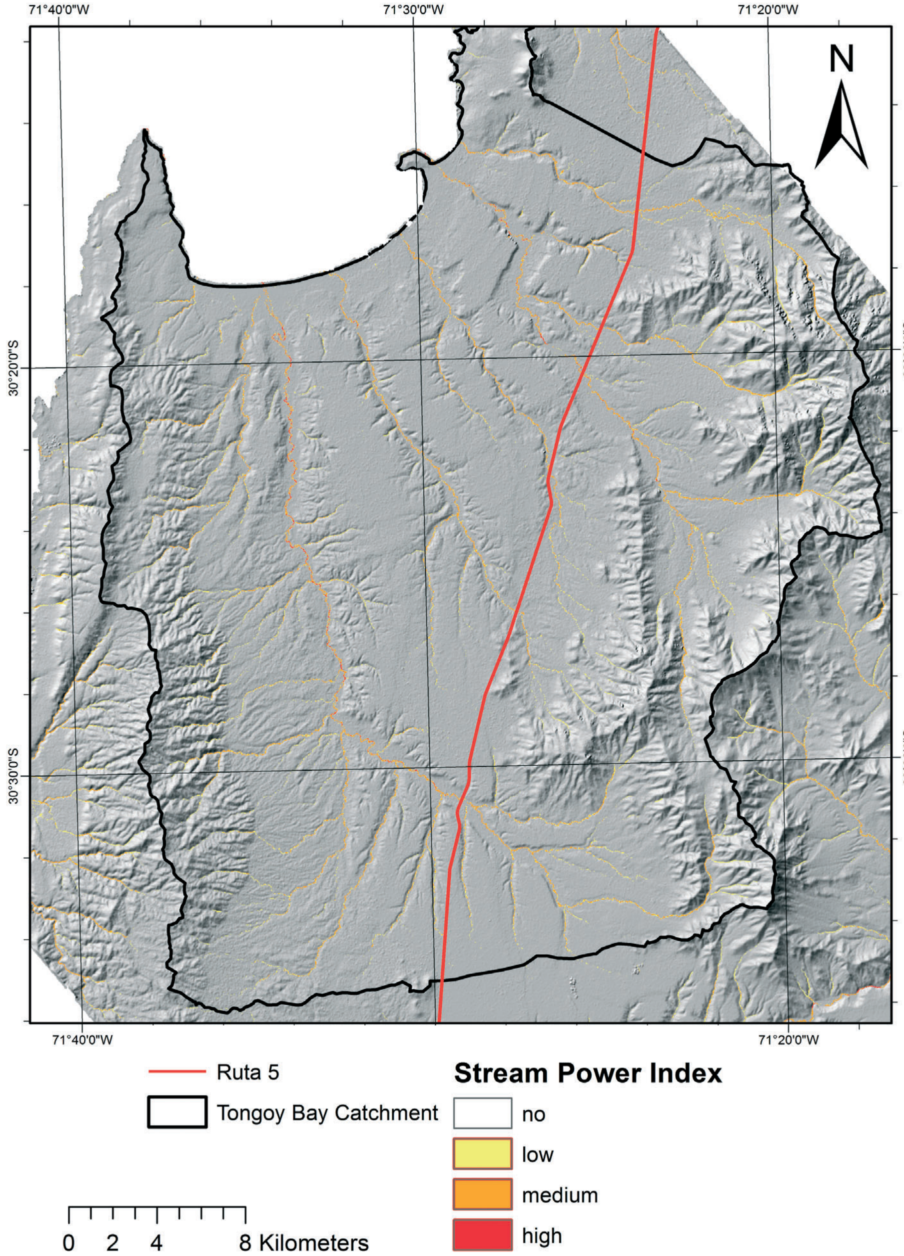
Linear erosion and incision is mainly concentrating in the already existing channels and entrenched terrace levels. Additionally, areal rill and inter-rill erosion is mainly correlated with the convex upper parts of the escarpments of the entrenched terraces.

Furthermore the area is characterized by the highest rainfall Concentration Index of Central Chile (Sarricolea & Martín-Vide 2012). The recorded rainfall generally reach the debris flows triggering thresholds documented by Vargas & *alii* (2000), Sepúlveda & *alii* (2006) in northern and central Chile. Hence, the conditions causing river flooding, debris flows and erosion are given under the present day climatic situation. Particularly when the low rainfall amount in the area is strongly increasing during El Niño, La Niña (ENSO) and Pacific Decadal Oscillation (PDO) events (Romero & Mendoca, 2011).

However, the field analysis of the inherited and active forms point out that: i) the incised river beds still show active forming processes and ii) especially the smaller basins have a very rapid response to concentrated rainfall events.

This is in line with the quantitative assessment of the DEM yielding concentrated discharge along the main drainage systems up to very high runoff volumes. The 63 mm event registered at St. Julian Station, Quebrada Tongoy, on the 09.06.2011 yields a maximum runoff volume of about 22 m^3/s. These values indicate that incision processes may be very intensive during these events mainly in the upper parts of the catchment (fig. 15). Especially in the

FIG. 13 - Stream Power Index of the Tongoy Bay cacthments.



smaller tributaries still runoff volumes between 2 and 10 m^3/s were modeled. Concentrating runoff also provoke slumps and smaller landslides due to undercutting particularly on the steeper flanks of the incisions. The latter ones were observed also in smaller drainage catchments. However, the discharge may become also hyper-concentrated if such landslides occur along the river channel. Generally, in the lower sections of the river systems no further incision is observed. Here the discharge lead to lateral erosion processes that in turn further steepen the talus scarps.

The field work and the quantitative assessment also reveal very high activity along the scarp section of marine terraces due to slope gradients and erodible fossiliferous substrata. The fluvial terraces show similar dynamics. The terraces T' and T° are easily eroded by concentrated flows.

The impacts due to the reactivation of streams on slopes, alluvial fans and glacis, is local, limited to the forms in activity. Thus, especially the development of rills and gullies in micro catchments localized in the scarp-areas of the terraces, is very effective and favored by high slope gradients, erodible substrates and scarce vegetation density. These dynamics are typical for the coastal desert environment as also described by Vargas & *alii* (2000), Sepúlveda & *alii* (2006), Soto & *alii* (2012). The process dynamics during ENSO/PDO may be enhanced if coinciding with seismic events. The latter trigger landslides that in turn increase the amount of de-

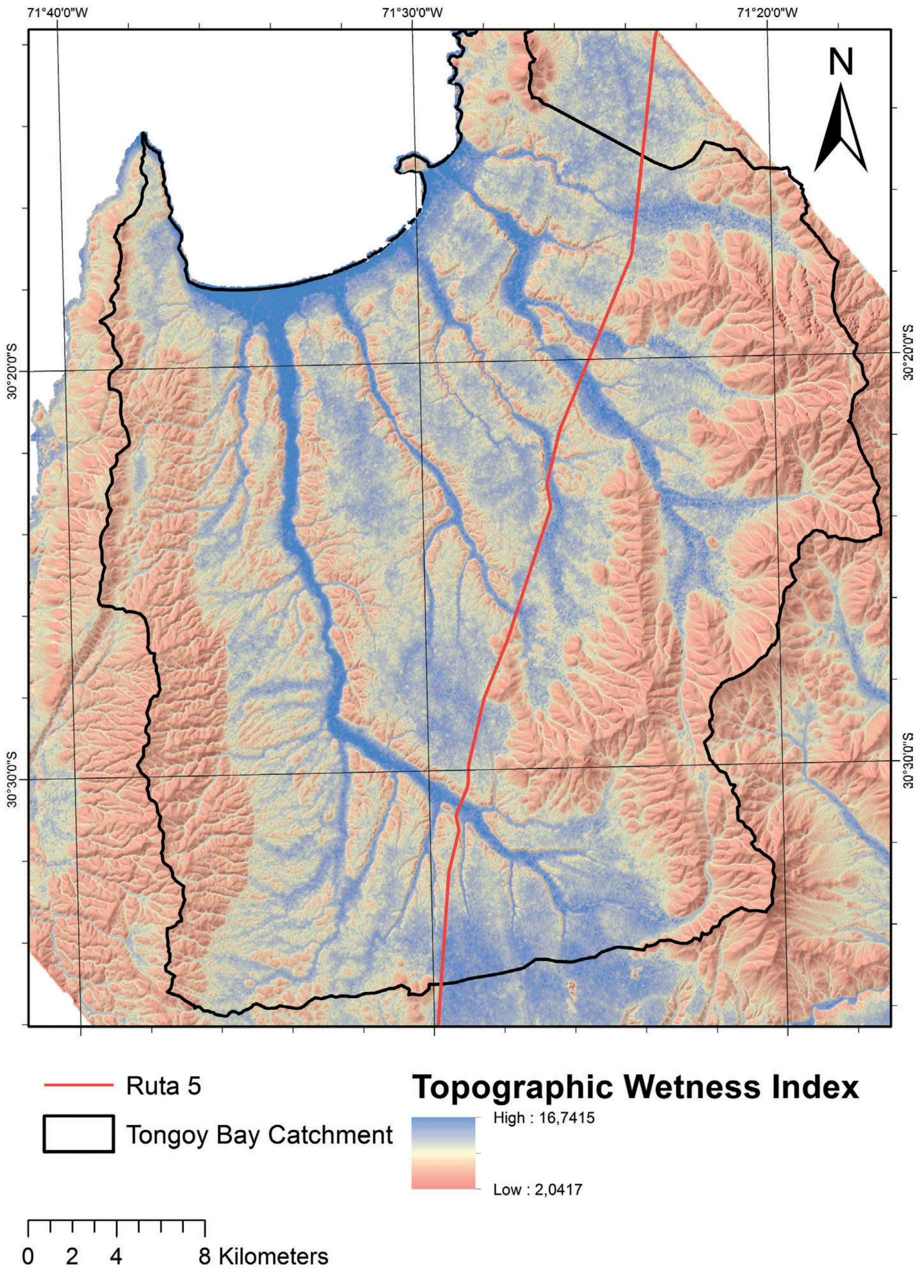


FIG. 14 - Topographic Wetness Index of the Tongoy Bay cacthmets.

tritic material on the slopes and in the river channels subsequently available to be remobilized by extreme rainfall events.

Even though topography and geomorphology do not reveal a clear evidence of present day, potentially hazardous processes, our results suggest that the rainfall-induced geohydrological processes are the main hazards in the study area. These processes such as floods, debris flows and local flash floods are induced by heavy, concentrated rainfall that has to be considered as their main triggering factor. As discussed earlier, this area is also subject of strong earthquakes that may potentially trigger different kinds of landslides or processes such as liquefaction, but field evidences suggest that these are less significant than geohydrological processes in the area. The lack of a detailed, long-term time series of flood and debris flow events preclude an accurate estimate of rainfall thresholds for the area, thus no probabilistic hazard assessment can be carried out. Nevertheless, these precipitations are higher than known thresholds in northern and central Chile. Sepúlveda & *alii* (2006) indicate that debris flow events in the coastal area of Antofagasta (26° S) in June 1991 and in the Andean piedmont of Santiago (33° S) in 1993 were triggered by 42 mm/day and 35.8 mm/day events, respectively, resulting in large destruction and fatalities. In the study area rainfall goes beyond these thresholds (tab. 3), but without triggering such large impacts.

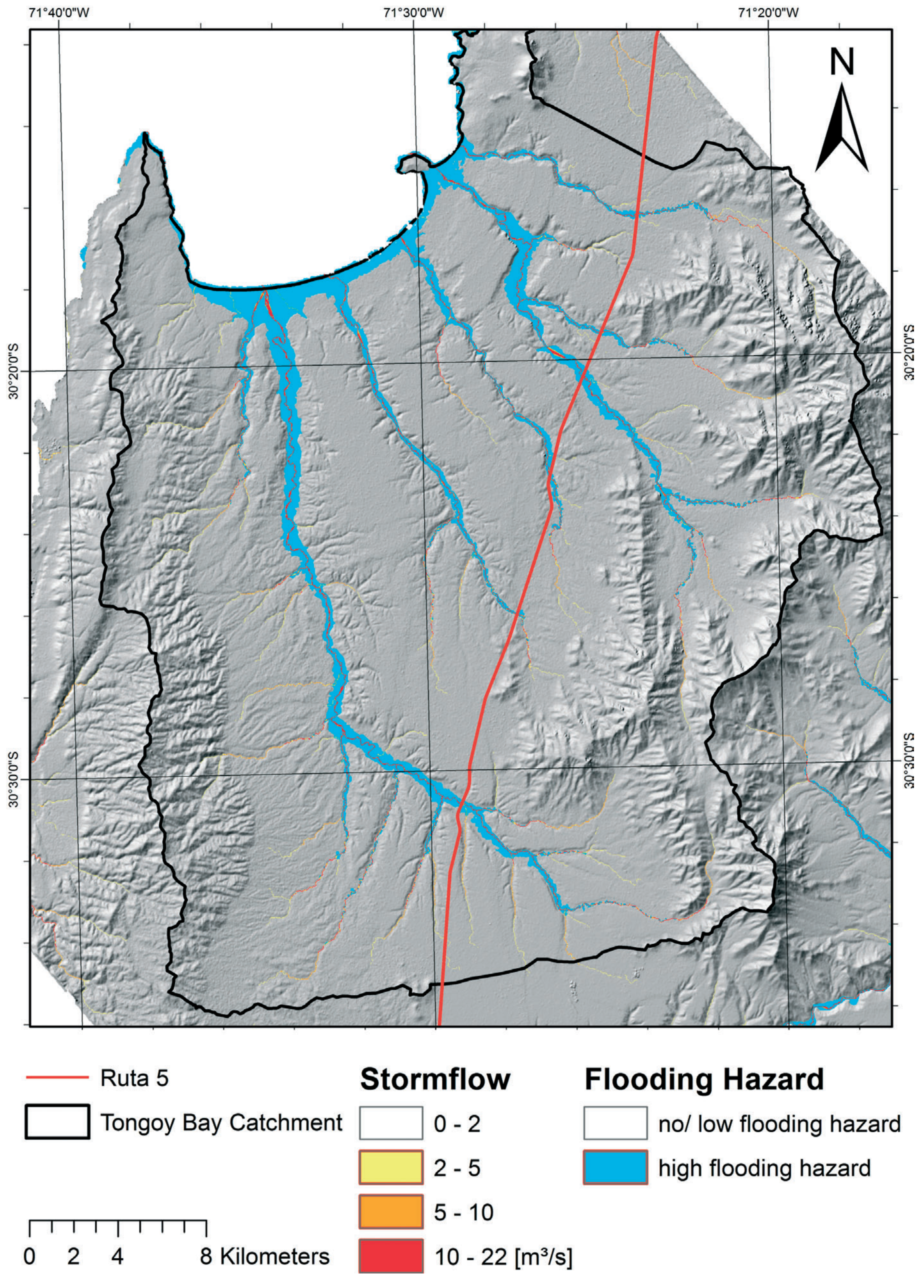


FIG. 15 - Storm flow volumes of Tongoy Bay catchments in m^3/s. Shown are discharges higher than 2 m^3/s and areas affected by flood ing (light blue).

CONCLUSIONS

The geomorphology of the study area is a product of inherited environmental conditions. The characteristics of a landscape composed by granitic slopes (chaos of rocks, tors), glacis and alluvial fans as well as incised marine and fluvial terraces lead to a concentration of present day geomorphological activities. This means that the already existing landscape triggers and directs surface runoff concentration and thus provoke a pronunciation of already pre-established drainage pattern by the active fluvial and slope geomorphological processes of the study area which in turn are mainly induced by extreme precipitations related to episodic events such as El Niño, La Niña and PDO.

The field observations and the quantitative modeling approach using DEM information emphasize the process intensities leading to landscape dissection and the favorable conditions for concentrated flows, erosion processes, flash floods, hyper-concentrated flows and mass movements. Generally these events show low frequencies but high intensities and magnitudes. Consequently, the study area is subject to episodic, high energy geodynamic events that induce natural hazards. However, the vulnerability is quite low due to scarce settlements, except along the coast, where road infrastructures and the resort town of Tongoy are located. In the delta areas of the Tongoy Bay catchments the debris flows or concentrated sediment discharges generate large frontal deposits, impacting the beach morphology and infrastructure.

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(Ms received 15 March 2013; accepted 15 January 2014)