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Field Survey of the 2015 Chile Tsunami with Emphasis on Coastal Wetland and Conservation Areas

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Abstract—The September 16th 2015 Illapel M8.3 earthquake, Chile, generated a tsunami that affected a sparsely populated region, causing 15 casualties and destroying 1069 houses (USGS 2015). A maximum surface elevation of +4.5 m was observed in Coquimbo's tide gauge while in other sites of the tide network, the tsunami did not exceed +2.0 m. A post-tsunami survey team comprised by local researchers was deployed from September 17th to November 14th 2015. The survey covered approximately 80 sites along 500 km of the primary impact zone, from the northernmost site where damage was reported, Bahía Carrizalillo (29.11°S; 71.46°W), southward to El Yali National Reserve (33.75°S; 71.73°W) beyond which no tsunami damage occurred. The results of the survey in coastal towns with evident damage and isolated sites where the tsunami signature remained almost intact are summarized in this paper. A large amount of quantitative material is presented; including (1) inundation lines in five coastal sites, (2) 157 profiles including wave runup and flow depths and (3) 47 interviews to eyewitness, generally 2–3 per site. About two-thirds of the data were collected in isolated areas to guarantee spatial homogeneity along the impact zone. The type of damage in specific areas of biological interest and in coastal cities such as Concón, Tongoy and Coquimbo is also reported. A maximum runup of 13.6 m was recorded in La Cebada (30.97°S; 71.65°W). The information presented herein provides spatial completeness in places that may have not been surveyed by other teams, and redundancy in areas surveyed by others.

Key words: Tsunami, field-survey, runup, 2015 Illapel earthquake.

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1. Introduction

The coast of Chile has been affected by four local tsunamis in the past 8 years. On April 21st, 2007, an Mw 6.2 earthquake triggered a landslide tsunami which caused ten casualties and significant damage to aquaculture farms in Aysén Fjord (Naranjo *et al.* 2009; Sepúlveda and Serey 2009). The February 27th, 2010, tsunami struck nearly 600 km along the coasts of central Chile, causing 181 casualties and damaging 17′000 homes (Fritz *et al.* 2011; Contreras and Winckler 2013). On April 1st, 2014, a Mw 8.2 earthquake generated a tsunami which reached amplitudes of the order of 1 m and was measured by 10 gauges in northern Chile (Catalán *et al.* 2015; An *et al.* 2014). The latest event, which is the focus of this survey, occurred as a consequence of the September 16th, 2015 Illapel Mw 8.3 earthquake in north-central Chile (Ye *et al.* 2015). This region has been affected by large earthquakes in 1730, 1880 and 1943 (Kelleher 1972; Nishenko 1985; Beck *et al.* 1998; Lomnitz 2004) and by the 1922 tsunami, caused by a rupture covering from 26°S to 30.25°S, to the north of the 2015 rupture zone (Miranda 1923;

Bobillier 1926). The southernmost portion of the area affected by the tsunami was also impacted on August 8th 2015 by a great storm surge, which damaged infrastructure, eroded beaches and dunes (Winckler *et al.* 2015).

The tsunami of 16 September 2015 affected 500 km of coastline between 33.73°S and 29.12°S. This region includes the ports of San Antonio, Valparaiso, Quintero and Coquimbo, as well as several cities and fishing villages. Numerous coastal wetlands are located in the area, including El Yali National Reserve (Ramsar site N°878), Mantagua wetland, Pullally Salt Marsh, Laguna Conchalí (Ramsar site N°1374), Las Salinas de Huentelauquén (Ramsar site N°2237), Tongoy Wetlands, El Culebrón Wetland in Coquimbo and Pingüino de Humboldt National Reserve. These conservation sites form part of the coastal wetlands system in central Chile (Davis 1994; Figueroa *et al.* 2009; Farina *et al.* 2012) and were all affected by the tsunami.

This paper focuses on tsunami effects in uninhabited places, especially coastal wetlands and sites for conservation of biodiversity, where little information is normally collected during field surveys. Data is also presented for major cities, supplementing the field information collected by other teams.

2. *Post Tsunami Field Survey*

Four survey groups documented tsunami runup, flow depth and inundation between September 17th to November 14th 2015, using three optical levels, surveying rods, five hand-held GPS with horizontal precision of 1–3 m and a laser distance meter of 1 m accuracy and 750 m range. Interviews to eyewitnesses were carried out following UNESCO's field guide (Dominey-Howes *et al.* 2014). A fifth group focused on beach profiles in Valparaíso, Viña del Mar and Quintero between September 21st and 25th using Emery's (1961) methodology. The main criterion for the selection of sites was to have, whenever coastal access was possible, evenly distributed data. In contrast to previous post-tsunami surveys in Chile (Fritz *et al.* 2011) and Japan (Mori *et al.* 2011, 2012), there was no coordination among different teams, resulting in overlapping on the most affected areas (e.g. Tongoy, Los Vilos and Coquimbo). Details of the dataset are included in Fig. 1 and Appendix Table 1.

The information presented herein includes 5 inundation lines in coastal sites and 157 profiles with maximum runups and flow depths. About two-thirds of the data were collected in isolated areas to guarantee spatial homogeneity along the impact zone. We also referenced the pre- and post-tsunami position of some objects that drifted with the flow, as a mean of defining a first order approximation to the trajectories. Measured runup was corrected to the tidal level at the time of tsunami arrival. Meteorological effects are neglected based upon the fact that normal weather conditions occurred during the different surveys. We estimate a vertical error of 1–3 decimeters in such data. Runup and flow depth were estimated by interpreting physical evidence observed in the field such as strand lines of debris, dried vegetation by the action of salty water, orientation of deflected branches, fishing nets and buoys, sediment deposits, signs of scour and lines of destruction in severely damaged areas. The rapid cleanup of beaches on urban areas made identification of tsunami traces somewhat difficult. In isolated areas, tsunami traces remained unperturbed for longer periods, but the lack of witnesses and walls made identification also somewhat difficult. We conducted 47 interviews with local residents and eyewitnesses, generally 2–3 per site, aiming to gather data of inundation extent, flow direction, number and sequence of significant surges, among other anecdotal accounts.

Water levels from tide gauges belonging to the Chilean Hydrographic and Oceanogaphic Service (SHOA 2010) were obtained from the Sea Level Station Monitoring Facility (IOC 2013). Records were detided using the T_Tide Harmonic Analysis Toolbox (Pawlowicz *et al.* 2002). Tsunami signals together with the predicted tide are shown in Fig. 2. Tsunami reached amplitudes below +2 m in most of the stations, with the exception of Coquimbo, where amplitudes exceeded +4 m. This station apparently did not capture troughs below −2 m, for unknown reasons. The first wave arrived shortly after low tide - midway between spring and neap tides- while secondary waves maintained significant amplitudes for about one tidal cycle. Amplification was observed on the south shores of U-shaped bays such as Coquimbo,

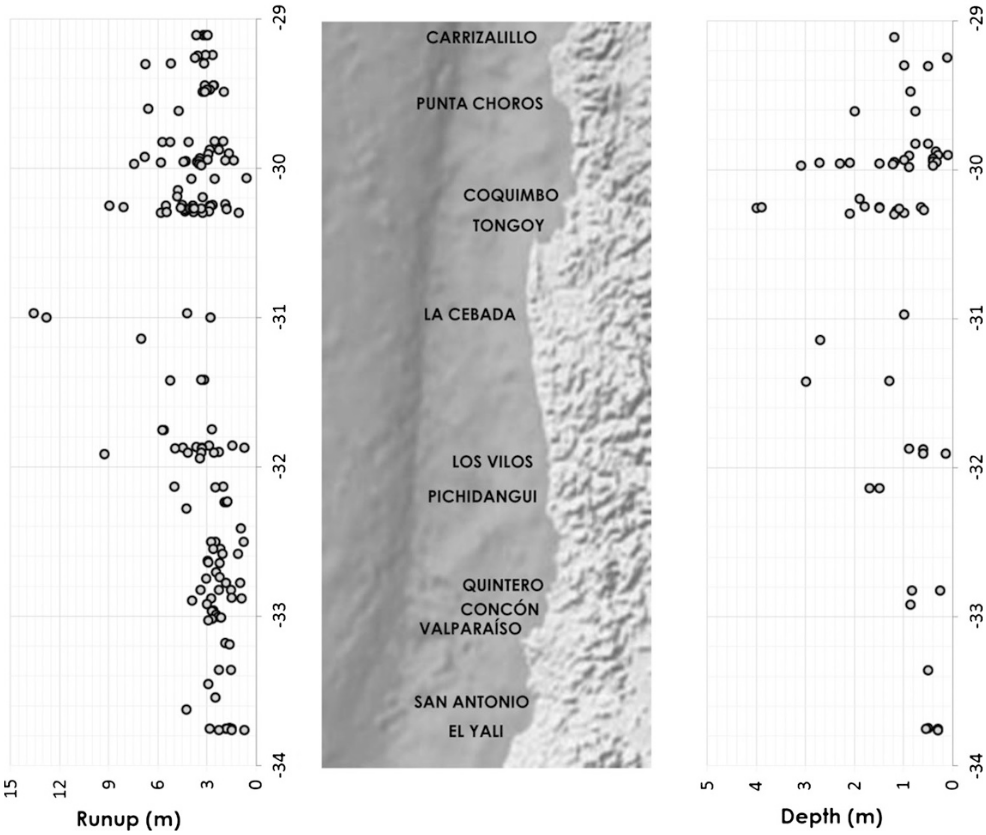


Figure 1
Measured inundation depths and run-up heights along the Chilean coasts

Guanaquero, Barnes and Tongoy. In several stations (e.g. Caldera and Constitución), important tsunami waves occurred several hours after the earthquake apparently as a consequence of edge waves and resonance. This phenomenon was earlier observed after the April 1st, 2014 earthquake (An *et al.* 2014; Catalan *et al.* 2015). Tsunami waves in oceanic islands were relatively small and occurred during the first hours after the arrival of the leading wave. Damage to infrastructure and dwelling is concentrated towards the north of Valparaíso region, most of the coastal zones of Coquimbo Region, and at Carrizalillo in the Antofagasta Region, which is the northern-most location where damage was observed. The maximum tsunami runup of 13 m was located at La Cebada (30.98°S; 71.65°W), 65 km away from the epicenter. Maximum flow depths of 4.0 m were measured in Socos beach at Tongoy while depths of 3.3 m and penetrations of up to 800 m were recorded at the Baquedano Area in Coquimbo, the most impacted area.

Many witnesses said they did not observe the tsunami as they evacuated the coastal zone immediately after the earthquake. This rapid response is explained by a natural hazard culture built up from the experience of past tsunamis (Gaillard *et al.* 2008), which was also observed during the February 27th, 2010 tsunami (Marín *et al.* 2010). Since the latter tsunami, several evacuation drills have been conducted and evacuation routes have been marked up and down the coast (ONEMI 2013), thus enhancing the awareness of the coastal communities. The majority of witnesses in various sites described an initial slow recession of the sea, followed by a quick flood, giving the feeling of an overflow more than a wave.

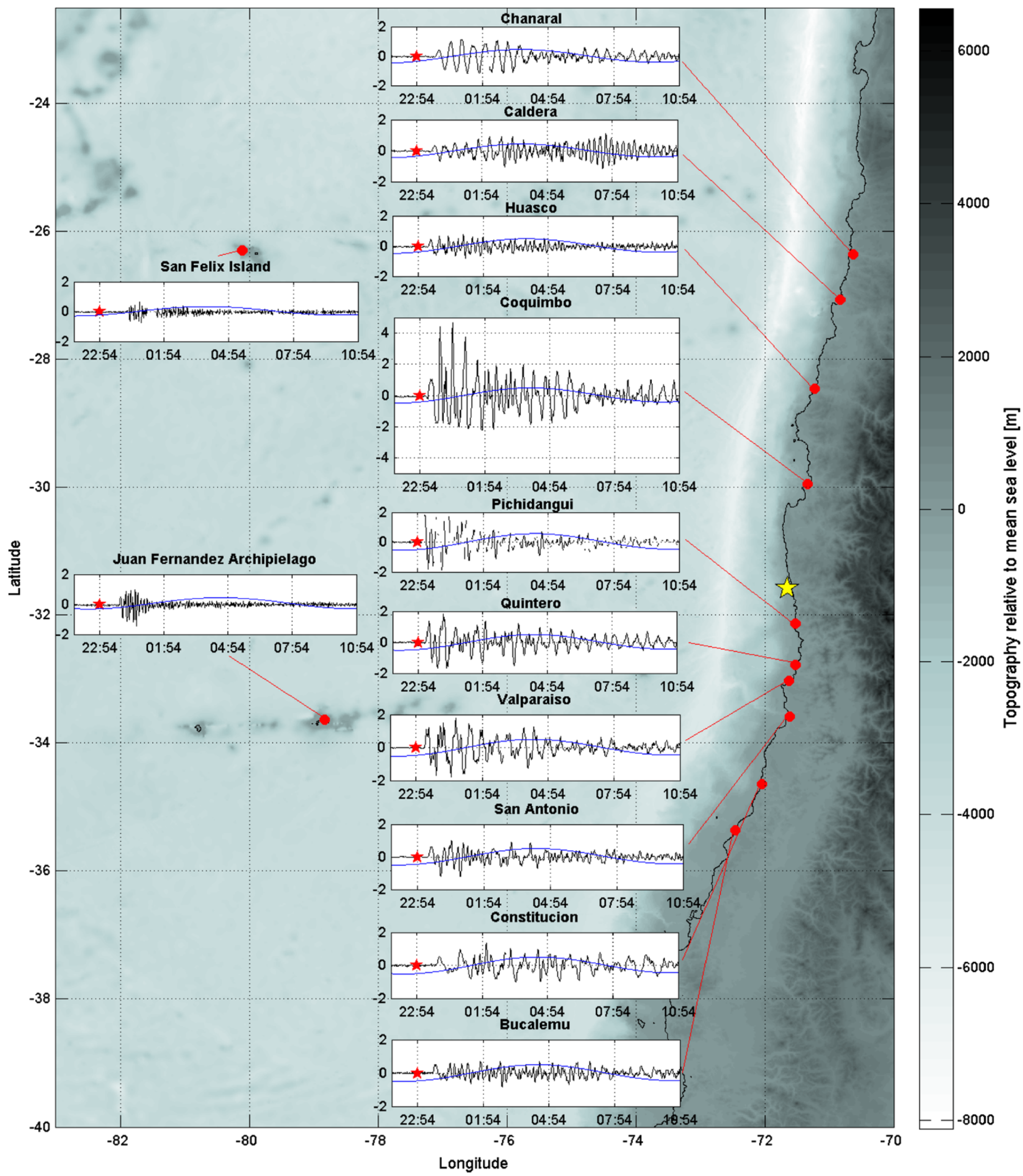


Figure 2
Filtered tsunami signals (*black*) and predicted tide (*blue*) in coastal tidal gauges along Chile in global time, using T-tide code. The *red stars* indicate the time of the earthquake (22:54 UTC), the *yellow star* indicates the earthquake epicenter. *Red circles* are the location of tidal stations. The topography corresponds to Gebco (IOC, IHO and BODC 2003) with resolution of 30 arcsec. San Felix and Pichidangui stations show gaps during the tsunami. Units in vertical scale in time series are meters above mean sea level

In general, tsunami traces were easily identified in uninhabited places. However, two problems complicated the identification of hydrodynamic data: (1) some sectors impacted by the tsunami were in fact affected more significantly by a major storm surge on August 8th, 2015 (WINCKLER *et al.* 2015) and, (2) a phenomenon locally known as the desierto florido -translated as 'blooming of the desert' or 'flowering desert- triggered the fast growth and abundant flowering within 2–3 days in places that had been flooded by the tsunami (MUÑOZ 1991). This phenomenon occurs in between periods of 2–5 years of drought in the coast of the southern Atacama Desert after short and infrequent pulses of rainfall (VIDIELLA *et al.* 1999). This year, the desierto florido has been enhanced by the ongoing El Niño Southern Oscillation, which has shown similar indices when compared to its devastating predecessor during 1997–1998 (NASA 2015a, b).

3. Site Specific Surveys

3.1. El Yali National Reserve

El Yali National Reserve (33.75°S, 71.73°W) consists of a shallow coastal lagoon connected to the sea via a tidal inlet in winter, which evolves into a bar during the dry summer season, a few brackish lakes and two artificial salt marshes (VILINA 1994; DUSSAILLANT *et al.* 2009). The February 27th, 2010 tsunami swept the coastal dunes located between El Yali's tidal inlet and the vicinities of the town of Santo Domingo (FRITZ *et al.* 2011; CONTRERAS 2014), which on normal conditions have an elevation slightly greater than 2 m above the sea level. However, at the moment of the September 16th tsunami, dunes were recovering from erosion caused by the August 8th, 2015 storm surge (WINCKLER *et al.* 2015). This erosion along with the bay's orientation to the northwest enabled the propagation of relatively small tsunami waves upstream, flooding 240 hectares of the surrounding wetlands (Fig. 3).

3.2. Santo Domingo to Quintay

The tsunami was not destructive and its effects were confined to the beach in Santo Domingo (33.63°S; 71.63°W), Quintay (33.19°S; 71.70°W), Cartagena (33.55°S; 71.61°W) and El Tabo (33.46°S; 71.66°W). The tide gauge at San Antonio Port (33.58°S; 71.69°W) showed maximum tsunami amplitudes in the range of 1 m (Fig. 2). In Algarrobo (33.36°S; 71.67°W), tsunami marks reported in a seawall showed a 0.5 m flow depth. Llolleo (33.61°S; 71.62°W) is an interesting site located in lowlands formed by the accumulation of sediment from Maipo River after the construction of San Antonio port (LIRA 1939). Illegal settlements established in this area were authorized during the following decades by the provision of infrastructure and basic services. As a consequence of the 2010 tsunami, 168 lightweight houses were destroyed and five people died (FRITZ *et al.* 2011; CONTRERAS *et al.* 2012). Today the place is a parking lot under the jurisdiction of the San Antonio Port, which had no free access during the survey. Though the September 16th tsunami did not cause damage or casualties, the site remains under high risk.

3.3. Valparaíso and Concón bays

The area from Valparaiso (33.03°S; 71.63°W) to Concón (32.92°S; 71.51°W) is an erosional coast characterized by alternating rocky cliffs and small inlets with sandy beaches of less than 500 m long. The tide gauge at Valparaiso harbor recorded wave amplitudes of about 2 m and no damage was observed within the bay. Beach profiles surveyed in Caleta Portales, Caleta Abarca, Acapulco, Playa Blanca beach and Reñaca as part of a campaign following the August 8th, 2015 storm surge (MOLINA *et al.* 2015), showed no relevant changes. From south to north, Concón was the first inhabited site to experience damage from the 2015 tsunami (Fig. 4). According to witnesses, numerous light-wooden buildings and containers located on low-lying ground adjacent to Aconcagua River mouth were washed away by a slow surge. Damage was focused on the area located 2–3 m above the mean sea level, and was

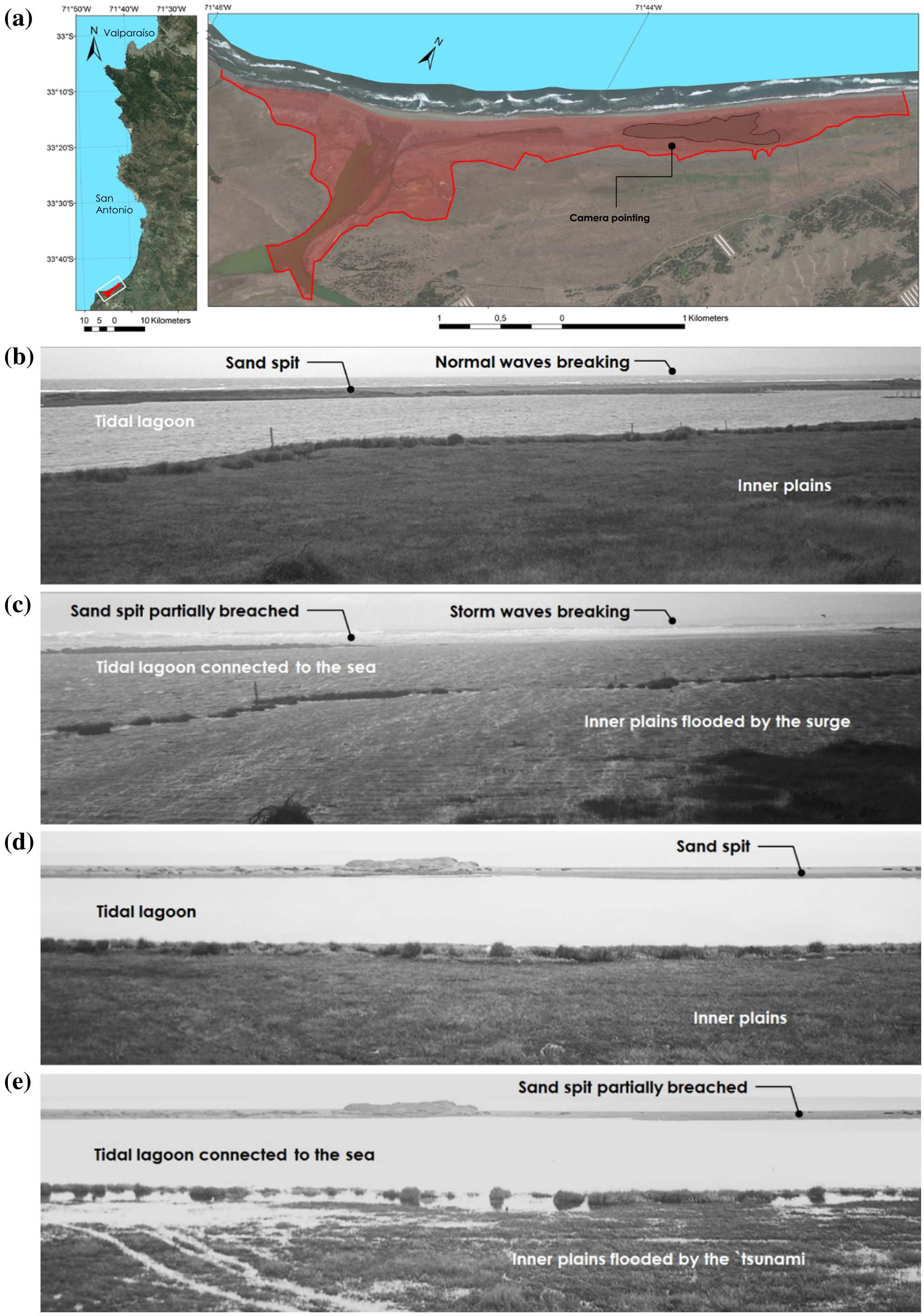


Figure 3

a Flooding line in El Yali coastal reserve. **b** Camera pointing northwestward before the August 8th 2015 storm surge (May 3rd). **c** Same as in **b** during the storm surge. **d** Camera pointing westward before the September 16th 2015 tsunami (Sep 16th). **e** Same as in **c** after the tsunami (Sep 17th)

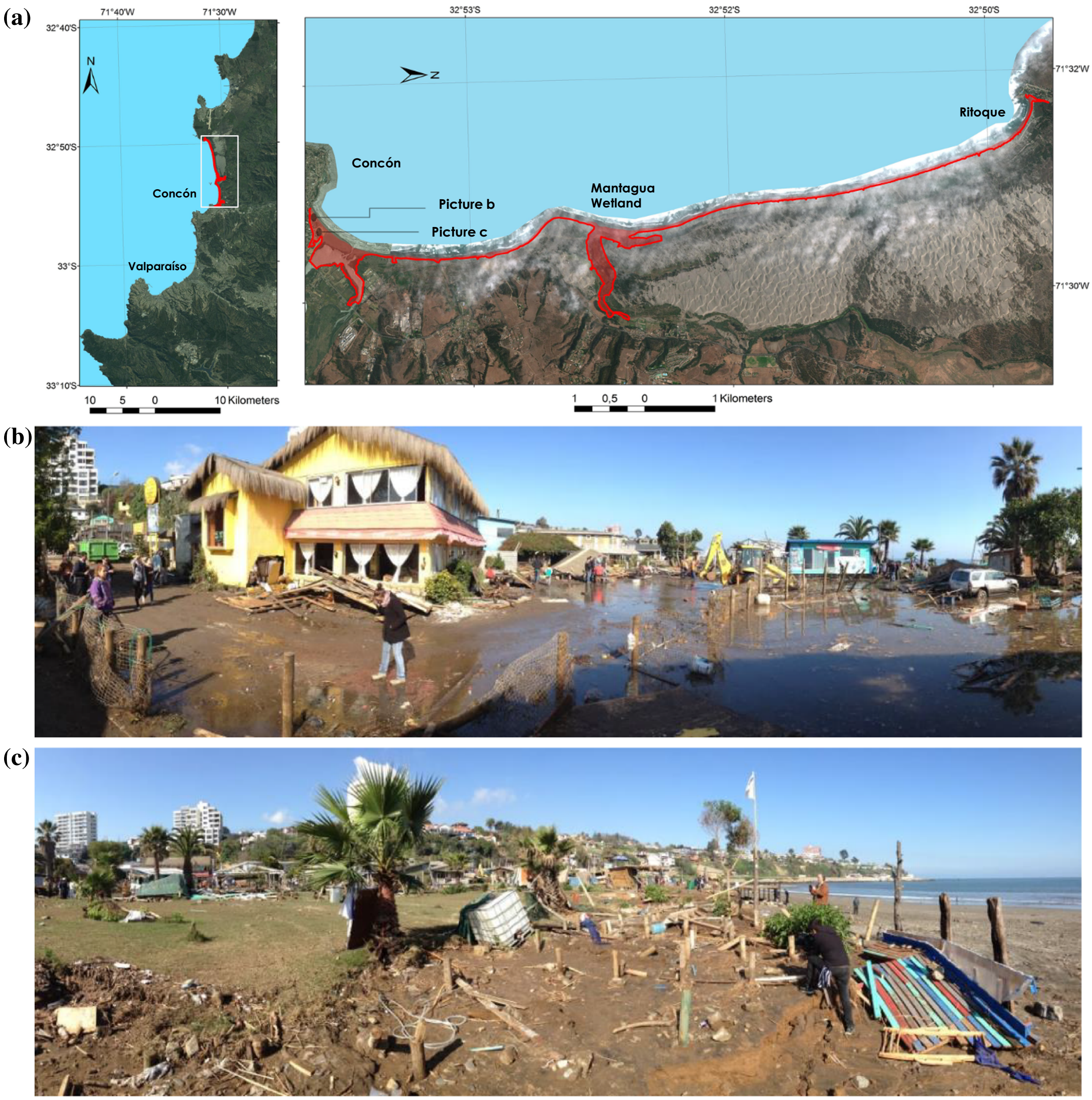


Figure 4
a Flooding area in Concón, Mantagua and Ritoque. **b**, **c** Flooding of low-lying areas in Concón

presumably attributed to buoyant forces. Clean up was remarkably rapid upon the return to normal conditions: in the early morning of September 17th, bulldozers were already piling debris while local stores in the flooded area opened as usual. The rapid reaction of the survey team enabled the identification of the flooding marks and flow depths, which were cleaned in the following days.

Mantagua coastal lagoon (32.88°S; 71.51°W), located 4 km north of Concón, was hit by a runup of 3 m. The tsunami overflowed a railway line, which was sheltered from the sea by coastal dunes of 3 m. The flow ascended the creek leaving dead bodies of fish (carps; *Cyprinus carpio*) in the floodplains. Evidence of inundation was found in the dune fields of Ritoque (32.86°S; 71.51°W) but it was not possible to distinguish whether it was caused by the tsunami or the severe storm surge of August. About 122 hectares were flooded in Mantagua and Ritoque altogether. Witnesses declared that the sea level was higher than in 2010 (Fritz *et al.* 2011).

3.4. Quintero to Pichidangui

From Quintero bay (32.78°S; 71.53°W) to Pichidangui (32.14°S; 71.53°S) the coast is dominated by coastal cliffs which offer natural protection to fishing towns (Soto and Arriagada 2007). In this area, tsunami runups gradually increased northward, exceeding the beach berm in few locations. In the salt marsh of Pullally (32.41°S; 71.41°W), flooding was moderate and no damage to the access road was observed. Witnesses affirmed that the tsunami impacts were milder than those observed after the August 8th storm.

3.5. Los Vilos to Playa Amarilla

This relatively straight coast shows no major bays except for the mouth of Choapa River (31.63°S; 71.56°W). South of Los Vilos (31.92°S; 71.52°W), marine terraces accompany the coastline with great regularity. The largest sand dunes of the region extend between Huentelauquén and Pichidangui (Novoa and Villaseca 1989). In addition, there are large fields of stabilized dunes, which have gradually been fixed by vegetation.

Moderate and evenly distributed runups were measured in the urban area of Los Vilos while larger flooding was found locally in steep rocky coasts south of the bay. A series of interviews made during the survey provided an accurate description on the tsunami impact in the town (ITIC 2015a, b). A fisherman who was sailing during the shock and returned to the harbor upon the arrival of the third wave, mentioned that while being approximately 400 m off the coast, he felt a smooth drift due to the wave, while observing confined turbulent motions at the coast (vimeo.com/146310509). A woman who immediately evacuated to a safe zone explained how boats near the coast drifted northward while those at a couple of hundred meters offshore remained in their positions (vimeo.com/146310512). A man who tried to escape the tsunami in his car, which drifted with no damage, mentioned that the sea surface remained completely flat for some minutes after the attack of the fourth wave (vimeo.com/146310511). These testimonies suggest that the flooding within the bay was slow and even, while complex flow patterns were triggered by infrastructure and buildings.

Coastal dunes stabilized by vegetation offered total protection at the north of the town (Fig. 5b; vimeo.com/146307332). The level of damage increased southward as the building line approached the beach (Fig. 5c), while those houses sited on the beach berm were washed away (Fig. 5d). A woman declared that the damage to wooden houses was caused by a combination of the flow and drifting boats (vimeo.com/146310510). The protecting role of dunes has earlier been observed in Punta de Lobos, Chile, in 2010 (Fritz *et al.* 2011) and after the large tsunami of 2004 in Sumatra (Mascarenhas and Jayakumar 2008) and 2011 in Japan (Tanaka 2012; Tanaka *et al.* 2013; Suppasri *et al.* 2012), where overtopping was reduced and villages shielded by dune fields. The present case is an example where the horizontal extent of the dune field becomes relevant on its sheltering attributes.

Damage on dwellings within a focused area of the city was caused by overtopping of a recently constructed seawall (Fig. 5d, vimeo.com/146310512). Tsunami loads were not considered in the design of this seawall, in contrast to other promenades built by the Ministry of Public Works after the 2010 tsunami (Khew *et al.* 2015). It should be noted that, although national building codes including tsunami loads for structures within inundation zones have recently been enacted (MINVU 2013; INN 2015), comprehensive implementation has not been observed nationwide. In an inhabited site towards the south of Los Vilos, localized a runup of 9 m, much larger than the average of 5 m in the area, was measured.

Laguna Conchalí (31.88°S; 71.50°W) is a Ramsar site located 2.5 km to the north of the main beach of Los Vilos. The beach and dunes appear to have been severely affected by August 8th, 2015 surge enabling the tsunami penetration in at least three points along the wetland. In Playa Amarilla (31.86°S; 71.51°W) the tsunami flooded the northern sector of beach,

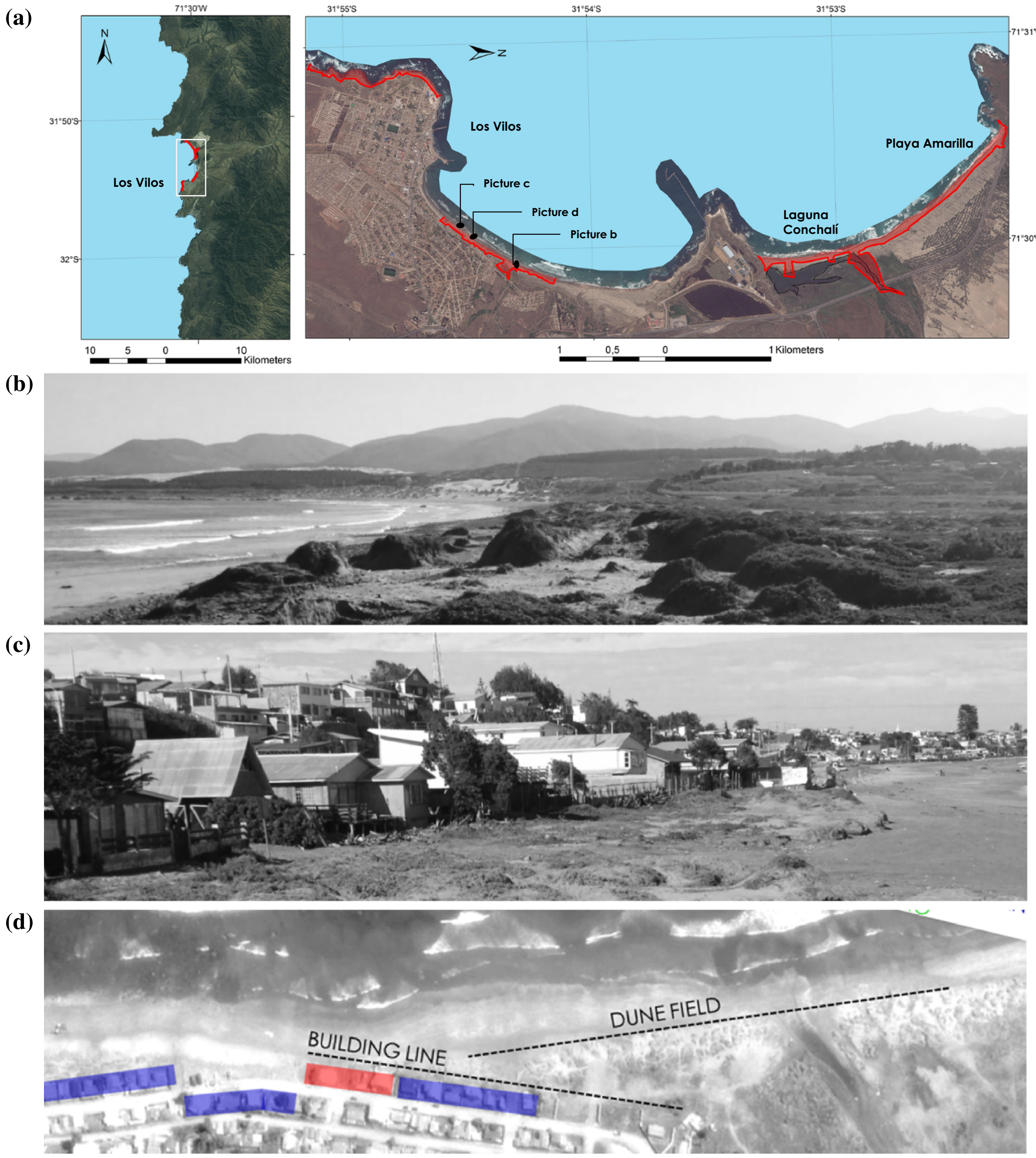
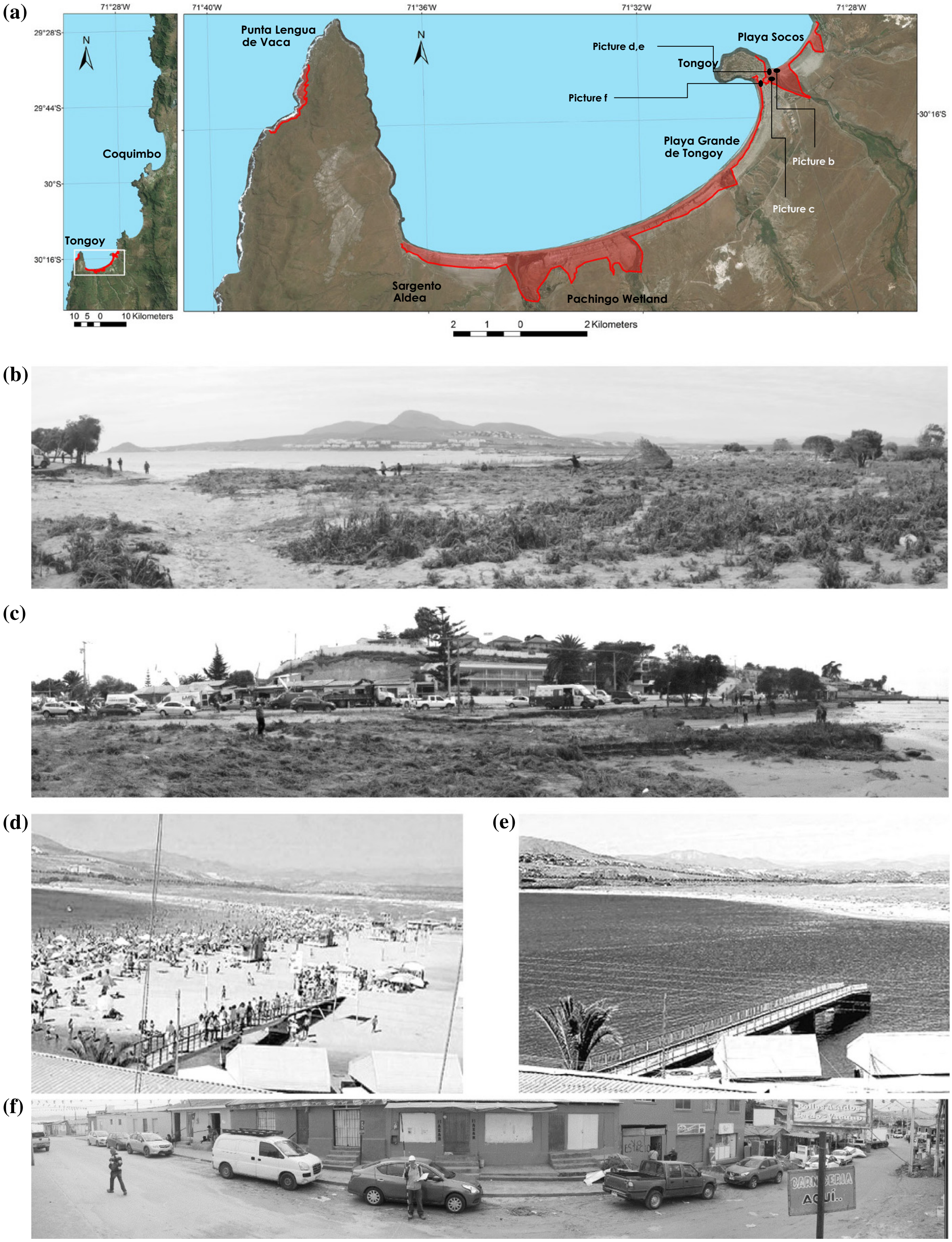


Figure 5
a Flooding area in Los Vilos, Laguna Conchalí and Playa Amarilla. **b** Coastal dunes stabilized by vegetation towards the north of the town. **c** Building line approaching the beach towards the south. **d** Building line and seaward border of the dune field. Houses in *red* were washed away. Houses in *blue* we partially damaged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◀Figure 6
a Flooding area in between Punta Lengua de Vaca and Tongoy. Outlet of the estuary towards **b** the north and **c** the south. Socos beach **d** before and **e** after the tsunami (Tercera 2015b, September 22). **f** Sediment mark on Gomez Carreño Street

sidestepping the higher dunes while reaching the access road at a low elevation. The tsunami runup was confined by a cliff at the back end of the beach.

3.6. *Chigualoco to La Cebada*

This sparsely populated area, directly onshore of the area of greatest sea-floor deformation, showed the highest tsunami runup. A maximum coastal uplift in the order of 20 cm was preliminary estimated from satellite interferometry (Insarap 2015) in the outlet of Quebrada Amolanas (31.21°S; 71.64°W) while subsidence of the same order was inferred in Fray Jorge National Park (30.65°S; 71.69°W). No significant evidence of uplift or subsidence was found during the field survey, with the exception of Puerto Oscuro (31.42°S; 71.59°W), where coastal uplift of 20 ± 10 cm was observed. These values are significantly smaller than those triggered by the February 27th, 2010 earthquake in central Chile (e.g. Farías *et al.* 2010).

Witnesses mention that the tsunami arrived immediately after the earthquake, giving a considerably short time for evacuation. At the beach of Chigualoco (31.75°S; 71.51°W), the penetration reached 100 m, inundating a camping area and damaging structures. Caleta Sierra (31.15°S; 71.66°W) was completely washed away and 23 fishing boats were lost (SUBPESCA 2015). Maximum runup of 12–13 m was measured in La Cebada (30.98°S, 71.65°W), a fishing town located on an outlet surrounded by coastal cliffs. Caleta El Toro (30.73°S, 71.70°W) and Caleta El Sauce (30.55°S, 71.70°W) in the outlet of Limarí river, were severely affected. In the latter, a boat was displaced by the bore for about 3 km upstream. This is undoubtedly the area where the tsunami was most intense but the scarce number of coastal settlements explains the small level of damage.

3.7. *Punta Lengua de Vaca a Totoralillo*

In the exposed coastline of Punta Lengua de Vaca (30.27°S; 71.63°W), tsunami runup reached 7 to 8 m, while in the sheltered area of the bay runup did not exceed 4 m (Fig. 6). In Puerto Aldea (30.29°S; 71.61°W), a small fishing town within the bay, light houses were destroyed and the road northward was severely scoured. The tsunami traces gradually became smaller towards the southern border of Tongoy (30.30°S; 71.55°W).

Tongoy is characterized by a peninsula surrounded by Socos beach and a small estuary to the east, and Playa Grande to the west. Though the area was apparently affected by the 1922 tsunami, no reliable reference was found in the scientific literature. Tongoy was severely attacked by waves in Socos beach and, to a lesser degree, by waves coming from Playa Grande immediately after the earthquake. In the outlet of the estuary (Fig. 6b, c), we noted fallen and displaced trees caused by tsunami action. Flow depths of 3.9 m were observed in the vegetation. The sandy beach and dunes of Socos that resisted the storm in August, were wiped out by the tsunami (Fig. 6d, e). The maximum runup of 8–9 m in Gomez Carreño Street—connecting both sides of the peninsula (Fig. 6f)—was followed by and intense flow towards Playa Grande, which damaged shops and affected large areas along the sea front. Water depths of 1.65 and 1.5 m were recorded on the east and west sides of the street.

Runup decreased towards the north of Tongoy, yet lowlands with no dune protection were flooded. For example, approximately 20 hectares in Puerto Velero (30.25°S; 71.48°W) with flow depths of 1 m were recorded. In Guanaqueros (30.20°S; 71.43°W) and Totoralillo (30.02°S; 71.38°W), light infrastructure was affected. In the latter, 10 fishing boats were lost. In Morrillos (30.15°S; 71.37°W) the tsunami was confined to the beach and witnesses indicated that the storm of August was more severe.

3.8. *La Herradura, Coquimbo to Punta Teatinos*

The smaller bay of La Herradura (29.98°S; 71.36°W) is located 8 km south of Coquimbo Bay. The tsunami was confined to the beach in the south of the bay and affected a few facilities. No significant resonance was observed presumably due to the small dimensions of the bay.

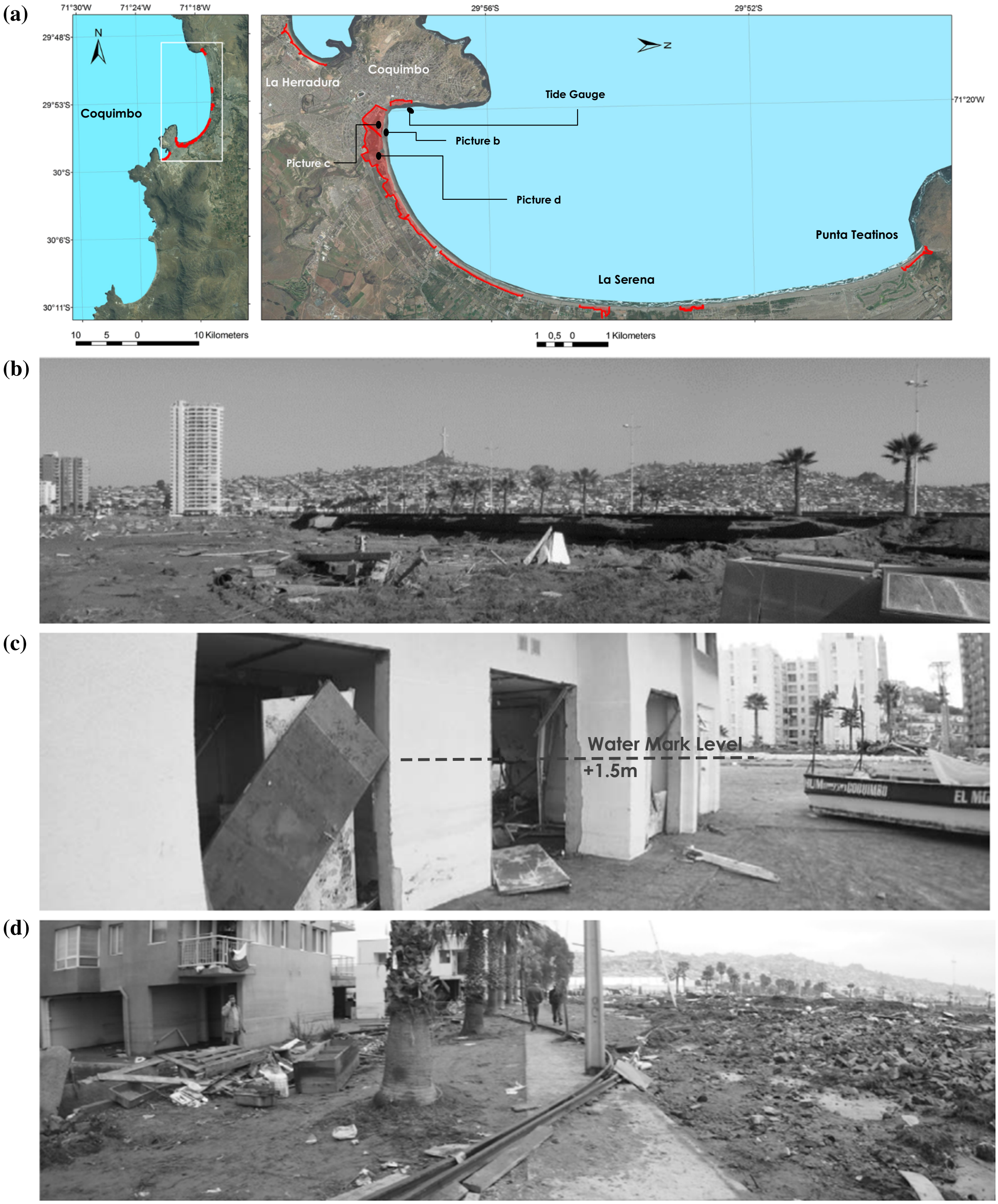

Figure 7

a Flooding area in Coquimbo and La Serena. **b** Eroded coastal road at El Culebrón Wetland (**c**). Watermark on a building (**d**) Landfill in El Culebrón Wetland

Coquimbo Bay (29.90°S; 71.30°W), located immediately north of La Herradura, includes a wide coastal strip of about 15 km of long beaches. Morphology is characterized by a series of staggered terraces (Villagrán 2007), gently sloping towards the west and separated by cliffs (Paskoff 1970). The city was severely affected apparently as a consequence of resonant modes on the southern end of the bay. The city has historically been affected by tsunamis in 1849, 1922 and 1943 (Lomnitz 2004). According to Bobillier (1926), the 1922 tsunami flooded Coquimbo with three waves, the third of which reached an elevation +4.6 m above sea level, preceded by a minimum trough of −5.8 m. Lomnitz (2004) in contrast, refers to a tsunami of 7 m in the same area. The 1922 tsunami flooded 4 blocks, washed away 200 houses and caused 24 casualties in Victoria district (Bobillier 1926). From a historical perspective, the size of the earthquake and tsunami of 2015 seems intermediate between the size of the events of 1922 and 1943 (Cisternas *et al.* 2015).

For the 2015 tsunami, maximum surface elevations exceeding +4 m were measured in Coquimbo's tide gauge (Fig. 2). Some of the witnesses in the south sector of Coquimbo bay indicated that immediately after the earthquake, the sea began to slowly rise beyond the beach, then retreated and subsequently returned as a large wave. A state of emergency was declared in Coquimbo a day after the tsunami, with troops deployed in the area (BBC News Online 2015). As in 1922, Victoria district -referred also as Baquedano- was the most severely affected area in town. Flow depths of 3 m and inundations distances of up to 800 m were recorded in a relatively low-lying area of the town. The fishing port of Coquimbo (29.98°S; 71.36°W) was completely flooded and one person was killed inside the management building. Five industrial fishing vessels were stranded on the coast and several small boats were lost. Coastal restaurants built with lightweight materials were completely swept away and destruction was observed along Condell Street. Scour of fillings and pavements was observed on the coastal road, Costanera Avenue, where a depth of 1.5 m was surveyed from watermarks on a building (Fig. 7c). The flood brought down the railway, folding the rails and spreading the gravel bed from its foundation along Maipu Avenue (Fig. 7d). In this area, the flooding depth reached a maximum of 3.1 m. At least two people were carried away by the tsunami and their bodies recovered on land reclamations at El Culebrón wetland (29.96°S; 71.32°W).

Caleta Peñuelas (29.95°S; 71.30°W) was severely affected, with smaller runup than Baquedano. Despite the proximity of La Serena (29.90°S; 71.27°W) to Coquimbo, a lesser degree of destruction was observed. Depths of 40 cm were recorded in the Lighthouse, a coastal landmark in the promenade, while tourism infrastructure along Avenida del Mar was damaged by debris impact on walls and fences. Presumably the beach erosion caused by the storm in August increased the overall impact of the tsunami. Coastal dunes sheltered the fishing town of San Pedro (29.88°S; 71.27°W). Near Punta Teatinos, the tsunami flooded La Serena Golf resort (29.82°S; 71.28°W), where the coastal dunes were initially eroded by the earlier storm.

3.9. *Caleta Los Hornos to Chungungo*

Caleta de Hornos (29.62°S; 71.29°W) is a highly energetic and dissipative beach whose morphology has been constantly influenced by the sediment contributions from the basin (Emparan and Pineda 2000). In the surroundings of the fishing town Caleta Los Hornos steep cliffs stopped the tsunami. A female victim declared missing in Caleta El Totoral (31.31°S; 71.62°W) was found in Caleta Los Hornos 7 days after the tsunami (Tercera 2015a, September 23), drifting northward for about 200 km. About 1.3 km north, at Quebrada Honda, significant flooding was observed. Contradictory witness accounts did not provide sufficient evidence to distinguish whether debris traces at 11 m were caused by the tsunami, rain runoff occurring before and after the earthquake or the storm in August. Abundant flowering was also a source of uncertainty in this site. Overall, estimates of the runup are of the order of 5–6 m. In Totoralillo Norte (29.49°S; 71.33°W), inundation distances of 30 m and runups of 3 m were measured. Tsunami impacts gradually became milder towards the north. No damage was reported in El Temblador beach (29.48°S; 71.31°W) and Chungungo (29.45°S; 71.30°W), where runup was below 2.5 m.

3.10. Playa Los Choros to Carrizalillo

The coastline of Playa los Choros (29.29°S; 71.38°W) is a favorable area for the development of the dune systems built by wind action (Castro and Brignardello 2005). In some places of the 15 km sandy beach facing a wide surf zone, the tsunami inundated 50 m inland with runup of about 3 m. An intermittent flow from Los Choros creek irrigates an ecologically important wetland sheltered by the dunes field, where the tsunami entered about 500 m. The geomorphological system of the coastal area of Punta Choros comprises a continental archipelago of steep morphology that was not affected by the tsunami according to witnesses. In Punta Choros (29.25°S; 71.46°W) slight damage was observed; some cabins were flooded in an area further south. In Carrizalillo (29.11°S; 71.46°W) flooding extent reached 60 m from the shore, destroying a few wooden houses; a boat drifted 4 km within the bay. According to witnesses, Carrizalillo was the northernmost site where damage occurred.

4. Conclusions

A valuable dataset for the September 16th 2015 tsunami covering around 80 sites along 500 km of a sparsely populated area is presented here. About two-thirds of the data were collected in isolated areas to guarantee spatial homogeneity. These data provide spatial completeness in uninhabited places, especially in sites for conservation of biodiversity, and redundancy in urban areas covered by other survey teams. Tsunami traces were easily identified in uninhabited places but in some sites were over shadowed by the August 8th 2015 storm and by abundant flowering triggered 2–3 days after the tsunami. Witnesses mention that the tsunami arrived immediately after the earthquake, giving a considerably short time for evacuation. Clean up of urban areas was remarkably rapid the following days, making the identification of tsunami traces difficult. No significant evidence of uplift or subsidence was found in the primary impact zone.

Despite the destruction caused by the February 27th 2010 and the April 1st 2014 tsunamis, no adaptive measures to regulate the land use in places such as Concón and Coquimbo were taken before this tsunami. Furthermore, recently enacted tsunami building codes within inundation zones have yet no comprehensive implementation within coastal communities. The recent events should be a call for the development of better planning tools in vulnerable zones.

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Appendix

Five survey groups documented tsunami runup, flow depth and inundation following UNESCO's field guide (Dominey-Howes *et al.* 2014). The first group covered de municipalities of Concón, Quintero, La Ligua and Santo Domingo between September 17th and 20th. A second group surveyed the area between Zapallar and La Higuera from September 22nd to 28th. A third group operated between October 3rd and 4th covering between Coquimbo and Freirina. The fourth group covered Santo Domingo, Casa Blanca, Concón and Puchuncaví between October 23rd and 25th. The fifth group focused on beach profiles in Valparaíso, Viña del Mar and Quintero between September 21st and 25th using Emery's (1961) methodology.

See Table 1

Table 1

Tsunami dataset recorded between 17 September to 14 November 2015

Pt	Site	Latitude (N)	Longitude (E)	Z (M)	R (m)	I (m)	Date	Time UTC
1	Carrizalillo	–29.11205	–71.46422		3.2	42	2015-10-03	22:08
2	Carrizalillo	–29.11318	–71.46455		3.1	53	2015-10-03	22:15
3	Carrizalillo	–29.11409	–71.46539		3	50	2015-10-03	22:20
4	Carrizalillo	–29.11476	–71.46727	1.2	3.7	65	2015-10-03	22:09
5	Caleta San Agustin	–29.24688	–71.46816		2.7	59	2015-10-03	21:13
6	Punta Choros	–29.24714	–71.46832		3.1	26	2015-10-03	21:25
7	Caleta Corrales	–29.24982	–71.46234	0.12	3.6	22	2015-10-03	20:22
8	Playa Choros	–29.26279	–71.42209		3.8	56	2015-10-03	19:43
9	Playa Choros	–29.30396	–71.3664		5.2	43	2015-10-03	18:41
10	Los Choros wetland	–29.30287	–71.36179	1	3.2	494	2015-10-03	18:35
11	Playa Choros	–29.30663	–71.35839	0.5	6.8	417	2015-10-03	18:35
12	Chungungo	–29.44828	–71.30342		2.6	14	2015-10-03	15:45
13	Chungungo	–29.44871	–71.30332		3.2	25	2015-10-03	15:52
14	Chungungo	–29.44971	–71.30348		2.6	12	2015-10-03	16:00
15	El Temblador	–29.47763	–71.30854		2.9	25	2015-10-03	14:50
16	El Temblador	–29.47855	–71.30869	0.87	3.0	55	2015-10-03	15:09
17	Totoralillo	–29.49158	–71.32887		3.3	16	2015-10-03	14:09
18	Totoralillo	–29.49234	–71.32453		2.0	22	2015-10-03	13:53
19	Totoralillo	–29.49249	–71.3265		3.2	14	2015-10-03	13:41
20	Los Hornos	–29.60806	–71.28789		6.6	61	2015-09-25	17:41
21	Quebrada Honda	–29.61107	–71.28684	0.77		108	2015-09-25	17:10
22	Quebrada Honda	–29.61164	–71.28484	2		303	2015-09-25	15:56
23	Caleta Los Hornos	–29.61943	–71.28672		4.7	78	2015-09-25	18:30
24	Punta Teatinos	–29.82291	–71.29012		2.0	59	2015-09-25	14:43
25	Punta Teatinos wetland	–29.82313	–71.28955		2.6	37	2015-09-25	13:16
26	La Serena Golf	–29.82701	–71.28497	0.77	5.8	87	2015-09-25	13:44
27	La Serena Golf	–29.82871	–71.28439		5.3	35	2015-09-25	14:01
28	La Serena Golf	–29.82863	–71.28438	0.98	4.2	132	2015-09-25	14:20
29	Caleta San Pedro	–29.88126	–71.27346	0.35	2.9	88	2015-09-25	20:58
30	Caleta San Pedro	–29.88269	–71.27353		2.3	69	2015-09-25	20:48
31	Faro La Serena	–29.90545	–71.27138	0.1		320	2015-09-25	12:35
32	Faro La Serena	–29.90675	–71.27373	0.3	1.7	94	2015-09-25	12:19
33	La Serena	–29.90757	–71.27434	0.9	2.9	58	2015-09-25	12:30
34	La Serena	–29.90999	–71,27446	0.4	6.8	72	2015-09-18	10:55
35	La Serena	–29.92974	–71.27985	0.1	3	68	2015-09-25	19:37
36	La Serena	–29.93619	–71.28343	1	3.4	66	2015-09-25	21:56
37	La Serena	–29.94743	–71.29271	0.4	3.0	65	2015-09-25	22:09
38	La Serena	–29.94961	–71.29544	0.33	1.9	59	2015-09-25	22:30
39	Caleta Peñuelas	–29.95376	–71.30092	1.2	1.4	106	2015-09-25	22:21
40	El Culebron wetland	–29.95533	–71.33666	2.1	4.3	50	2015-09-18	12:35
41	El Culebron wetland	–29.9614	–71.31748	1.5	4.4	265	2015-09-26	12:42
42	Coquimbo	–29.96474	–71.3305	1.22	5.8	787	2015-09-26	13:33
43	Coquimbo	–29.9603	–71.33183	2.3	3.6	420	2015-09-26	13:44
44	Coquimbo	–29.97682	–71.3481	3.1	7.5	419	2015-09-26	14:00
45	Puerto Pesquero	–29.95533	–71.33666	2.72	3.5	184	2015-09-26	14:50
46	La Herradura	–29.97682	–71.3481	0.3	3.5	40	2015-09-26	15:29
47	La Herradura	–29.98426	–71.3578	0.9	3.4	97	2015-09-26	15:47
48	Totoralillo Centro	–30.0715	–71.37529		0.6	72	2015-09-26	16:17
49	Totoralillo Centro	–30.07306	–71.3749		2.6	158	2015-09-26	16:31
50	Totoralillo Centro	–30.07276	–71.37475		4.0	72	2015-09-26	16:31
51	Dunas de Morrillos	–30.15177	–71.37397		4.8	47	2015-10-04	14:42
52	Guanaqueros	–30.19432	–71.41613		4.9	50	2015-09-26	17:10
53	Guanaqueros	–30.19611	–71.4301	1.9	3.3	85	2015-09-26	17:24
54	Puerto Velero	–30.24521	–71.47792		1.9	152	2015-09-26	18:15
55	Playa Socos	–30.25742	–71.49346	4	2.9	414	2015-09-26	18:40

Table 1 *continued*

Pt	Site	Latitude (N)	Longitude (E)	Z (M)	R (m)	I (m)	Date	Time UTC
56	Playa Socos	–30.25721	–71.49507	3.9	9.0	461	2015-09-18	17:00
57	Tongoy	–30.25433	–71.49402	1.5	3.9	23	2015-09-26	19:13
58	Tongoy	–30.25087	–71.49568		2.7	41	2015-09-26	19:25
59	Tongoy	–30.25021	–71.49682	1.8	4.6	39	2015-09-26	19:41
60	Tongoy	–30.25581	–71.49621	0.65	3.9	93	2015-09-26	20:16
61	Tongoy	–30.25742	–71.49575	1.5	5.5	92	2015-09-18	17:40
62	Playa Grande	–30.2588	–71.49536		2.8	48	2015-09-26	20:23
63	Playa Grande	–30.27209	–71.49787	0.59	1.8	79	2015-09-26	20:40
64	Salinas Chicas wetland	–30.28034	–71.50508	1.15	1.8	120	2015-09-26	20:51
65	Playa Grande	–30.29496	–71.52746	1	2.9	235	2015-09-26	21:08
66	Playa Grande	–30.30015	–71.55149	1.2	1.1	590	2015-09-26	21:37
67	Pachingo wetland	–30.30473	–71.57618		3.3	312	2015-10-04	16:17
68	Puerto Aldea	–30.30117	–71.60641		5.9	246	2015-10-04	17:38
69	Puerto Aldea	–30.29978	–71.60776	2.1	5.5	191	2015-10-04	17:18
70	Puerto Aldea	–30.29886	–71.60795		3.8	109	2015-10-04	17:37
71	Puerto Aldea	–30.29112	–71.60853		4.4	33	2015-10-04	17:59
72	Lengua de Vaca	–30.27843	–71.61137		4.3	50	2015-10-04	20:24
73	Lengua de Vaca	–30.2769	–71.61234		4.4	51	2015-10-04	20:12
74	Lengua de Vaca	–30.27576	–71.61321		4.1	36	2015-10-04	20:04
75	Lengua de Vaca	–30.27439	–71.61422		3.4	25	2015-10-04	19:56
76	Lengua de Vaca	–30.27358	–71.61503		3.9	20	2015-10-04	19:48
77	Lengua de Vaca	–30.27273	–71.61567		3.8	29	2015-10-04	19:24
78	Lengua de Vaca	–30.26316	–71.63854	1.1	8.1	85	2015-10-04	19:59
79	Lengua de Vaca	–30.26779	–71.64731		4.6	49	2015-10-04	19:35
80	La Cebada	–30.97487	–71.64986	1	13.6	33	2015-09-28	19:38
81	La Cebada	–30.97561	–71.64858		4.2	68	2015-09-28	19:13
82	La Cebada	–31.00389	–71.64738		12.8	126	2015-09-28	17:14
83	La Cebada	–31.00432	–71.6404		2.8	671	2015-09-28	16:44
84	Caleta Sierra	–31.14609	–71.66175	2.7	7.0	220	2015-09-28	20:32
85	Puerto Oscuro	–31.42298	–71.59703	3	5.3	12	2015-09-28	22:00
86	Puerto Oscuro	–31.42213	–71.59537	1.3	3.2	16	2015-09-28	21:47
87	Puerto Oscuro	–31.42264	–71.59311		3.4	16	2015-09-28	22:14
88	Chigualoco	–31.75271	–71.51384		2.7	116	2015-09-24	22:28
89	Chigualoco	–31.75529	–71.51147		5.7	35	2015-09-24	21:49
90	Chigualoco	–31.75621	–71.50992		5.8	50	2015-09-24	22:03
91	Playa Amarilla	–31.86034	–71.51101		2.9	56	2015-09-22	17:46
92	Playa Amarilla	–31.8604	–71.51016		1.5	80	2015-09-22	17:33
93	Laguna Conchalí	–31.8712	–71.49993		3.7	35	2015-09-22	15:44
94	Conchalí wetland	–31.87355	–71.49874		0.7	6	2015-09-22	15:12
95	Laguna Conchalí	–31.87381	–71.4988		4.5	84	2015-09-22	14:59
96	Laguna Conchalí	–31.87541	–71.49856	0.9	3.3	105	2015-09-22	14:25
97	Laguna Conchalí	–31.87934	–71.498		5.0	45	2015-09-22	16:14
98	Laguna Conchalí	–31.8811	–71.49727	0.6	3.3	125	2015-09-22	16:30
99	Los Vilos	–31.90349	–71.49815		2.3	74	2015-09-28	14:16
100	Los Vilos	–31.90652	–71.50094	0.61	2.6	34	2015-09-28	14:27
101	Los Vilos	–31.90869	–71.50303		3.4	37	2015-09-28	13:59
102	Los Vilos	–31.90986	–71.51738	0.15	4.2	33	2015-09-22	18:39
103	Los Vilos	–31.91934	–71.51841		9.3	32	2015-09-22	22:34
104	Isla Los Lobos	–31.9484	–71.52459		3.5	20	2015-09-22	20:00
105	Pichidangui	–32.1379	–71.52605	1.5	2.0	102	2015-09-24	18:47
106	Pichidangui	–32.13837	–71.52726	1.7	2.5	131	2015-09-24	18:30
107	Pichidangui	–32.13504	–71.53546		5.0	28	2015-09-24	19:09
108	Los Molles	–32.23892	–71.51224		1.9	28	2015-09-24	17:18
109	Los Molles	–32.23775	–71.51167		1.8	54	2015-09-24	17:33
110	Los Molles	–32.23696	–71.5099		1.8	26	2015-09-24	17:44
111	La Ballena	–32.28374	–71.47175		4.3	57	2015-09-24	16:47
112	Pullally	–32.41607	–71.41286		0.9	507	2015-09-19	22:37

Table 1 *continued*

Pt	Site	Latitude (N)	Longitude (E)	Z (M)	R (m)	I (m)	Date	Time UTC
113	Papudo	−32.5045	−71.44381		2.5	22	2015-09-23	19:29
114	Papudo	−32.505	−71.44491		0.8	11	2015-09-23	19:19
115	Papudo	−32.50613	−71.44885		2.8	42	2015-09-23	19:46
116	Zapallar	−32.5504	−71.46043		2.2	8	2015-09-23	18:44
117	Zapallar	−32.55299	−71.46699		2.6	28	2015-09-23	18:10
118	Cachagua	−32.58423	−71.4513		2.1	10	2015-09-23	17:04
119	Cachagua	−32.58779	−71.44471		1.1	9	2015-09-23	17:32
120	Laguna Zapallar	−32.63244	−71.43013		3.0	58	2015-09-23	21:30
121	Maitencillo	−32.64494	−71.43493		2.9	28	2015-09-23	21:01
122	Maitencillo	−32.64873	−71.43874		2.3	26	2015-09-23	20:49
123	Horcón	−32.70955	−71.4908		2.5	15	2015-09-23	20:30
124	Puerto Ventanas	−32.74331	−71.4871		2.2	25	2015-09-23	19:45
125	Puerto Ventanas	−32.75313	−71.48468		3.0	12	2015-09-23	19:04
126	Quintero	−32.78161	−71.52669		1.0	0	2015-09-23	16:55
127	Quintero	−32.78175	−71.52702		1.9	30	2015-09-23	16:38
128	Ritoque	−32.8279	−71.52919	0.83	2.3	30	2015-09-23	14:48
129	Ritoque	−32.82545	−71.52806	0.26	3.4	231	2015-09-23	15:07
130	Ritoque	−32.82855	−71.52504		1.6	27	2015-09-23	15:46
131	Mantagua	−32.8836	−71.50901		0.9	195	2015-09-17	20:18
132	Mantagua	−32.88338	−71.50905		2.8	155	2015-09-17	19:46
133	Mantagua wetland	−32.88164	−71.50274		1.5	75	2015-09-17	19:53
134	Punta Piedra	−32.89677	−71.50665		3.9	12	2015-09-23	22:30
135	Concón	−32.92039	−71.51151	0.86	3.0	143	2015-09-23	13:27
136	Reñaca	−32.96327	−71.54669		2.7	35	2015-09-21	13:00
137	Reñaca	−32.971	−71.54521		2.7	25	2015-09-21	13:40
138	Viña del Mar	−32.99461	−71.54837		2.5	15	2015-09-25	17:20
139	Viña del Mar	−33.00613	−71.55114		2.4	14	2015-09-25	16:50
140	Viña del Mar	−33.01299	−71.55499		2.2	17	2015-09-25	16:20
141	Viña del Mar	−33.02302	−71.56914		2.7	16	2015-09-25	15:00
142	Portales	−33.03221	−71.59218		2.9	19	2015-09-25	14:00
143	Quintay	−33.18264	−71.68498		1.9	17	2015-09-25	21:59
144	Quintay	−33.19393	−71.69966		1.7	12	2015-09-25	21:24
145	Algarrobo	−33.36132	−71.67159		2.3	19	2015-09-25	19:29
146	Algarrobo	−33.36239	−71.67193	0.5	1.6	7	2015-09-25	19:14
147	El Tabo	−33.45886	−71.6642		3.0	15	2015-09-25	17:00
148	Cartagena	−33.54919	−71.60588		2.5	20	2015-09-25	15:26
149	Santo Domingo	−33.62663	−71.63284		4.3	18	2015-09-25	14:00
150	El Yali	−33.75035	−71.71384	0.5	1.7	197	2015-09-18	15:45
151	El Yali	−33.75432	−71.71845		1.9	395	2015-11-14	22:39
152	El Yali wetland	−33.75656	−71.72301	0.55	1.5	360	2015-09-18	16:38
153	El Yali	−33.75655	−71.72292	0.3	1.8	318	2015-11-14	22:09
154	El Yali	−33.75421	−71.72451		2.8	28	2015-11-14	21:45
155	El Yali	−33.76352	−71.73855		0.8	345	2015-11-14	20:53
156	El Yali	−33.76366	−71.74046		2.3	302	2015-11-14	20:31
157	El Yali	−33.7652	−71.74296	0.3	1.5	337	2015-11-14	19:40

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