Chapter 8
El Yali National Reserve: A System of Coastal Wetlands in the Southern Hemisphere Affected by Contemporary Climate Change and Tsunamis

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Abstract El Yali is a complex wetlands system composed by more than 14 waterbodies, located in central Chile and delimited by two basins of the most important rivers of the region. Among the waterbodies is a coastal lagoon, some estuaries, artificial wetlands, salt mine and inner lagoons that were coastal lagoons in the past but due to tectonic processes have been moved and raised to their current location.

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The damming of the river that delimits the system to the south in 1968 cutoff the natural the sedimentary supply to the extensive beach and dunes, leaving the wetlands in a situation of vulnerability before climate change and variability, anthropic pressure, ocean swells and tsunamis. In the present chapter is illustrated the degradation that the wetlands system is suffering, by means of the estimation of tendencies of the long term records available in the zone, antecedents about its natural history, anthropic pressure and natural disasters like earthquakes, tsunamis, ocean swells and ENSO, along with field monitoring that has been carried out with the objective of implementing an ecological restoration. These antecedents show a decrease of precipitations and river discharges, an increase of ambient temperature and sea surface temperature, a rising of sea level and a change of the incident waves.

El Yali was severely affected by the earthquake and tsunami in 2010, which destroyed 800 ha of beach and coastal dunes that provided natural protection. In many opportunities, El Yali was affected by earthquake and tsunamis, intense ocean swells and ENSO, all phenomena that dissipate energy destroying the natural barrier the dunes represent. However, before the construction of Rapel reservoir, the sedimentary supply allowed a rapid recovery of the beach, sandbar and dunes. When this sediment supply was cutoff, the dunes has enough material to support the equilibrium of the system for some decades, but when tsunami waves destroyed the dunes, there was no sand supply to restore the beach nor the dunes. This generated a substantial change in the system, turning it more vulnerable to tsunamis, even smaller, ocean swells, and sea-level raising associated to ENSO Kelvin waves and climate change. For this reason, the first proposed restoration action is to restore the dunes and plant a vegetal cover with native species that reinforce and maintain the dunes.

Keywords Ramsar site • ENSO • Dune • Beach • Sandbar

8.1 Introduction

Coastal wetlands in central Chile are extremely dynamic and fragile environments, whose existence is conditioned by a number of natural and anthropic factors, including hydrologic and climatic variability, high littoral energy content, variability of sediment deposition, seismicity, and tectonic processes on the Chilean coast, which generate large morphological changes in coastal areas. This so particular combination only has similar referents in some areas of South Africa, Australia (Cienfuegos et al. 2012) or New Zealand (Nichol et al. 2007).

This chapter aims to show the degradation that El Yali coastal wetland system (33°45′S; 71°43′W) is currently suffering, from a multidisciplinary perspective, as result of a combination of different factors:

(a) The effects of the contemporary climate change by a diminution of precipitations and the increase of temperature seem to be changing the hydrologic equilibrium of these systems and this represents a pressure forcing changes in agriculture and use of soils that increase the demand for hydric resources.

(b) Climate variability effects, such as ENSO phenomenon that modifies the seasonal evolving and other intra-annual cycles, generating a significant interannual variation in sea-level, sea surface temperature, air temperature, rainfall and river discharges;
(c) Anthropic effects, some of the contemporary, such as real estate demand, change of land uses, competition for water, the increase of recreation activities associated with the transit of vehicles on coastal dunes, as well as past activities, like the construction of a damn in Rapel river (basin that represents the southern limit of El Yali), which represented a cutoff in the contribution of sand to beaches and coastal dunes in this area; and
(d) The recurrent earthquakes, tsunamis and ocean swells that have affected this zone, producing morphological changes due to co-seismic vertical movements, eroding beaches and sand dunes and changing the characteristics of the water body by seawater intrusion.

These changes appear to have accelerated as consequence of the earthquake and tsunami of February 2010. Even when in 2009 some problems of environmental quality were already detected in the wetland system, when Figueroa et al. (2009) utilized the index of conservation of lentic ecosystems (ECELS, proposed by the Catalan Water Agency 2004) and found that El Yali characteristics qualified as regular to bad, some bird census showed a high biodiversity (Vilina et al. 2014) and there were no signs of severe degradation. After that event, a permanent monitoring is being carried out in this area. This monitoring program allowed registering a dramatic decrease of waterbodies extension, especially in inner lagoons, the loss of regeneration capacity of beaches and coastal dunes, the appearance of new vegetal species and presence of invasive flora and fauna, and the massive death of the amphibian *Calyptocephalella gayi* (Acuña-O et al. 2014; Mizobe et al. 2014), known as the big Chilean frog, a specie in danger of extinction and endemic of Chile. This chapter is based on the information obtained from this monitoring program. Additionally, an initiative funded by Parks Canada allowed carrying out a study to plan the ecological restoration of the area. That study provided information to define the base line and objectives for restoration. Currently, the restoration plan is in its initial stage of implementation.

In the littoral zone of central Chile there is a confluence of at least two aspects that have influenced the formation of numerous coastal wetlands:

(a) The oceanic Nazca tectonic plate is slipping beneath the continental South America plate at a relative rate of 8 cm/year and with a convergence angle of 78° at NE (Pardo et al. 2001) provokes an imperceptible but continuous lifting of the South American Plate. On the other hand, this same process is responsible of episodic big earthquakes subduction (Mw >8.0) in this zone. These earthquakes produce important horizontal and vertical co-seismic movements (Farías et al. 2010; Quezada et al. 2012a; Wesson et al. 2015). This process alone is able to form a coastal lagoon, as in the case of El Yali. But this process can also destroy coastal wetlands, as in the case of Tubul-Raqui wetland (37°13′S; 73°26′W), which, with an extension of 2000 ha, suffered a co-seismic lifting of 1.6 m during the earthquake occurred on February 27th, 2010, causing a partial desiccation of the wetland that has been well documented (Valdovinos et al. 2010, 2012).

(b) On the other hand, river in this zone, with snow-rain regimes and important slopes and discharges, are able to transport large quantities of material from the Andean cordillera to the coast (Cienfuegos et al. 2012). In the recent past, there have been cases where the alteration of hydrodynamic equilibria has an immediate morphological response, as that documented by Pomar (1962), which describes the accretion of a sand beach and consolidation of lagoon Llolleo (33°36.4′S; 71°37.4′W) nearby Maipo river mouth, whose basin represents the northern limit of the wetlands system, after the construction of a sheltering structure in the port of San Antonio. In other cases, a rapid recovery has been observed, as in the case of the 8 km length sand bar in Mataquito river mouth (34°52′S, 72°09′W), which almost completely disappeared under the combined action of tsunami waves and the relatively large land subsidence (Lario et al. 2016; Vargas et al. 2011). This zone river mouth is located right off the rupture zone where most of the February 2010 earthquake energy was liberated (Lay et al. 2010). After the earth quake and tsunami, the coastal evolution of this zone has been monitored by using field work techniques and satellite imagery (Cienfuegos et al. 2014), evidencing that most of the original sand bar recovered in less than 18 months, even showing a rapid recovery in less than 6 months (González et al. 2012). These examples show that changes produced by anthropic alterations as well as tectonic and seismicity can provide conditions for beaches accretion and dune and sandbar formation (Martínez et al. 2015; Veas et al. 2016) that also favor consolidation of coastal wetlands. This explains the fact that there are more than 400 coastal wetlands along the coast between 30°S and 44°S (Marquet et al. 2012), conforming a, ecological corridor for migratory birds and other species. However, these wetlands, that are fragile environments due to those conditions that influence their construction and destruction, are under a growing pressure due to a persistent anthropic activity around them: using wetlands as sink of liquid residues, receiving contamination from agriculture products, draining wetlands to extract water or expansion of real estate projects. Moreover, contemporary climate change represents an additional pressure, influencing the delicate equilibrium of these systems.

Besides describing a so far poorly known system, the novelty of this chapter is based in two main aspects:

(a) To incorporate the effect of tsunamis and resilience to the discussion about coastal wetlands. During more than 50 years after the construction of the damn in Rapel River, the system of beaches to the north maintained an unstable equilibrium, where the coastal dunes that protected the coastal lagoon and beach stopped receiving a continuous supply of sand. In spite of that, the material accumulated over years was able to stay in fragile equilibrium, not showing significant changes. However, the tsunami of 2010 swept all the coastal dunes and removed a significant part of the sand form the beach, triggering a loss of functionality that will be detailed next.

(b) To describe the changes that the El Yali wetland is experiencing as response to Climate Change and the influence of multiple anthropogenic pressures. El Yali coastal wetland is located in the southern limit of the semi -arid wetland (Figueroa et al. 2009; Vidal-Abarca et al. 2011), but on its RAMSAR file it has been described as a Mediterranean wetland (RAMSAR 1996). This confusion is because of its location in the limit where the semi-arid climate is extending southwards, over the Mediterranean Central Chile. This situation offers an opportunity to study the effects of these changes on waterbodies and associated biotopes.

8.2 Geological Context and Natural History of the Site

El Yali is a complex system of coastal wetlands located in Central Chile (Fig. 8.1), between Maipo River (to the north) and Rapel River (to the south) basins. The latter was dammed in 1968, what caused an important decrease in the sand supply that used to maintain the important dunes system nearby the wetland and the coastal lagoon (Vergara 2014). This system is composed of more than 14 waterbodies, from which three of them are part of the protected RAMSAR site N°878. These three protected water bodies are the Albufera, Matanzas lagoon and Colejuda lagoon (Fig. 8.2). The wetland is characterized for the differences in the chemical composition and seasonality of its waterbodies (Figueroa et al. 2009), what explains the richness and biodiversity in this area. Thus, this condition highlights El Yali as one of the most important coastal wetlands in Central Chile (Vilina 1994; Dussaillant et al. 2009; Dussaillant 2012; Fariña et al. 2012).

El Yali wetland sustains 28% of the bird species in Chile (about 139 species) and this Mediterranean eco-region poses 3% of the endemism in aquatic bird population (Victoriano et al. 2006). Approximately 29 migratory and visiting bird species, 18 coming from the northern hemisphere and 11 form the southern hemisphere,

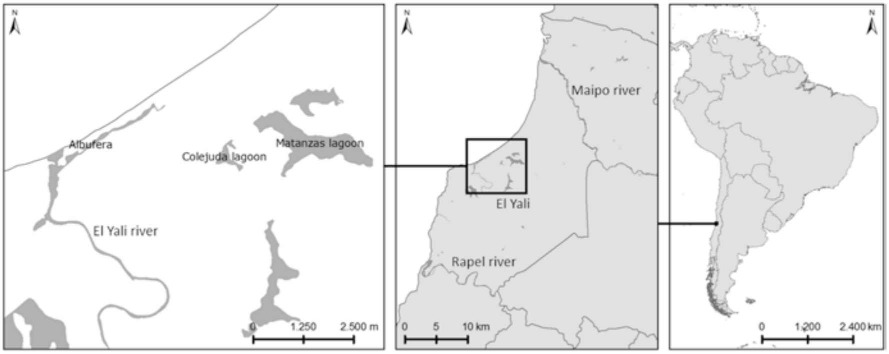

Fig. 8.1 Map of El Yali and its location on the coast of the central Chile and South American context. Three protected waterbodies are shown: Matanzas lagoon, Colejuda lagoon and Albufera (coastal lagoon). El Yali River mouth discharges at the SW extreme of the Albufera

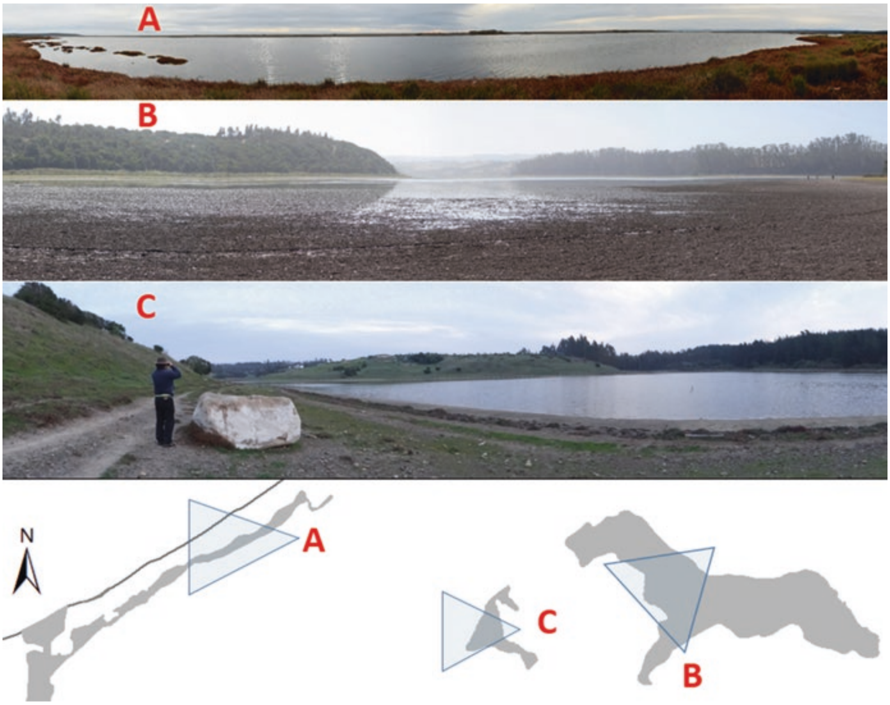

Fig. 8.2 (**a**) Albufera in August 2015. It is possible to observe a remnant of the coastal dunes on the horizon. (**b**) Matanzas lagoon in December 2014. Desiccation being suffered by this water body is easily observed. (**c**) Colejuda lagoon in July 2014. At the forefront is the gneiss block located in this place. *Below* are shown the positions where these photos were taken and the estimated direction of the sights

respectively, arrive in this wetland (Vilina 1994; Brito 1999; Victoriano et al. 2006; Fariña et al. 2012; Vilina et al. 2014).

The inner lagoons were coastal lagoons in the past, but due to seismic displacements and elevations, they are in their current position (10 or more meters above sea level and some km inland). However, they still conserve saline characteristics that favor a high abundance and biodiversity of flora and fauna.

Contreras-López et al. (2014) described the current configuration of El Yali basin, taking into account the big tectonic movements that occurred by the middle of the Tertiary Period, and that provoked strong dislocations by faults on the coast of central Chile, along with a lifting of the Andean cordillera to its current level, the sinking of the longitudinal valley and the formation of the coastal cordillera (Noguera 1956). The small streams that originated in the coastal cordillera and flowed toward the sea with tilted slopes deposited diverse coarse sediment whereas finer material was swept along to the sea. New violent tectonic movements lifted the adjacent seabed and formed the successive systems of marine terraces that can be observed nowadays along these coasts. In particular, five main movements can be identified in

El Yali area: two raisings, one sinking followed by a new raising (Noguera 1956), and a rising associated to the 1985 earth quake (Barrientos and Kausel 1990).

Thus, the development of El Yali and the system it belongs to, obeys to the interaction of several dynamic factors that have determined the geomorphological evolution that the central Chilean coast has experienced during the last 18,000 years (Fariña et al. 2012).

Marine transgressions occurred during the last glaciation (14,000 years ago) and during the middle Holocene (6000 years ago) allowed the accumulation of marine and/or fluviomarine sediment throughout the basin (Fariña et al. 2012). The tectonic activity expressed in the co-seismic vertical movements that characterized the last 3000 years (Lower Holocene), produced the regional raising of the coast that caused the emersion of a littoral terrace where is located the wetland. A sign of this process is gneiss block present to the southwest of the lagoon Colejuda (Contreras-López et al. 2014).

As result of the coastal raising, a marine regression occurs and initiates the progradation of the coastal line by means of eolic and fluvial sedimentary processes (Paskoff et al. 2000). The existence of fluvial refills and transgressive and parabolic dunes in the area indicates that progradation occurred through sedimentary loads from Rapel and Maipo rivers, by means of littoral drift and eolical transport (Paskoff and Manríquez 2004).

Paleoclimatic studies based on the analysis lacustrine sediment cores from lagoons Matanzas (Jenny et al. 2000; Villa-Martínez 2002) and Colejuda (Valero-Garcés et al. 2010, cited by Fariña et al. 2012) suggest that the evolution of the wetlands complex has been mostly modeled by changes in eolic sedimentations and significant variations in precipitations associated to ENSO (El Niño – Southern Oscillation), which increases in frequency and intensity during the Holocene.

Pollen, sediment, geochemical and chironomid fossils analyses show that 5000–3300 years ago lagoon Matanzas was a littoral lagoon with moderate to low salinity conditions (Villa-Martínez 2002). During this period, precipitations had important fluctuations, showing two rainy intervals, 4900–4800 years ago and 4500–3300 years ago, separated by an dryer interval 4800–4500 years ago (Villa-Martínez 2002).

From 3300 to 2600 years ago there would have occurred an important increment in salinity, probably representing a change in the system from a littoral lagoon a hyper-saline lake (Villa-Martínez 2002). Likely this change would be related with the closure of lagoon Matanzas basin, some 2600 years ago, due to predominance of eolic sedimentary processes that formed a dunes chord that presently dam this system (Fariña et al. 2012; Paskoff and Manríquez 2004; Martínez 2009), and that is locate immediately to the north of Navidad Formation (Encinas et al. 2006), a geological formation that attracted great interest from the naturalist Charles Darwin when he passed by this area in 1834 (Darwin 1846). This consolidated dune (El Convento), with an extension of over 1000 ha, is one of the most important in the region (Castro-Avaria 2015). Nowadays, it is difficult to appreciate its extension, due to the efforts realized during the twentieth century to consolidate its advance by planting pines and eucalyptus (Albert 1900). These plantations contribute to hide the presence of the dune.

During the gradual closure process of lagoon Matanzas, fluvial sedimentation associated to floods of Las Rosas brook would have also been an important factor (Fariña et al. 2012). Appearance of species intolerant to salinity along with low chlorine concentrations found in sediments suggest that 2400 years ago existed moderate to low salinity conditions in lagoon Matanzas (Jenny et al. 2000). During that lapse, sediments show at least 20 different flood periods, what would indicate marked fluctuations in winter rains (Villa-Martínez 2002).

During the last 150 years, Villa-Martínez (2002) recognizes a deterioration of vegetation associated to forest surrounding lagoon Matanzas, what is attributed to anthropic activity. Notwithstanding, Fariña et al. (2012), point out that an alternative but not excluding explanation is the decrease in precipitations detected in the sediment core from lagoon Colejuda by Valero-Garcés et al. (2010).

8.3 Some Aspects About Climate Change in Central Chile

El Yali is located in a region threatened by the effects of the contemporary climate change. An analysis about the registers of temperature and precipitation in this region show that temperature has risen 0.5 °C in the last 50 years, whereas annual precipitations have decreased in a 12% during the same period, which is consistent with global warming (Fig. 8.3). On the other hand, a recent analysis about the response of bio-climates of the region to different climate change scenarios showed a decrease in precipitation and an increase of temperature in Valparaiso region by 2080 (Luebert and Pliscoff 2012).

For the case of annual precipitations, it is expected to observe a latitudinal pattern of decrease in the coastal and Andean areas (a decrease that can be ~280 mm), whereas the inner areas would present a less decrease (50–80 mm per year). Similarly, the mean annual temperature shows a longitudinal increase pattern, with lower values in the coastal zone (1 °C), reaching an increase of 2.4–3.5 °C in the Andean area. Under these climatic conditions it is expected in the long term an ascendant altitudinal displacement of vegetation floors, especially in the Andean area, as well as a latitudinal displacement, with the intrusion of species typical of semi-arid and arid zones in central-north Chile, especially in the coastal zone. The recent finding of *Suaeda foliosa* (typically found in northern Chile) in El Yali wetland (Flores-Toro and Contreras-López 2015), extending its distribution in 300 km, seems to be an early expression of this phenomenon. As an additional element, centuries of agriculture in central Chile have produced a progressive degradation of soils and a severe fragmentation of the sclerophyll forest, which has consequences on the habitat (Grez and Bustamante-Sánchez 2006), causing a reduction of biodiversity and making the system more vulnerable to climate fluctuations and a decrease of the available hydric resources.

A series of historical records collected in the vicinity of El Yali wetland is shown in Table 8.1. Except the annual series of precipitations in Valparaiso (1900–2015), which corresponds to the total precipitation during 1 year, all series were averaged or accumulated to transform into monthly averages. Combined by means correlations, the

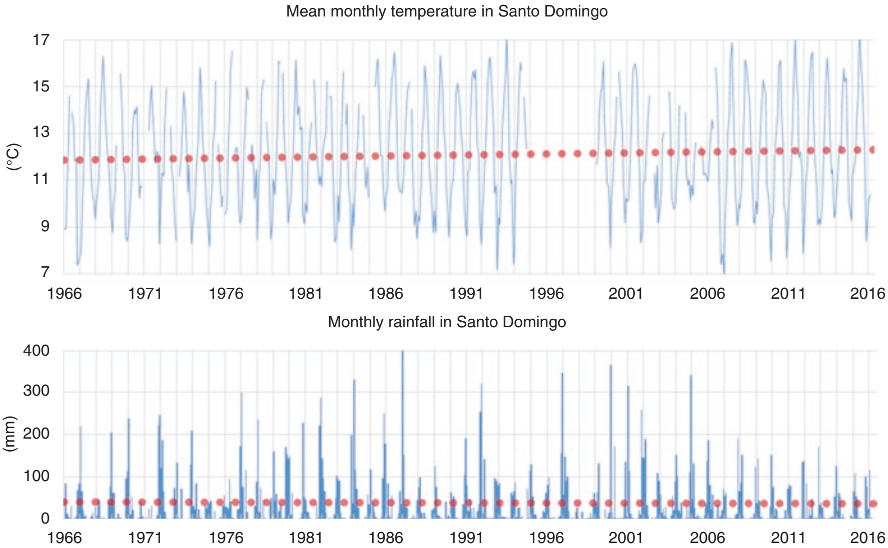

Fig. 8.3 Time series of temperature monthly averages (*top*) and monthly accumulated rainfall (*down*) registered during the last 50 years at aerodrome of Santo Domingo, far 15 km from the wetland. A 0.5 °C increment can be observed in ambient temperature and a decrease in rainfall, even when the latter present large intra-annual fluctuations associated to ENSO

hourly sea level record for almost 30 years, air temperature for 50 years, precipitations for 76 years, and three series of coastal water surface temperature allow to construct a series of 71 years, 45 years of water discharge nearby Maipo river mouth (delimiting the wetland to the north) and a 41 years record of Rapel dam (delimiting the wetland to the south) discharges. During the last years it has been possible to monitor the wetland by combining different instruments, measuring atmospheric variables with two weather stations and four temperature loggers. One of the weather stations was located in lagoon Matanzas. The available data is summarized in Table 8.1.

To estimate linear trends, all series were transformed to monthly series and a linear fit was applied by the minimum square method, determining the uncertainty at 95% confidence.

From 2010 on, some parameter of the water bodies have been measured in situ (temperature, pH, conductivity, dissolved oxygen). Additionally, with monthly frequency, the surface of coastal lagoons and lagoon Matanzas was measured by walking along their perimeter with a GPS whose positioning error is less than 3 m. This was complemented with satellite imagery and maps from the Military Geographical Institute, that allow having an almost inter-decadal sequence to observe the morphological changes experienced by the coastal lagoon and El Yali brook mouth.

El Yali National Reserve is located in a coastal region with template-warm climate, with winter rain and long dry season (7–8 months). This climate is characterized by a high cloudiness almost all year long, with major intensity in winter, associated to fog and drizzle and low thermic amplitude. Atmospheric humidity during this period is high. Precipitation is relatively more abundant than in northern regions, with over 350

Table 8.1 Available time series to characterize El Yali costal wetland

N	Parameter	Location	Start (D/M/Y)	End (D/M/Y)	Length (years)	Frequency of original record	Source
1	Sea level	Puerto San Antonio	02/08/1985	16/11/2014	29	Hourly	SHOA
2	Air temperature	Santo Domingo	01/08/1966	21/09/2016	50	Daily average	DMC
3	Air temperature	Albufera	09/03/2015	11/08/2016	1	Hourly	UPLA
4	Air temperature	Mirador Matanzas	09/03/2015	11/08/2016	1	Hourly	UPLA
5	Air temperature	Administración	09/03/2015	11/08/2016	1	Hourly	UPLA
6	Air temperature	El Yali-01	2013	2016	3	Hourly	UPLA
7	Air temperature	El Yali-02	2014	2016	2	1 Minute	UPLA/SERVIMET
8	Water temperature	Laguna Matanzas	09/03/2015	16/06/2016	1	Hourly	UPLA
9	Sea surface temperature	Valparaíso	01/01/2002	31/08/2016	14	Monthly	SHOA
10	Sea surface temperature	Valparaíso	01/01/1945	31/05/2011	66	Daily	SHOA
11	Sea surface temperature	Montemar	01/01/1961	31/12/1998	37	Daily	UV
12	Precipitation	Fundo Las Dos Puertas	01/06/1990	30/06/2016	26	Daily	DGA
13	Precipitation	Rapel	01/07/1940	31/07/2016	76	Daily	DGA
14	Precipitation	Cabimbao	01/09/2010	31/05/2016	6	Daily	DGA
15	Precipitation	Faro Punta Panul – San Antonio	01/01/1988	31/03/2016	28	Daily	DGA
16	Precipitation	Santo Domingo	01/08/1966	30/08/2016	50	Daily	DMC
17	Precipitation	El Yali-01	2013	2016	3	Hourly	UPLA
18	Precipitation	El Yali-02	2014	2016	2	1 Minute	UPLA/SERVIMET
19	Precipitation	Valparaíso	01/01/1900	31/12/2015	115	Annual	SERVIMET
20	River discharge	Río Maipo en Cabimbao	1971	2016		Daily	DGA
21	N° of days with discharge	Embalse Rapel	01/01/1975	01/08/2016	41	Daily	ENDESA
22	Wave parameters	Valparaíso	1963	2013	50	Every 3 hours	ULEAM

Long time series of sea surface temperature, ambient temperature, river discharge, rainfall, sea level I nearby locations and meteorological parameters in the wetlands system (although of shorter extension) are available. The series of ocean wave parameters correspond to summary statistics (significant wave height, wave direction, and wave period) reconstructed for this region

Sources: Universidad de Playa Ancha (UPLA), Servicio Meteorológico de la Armada de Chile (SERVIMET), Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA), Universidad de Valparaíso (UV), Dirección General de Aguas del Ministerio de Obras Públicas (DGA), Dirección Meteorológica de Chile (DMC), Empresa Nacional de Electricidad Sociedad Anónima (ENDESA) y Universidad Laica Eloy Alfaro de Manabí (ULEAM) mm/year, although there are 8 months with less than 40 mm precipitation. Precipitation concentrates from May to August, with more of 80% of the annual precipitation. Intensity of precipitations and wind in winter can even reach intensities proper of storms.

The main source of climatic variability in this zone is ENSO, a natural climatic event that is cyclic and recurrent (Espino 1999), but not periodic (Capel 1999), that occurs in the central Equatorial Pacific from 7000 years ago (Arntz and Farhbach 1996). This phenomenon is characterized by unusually warm and humid conditions in the eastern equatorial Pacific Ocean that generate sea surface temperature and wind anomalies in the tropical Pacific. These anomalies affect the whole planet (Ramesh and Murtugudde 2013) and represent the most important source of interannual climatic variability (Guevara 2008), perturbing the meteorological conditions through droughts, floods, and heat and cold waves (Johnson 2014); what turns into severe environmental impacts and effects on the economic activities around the world.

There are several indexes to characterize the ENSO phenomenon. The southern oscillation index (SOI) measures the difference of the monthly mean atmospheric pressure between Tahiti and Darwin. El Niño 3.4 measures the anomaly of the sea surface temperature (SST) in the 5°N–5°S, 120°–170°W region. Finally, the Oceanic Niño Index (ONI) allows to identify El Niño (warm) and La Niña (cool) events in the tropical Pacific. It is the running 3-month mean SST anomaly for the Niño 3.4 region. Events are defined as five consecutive overlapping 3 -month periods at or above the +0.5 °C anomaly for warm (El Niño) events and at or below the −0.5 anomaly for cold (La Niña) events. The threshold is further broken down into Weak (with a 0.5–0.9 SST anomaly), Moderate (1.0–1.4), Strong (1.5–1.9) and Very Strong (≥2.0) events. There is uncertainty about how ENSO is going to respond to contemporary global warming, even though and increase in its frequency is being observed.

A comparison between the monthly anomalies of the SST off Valparaíso and the El Niño 3.4 from 1945 to 2015 is shown in Fig. 8.4. Very strong El Niño 1982/1983 and 1997/1998 events are associated to important positive anomalies of SST. However, the last ENSO 2015/2016 did not show a significant SST anomaly.

The warm phase of ENSO, known as El Niño, presents an increase of the SST and a decrease of the easterlies in the Pacific Ocean. These anomalous conditions generate strong precipitations (Fernández and Fernández 2002; Aceituno 1992), and notable changes in climate (Pizarro and Montecinos 2004) and fisheries (Parada et al. 2013: Arcos et al. 2004; Cañón 2004; Valdivia and Arntz 1985; Alvial et al. 1994). These anomalies are observed in riverine countries of the Southeastern Pacific (Colombia, Ecuador, Peru and Chile) and other parts of the continent, like Panama (Corredor-Acosta et al. 2011), Mexico (Aguirre-Gómez et al. 2012), Bolivia (Miranda 1998), Brazil (De Meló 1998; Coutinho et al. 1998), Argentina (Capüto et al. 1998) and so distance places as the Indian Peninsula (Yadav 2012).

The cold phase of ENSO, known as La Niña, is characterized for presenting lower SST than normal, intensification of easterlies in the eastern Pacific Ocean and periods of droughts.

Precipitations registered in Rapel location, along with the ONI and the adjusted linear trend are shown in Fig. 8.5. A decrease rate can be observed. In general, large intra-annual variations in precipitation can be explained by variations of ONI, what is

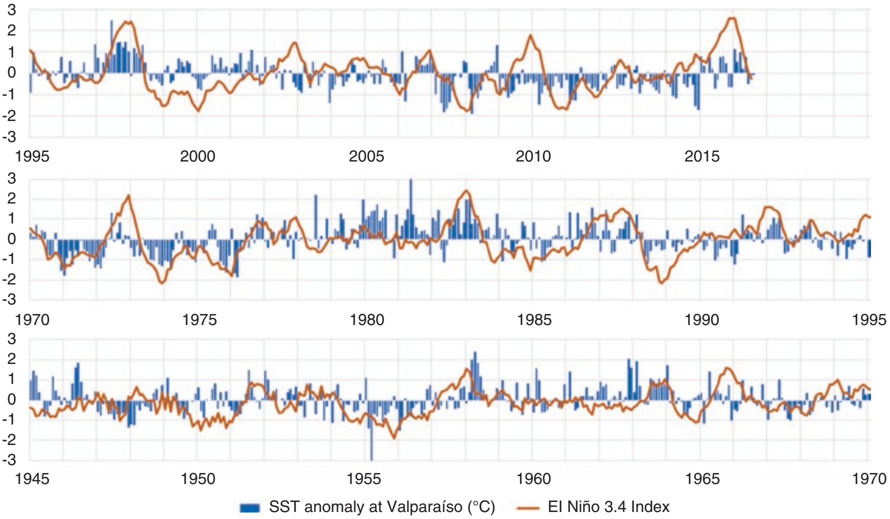

Fig. 8.4 Monthly SST anomaly (°C) off Valparaiso between 1945 and 2016. This series was constructed by means of correlations between Valparaíso and Montemar locations, in central Chile. It is also shown the monthly series of El Niño 3.4 index. In general, a good coherence exists between the monthly anomaly of SST off Valparaiso and El Niño 3.4 index

coherent with ENSO. Moreover, sharp oscillations in precipitations are observed but they are not always related to the ONI, as what was observed between 2001 and 2002.

Time series of Maipo river discharge at its mouth (20 km north of El Yali) is shown in Fig. 8.6. It is observed that the historic average of 200 $m^3 s^{-1}$ is exceeded many times, mostly associated to El Niño. The higher swellings correspond to years 1987/1988 and 2002/2003, which do not correspond to intense ENSO events. On the other hand, ENSO 1982/1983 and 1997/1998 have associated important swellings but not as severe as those observed during 1987/1988 y 2002/2003.

The mean se level (MSL) has increase during the recent decades due to the effects of thermic expansion and glacier, ice caps and polar ice melting. According to the IPCC (Magrin et al. 2014), the global mean sea level rose 0.19 m (0.17–0.21 m) during 1901–2010 and it is expected an increase of 0.26–0.82 during 2081–2100. In Chile, however, this variation is conditioned by the seismic activity between Nazca and South America plates. An analysis of 60 years records along Chile (Contreras et al. 2012) indicates that mean sea level variations significantly differ along Chile. In northern Chile, the MSL is decreasing at −1.4 mm/year (Arica, northernmost extreme of Chile), whereas in the center-south region the MSL is increasing at a rate of 2.2 mm/year (Puerto Williams, southernmost extreme of Chile). Predictions of conservative climate change scenarios for 2100 indicate a MSL rise between 0.2 and 0.3 m for different latitudes along the country; values that coincide with rates estimated by CEPAL (2015) and IPCC report (Magrin et al. 2014). By using numerical models, Albrecht and Shaffer (2016) Project MSL increase of 34–52 cm for RCP4.5 and 46–74 cm for RCP8.5 by the end of the twenty-first century.

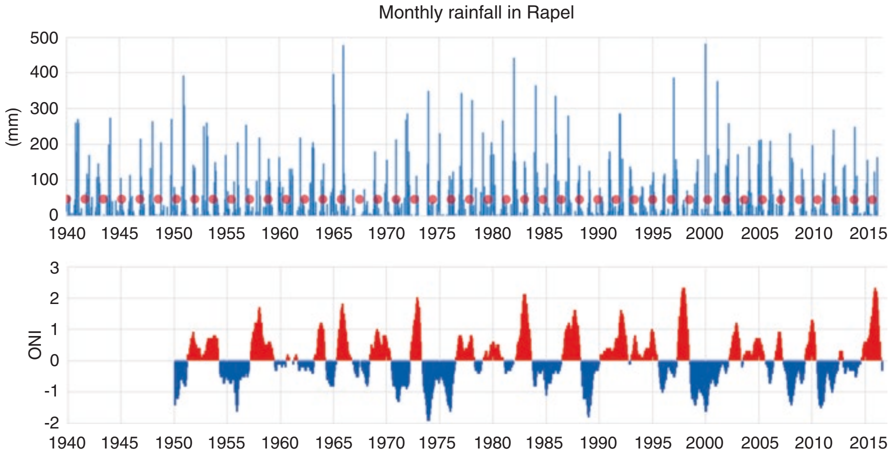

Fig. 8.5 Monthly precipitations in Rapel (1940–2016) and Oceanic Niño Index (ONI) (1950–2016). A negative lineal trend for precipitations fitted by means of minimum squares is also shown. Large intra-annual variations in precipitation can be explained by variations of ONI

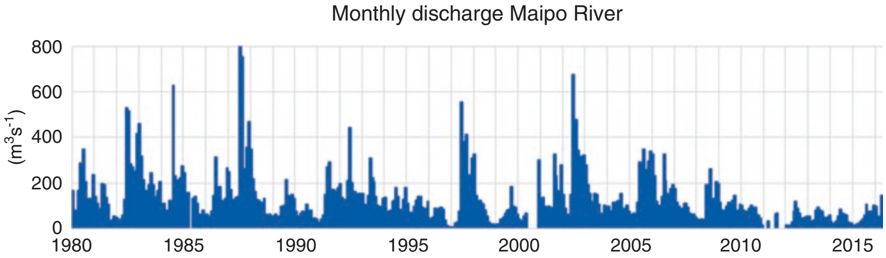

Fig. 8.6 Monthly river discharge ($m^3\ s^{-1}$) at Maipo river mouth between 1939 and 2012. The higher swellings correspond to years 1987/1988 and 2002/2003, which do not correspond to intense ENSO events. On the other hand, ENSO 1982/1983 and 1997/1998 have associated important swellings but not as severe as those observed during 1987/1988 y 2002/2003

It must be considered that MSL records are modified by geologic processes, due to the convergence of tectonic plates (Wyss 1976; Albrecht and Shaffer 2016). Within seismic cycle, co-seismic (during earth quake) and inter-seismic (between earth quakes) movements result in coastal raising or subsidence. Cases where the instrumental record shows descend of NSL can indicate the tide gauge is being raised faster than the MSL raising caused by climate change. Co-seismic vertical movements can produce descend of meters in the MSL (e.g. Farías et al. 2010), which equals centuries of raising associated to climate change.

MSL is also affected by irregular cyclic oscillations like ENSO. Contreras et al. (2012) observed that ENSO can increase MSL monthly averages up to 30 cm during El Niño and reduce these values in the same order during La Niña. The increase of the MSL during El Niño is therefore comparable to the raising that would be observed by the end of the century.

In Fig. 8.7 are shown the variations of the MSL in San Antonio, 20 km to the north of El Yali wetland. An increase rate of 3 mm/year is observed (95% confidence). However, El Yali coastal lagoon is far more threatened by an earth quake that could raise it or sink it, and more frequently by ENSO. In this sense, the same figure shows the raising caused by the strong El Niño 1997/1998.

Waves are the main driver of littoral processes on the open coasts of central Chile. This stressor is described by means statistic parameters like significant height (SH), direction and period, which have experienced historic variations due to contemporary climate change. Molina et al. (2011) indicate a 10 cm increase has been observed in HS in central Chile and an alteration of 12° in wave direction. This agrees with Church et al. (2013, AR5), who foresees a 5% increase in the average SH for most part of Chilean territory, and with Izaguirre et al. (2013), who detected a positive trend in extreme wave heights for all South America coasts. Variations and trends of SWH and direction off Valparaíso are shown in Fig. 8.8. This wave corresponds to reconstructed deep water climate.

Different antecedents show that ocean swell is a frequent phenomenon in Chilean coasts. Campos-Caba et al. (2015); Campos-Caba (2016) identified 201 events with effects on the Chilean coasts between Valdivia and Arica, during 1823–2015. Sixty four of these events occurred before 1979. The other 137 events occurred after 1979, with an average of 4 swell/year and marked seasonality. Brito (2009), described several events of swells and storms between Valparaíso and San Antonio, based on historic antecedents. Available studies, however, have no enough statistic robustness – data prior to 1979 is essentially qualitative – to assess the vulnerability of coastal settlements to contemporary climate change. On the other hand, the lack of a permanent network of wave records along the cost makes it difficult to capture

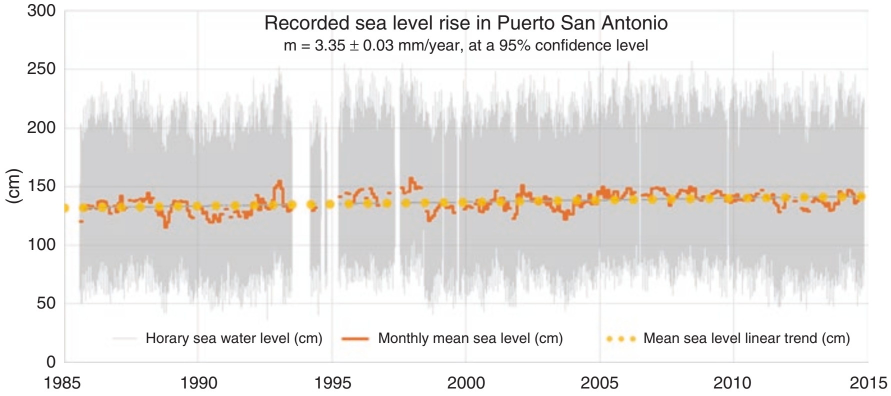

Fig. 8.7 Hourly sea level record in San Antonio port (1985–2014), 20 km to the north of El Yali wetland, along with monthly estimations of MSL and linear fit. An increase rate of 3 mm/year is observed (95% confidence). The figure shows the raising caused by the strong El Niño 1997/1998

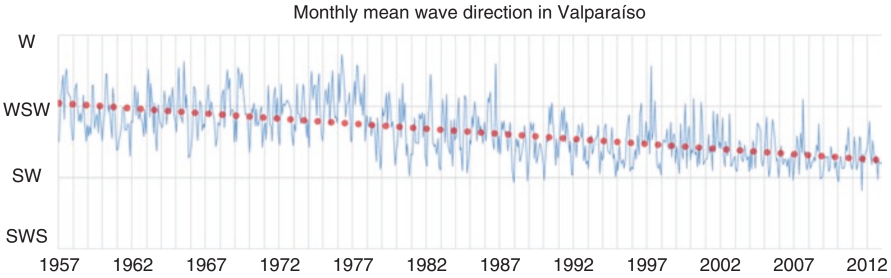

Fig. 8.8 Variation of incident wave direction off Valparaíso (1957–2013). This series corresponds to summary parameters reconstructed from satellite altimetry and records of wind and atmospheric pressure (Source: ULEAM)

Fig. 8.9 Comparison of Albufera (coastal lagoon) shore and costal dunes before and after the ocean swell in August 2015. Northward sight

storm events that are not represented by models used nowadays (Beyá and Winckler 2013; Vicuña et al.2014).

In August 2015, a strong ocean swell hit central Chile and severely affected the beach and coastal dune of El Yali, eroding the scarce material accumulated after the tsunami that occurred in 2010 (Fig. 8.9).

8.4 Earthquakes and Tsunamis

El Yali was severely affected by the earthquake and tsunami in 2010, when about 800 ha of beach and dunes were swept (Contreras 2014; Contreras-López 2014). The absence of these dunes has turned the wetland system more vulnerable to ocean swells, as occurred in August 2015 (Winckler et al. 2015). The recent earthquake and tsunami in September 2015 flooded about 280 ha too (Contreras-López et al. 2016).

The littoral zone of El Yali Natural Reserve is located 367 km far from the point where plates converge and that is part of one of the segments of the South American subduction area (von Huene et al. 1997; Pardo et al. 2001). In zone occurs earth quakes with important magnitudes and whose epicenter is close to the coast or above the deep seabed. These two conditions are sufficient to consider the area as of high tsunamigenic danger, due to the generation of near field tsunamis. Tsunamis are not always destructive when reaching the coasts, being able to reach from a few centimeters to several meters above sea level. A determinant factor is whether the arrival is under low-tide or high-tide conditions (mitigating or amplifying its effects). Likewise, it is necessary to consider a far field tsunami (generated in distant zones), whose contemporary example is the earth quake originated in Japan on 11 March 2011.

When consulting (a) Historic database about tsunamis in the Pacific (Gusiakov 2001), HTDB/Pac (2016); (b) World historic tsunami database (HTDB/WLD 2016), and (c) NOAA/WDC tsunami database (NOAA 2016), it is possible to infer that the coastal zone of El Yali Natural Reserve has been affected by eleven tsunamis since 1900 to present time: (1) Valparaíso 1906 Mw 8.2; (2) Constitución 1928 Mw 7.6; (3) Alaska 1946 Mw 8.1; (4) Rusia 1952 Mw 9.0; (5) Alaska 1957 Mw 8.6; (6) Valdivia 1960 Mw 9.5; (7) Alaska 1964 Mw 9.2; (8) Valparaíso 1971 Mw 7.5; (9) San Antonio 1985 Mw 8.0; (10) Cobquecura 2010 Mw 8.8; (11) Japón 2011 Mw 9.1 and (12) Illapel 2015 Mw 8.3 (Table 8.2).

As mentioned, El Yali National Reserve was very affected by the Mw = 8.8 27 February 2010 earthquake (Rubio and Basic 2011; Fariña et al. 2010). The tsunami wave entered, on average, more than 1 km inland, reaching 2 km in some cases and flooding about 800 ha, 200 ha corresponded to protected areas. This event affected mostly the lagoon, due to the break of the sandbar, producing a sever loss of the equilibrium in the ecosystem.

This event provoked changes in the wetland ecosystem, destroying the vegetation and leaving many dead birds, besides altering nesting and resting sites. Moreover, the landscape was altered because the wave transported algae and clastic debris of a wide granulometric spectrum, domestic garbage, fishery material and wreckage amounting 10 tons.

Due to the destruction of the dune by the tsunami, the first notorious change that was observed was the permanent connection of the Albufera with the sea in at least three sites. These connections would gradually close create, 6 months later, a drastic

Table 8.2 Summary of earthquakes generating tsunamis and that possibly have affected El Yali wetland

N°	Year	Month	Day	Mw	Country	Field	Runup Valparaíso	Runup San Antonio	Runup El Yali	Uplift
1	1906	8	17	8.2	Chile	Near	>0	>0		>0
2	1928	12	1	7.6	Chile	Near	>0			
3	1946	4	1	8.1	EEUU	Far	1.60			
4	1952	11	4	9.0	Russia	Far	1.80			
5	1957	3	9	8.6	EEUU	Far	2.10			
6	1960	5	21	9.5	Chile	Near	1.70			
7	1964	3	28	9.2	EEUU	Far	2.20			
8	1971	7	9	7.5	Chile	Near	1.20			+0.10
9	1985	3	3	8.0	Chile	Near	1.15	3.50		+0.50
10	2010	2	27	8.8	Chile	Near	2.61	3.90	5.20	−0.35
11	2011	3	21	9.0	Japan	Far	1.54	0.89	>1.00	0
12	2015	9	16	8.3	Chile	Near	2.00	1.00	2.80	

Source: NOAA (2016), HTDB/Pac (2016), HTDB/WLD 2016, IOC (2016), Fritz et al. (2011), Contreras-López et al. (2016), and Quezada et al. (2012b). 2011 run-up record corresponds to the autor observation that has not been published yet

Only the last three events have been registered with instruments so as to prove the occurrence of tsunamis hitting the wetland. Runup and uplift values are in meters (m)

segmentation of the coastal lagoon into two water bodies, one of which would completely disappear 2 years later.

In 2011, the far-field tsunami generated in Japan also hit El Yali river mouth and the coastal lagoon. When the sandbar and coastal dunes did not exist anymore, the tsunami waves trespassed the south part of the beach and flooded some meadows that were not reached like this since middle of the twentieth century.

During these years, it was possible to appreciate a moderate recovery of coastal dunes, at lower rates than in other places that were also affected by the tsunami 2010. However, any disturbance provoked the disappearance of the small coastal dunes being formed.

In 2015, a month after the occurrence of a severe ocean swell that erodes the beach and coastal dune, a local tsunami that had destructive effects 200 km to the north overpassed the Albufera (Contreras-López et al. 2016). In Fig. 8.10 is shown the beach and remnants of the coastal dune before and after the ocean swell, and before and immediately after the last tsunami that affected the wetland.

It has not been possible to find testimonies of what occurred in this site in 1985, when a Mw 8.0 earthquake had its epicenter nearby the wetland. It is known that this earthquake generated a tsunami in San Antonio port and, therefore, we can infer that it was also destructive in El Yali. Likewise, it is possible that the transoceanic tsunami that followed the Valdivia earthquake Mw 9.5 in 1960 must have had similar effects to what occurred in 2010.

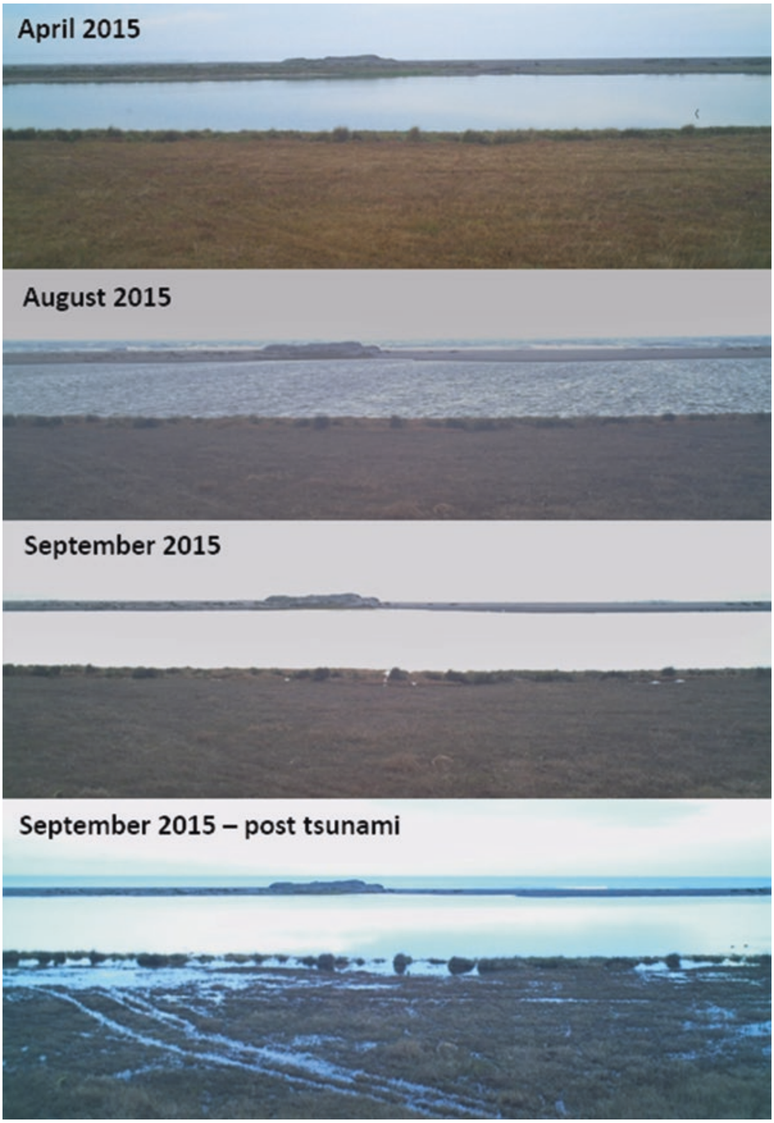

Fig. 8.10 Sights from a camera located on the south shore. It is possible to observe the effect of the ocean swell between April and August. The image captured in September was taken the day before the tsunami, whereas the next one was taken right after the waves

8.5 Evolution of Waterbodies

As it has been pointed out, El Yali brook mouth and the lagoon have experienced drastic changes in their recent morphology due to the effect of the 2010 tsunami. The destruction of coastal dunes implied an increase in the vulnerability of the lagoon ecosystem before ocean swells and tsunamis, as was demonstrated with the far field tsunami of Japan 2011, the ocean swell in August 2015 and the tsunami occurred in September 2015. In the case of El Yali, coastal dunes were doubly affected: first, by the impact and second, by the creeping mechanism; water eroded a volume of sediments from the area which was no quantified but estimated as significant when comparing the current dune field with pre-tsunami images. However, when analyzing historic geographic charts from the Military Geographic Institute and the recent evolution of the dune field, it is possible to appreciate the instability and fragility of the system since 1923 until present days (Fig. 8.11). The coastal lagoon is located where El Yali brook mouth used to be. This mouth moved to the south. Presumably, in many opportunities during the past these dunes were destroyed by intense tsunamis and/or ocean swells. However, they were reconstructed with the important sediment load from Rapel River. After Rapel dam was constructed (which allowed damming Rapel river in 1968), imposing a definitive cutoff of this continuous sand supply, the current situation suggests that this system lacks its natural regenerative capacity or requires a longer time to recover, since the volume of sediments that Rapel river used to supply experienced a sharp decrease after the dam.

Rapel hydroelectric central (34°02′S; 71°35′W) consists of a concrete vault which upper part has a curvature radius of 174 m and 350 m long. The wall height is 112 m and the dam can content 832 million m^3, with a maximum depth of 90 m (Vila et al. 1986). The importance of this reservoir for El Yali wetland arises because the material forming the dunes and the long beach surrounding it corresponds to material originally coming from Maipo River (Paskoff and Manríquez 2004). Because the river was dammed, this process does not longer occur in a natural fashion since 1968 (Paskoff et al. 2000).

The morphological evolution of the Albufera seems to react to the occurrence of tsunamis that affect the wetland. For instance, when comparing Table 8.2 with Fig. 8.11, it is observed that the most drastic changes in the shape of this wetland coincidently occurred right after a tsunamigenic earthquake. The segmentation that the Albufera suffered in 2010 was well documented (Contreras 2014), but also drastic changes in the shape of the river and the Albufera after tsunamis of 1960 and 1985 can still be observed. However, even when the tsunami of 1960 must have had similar characteristics to the tsunami of 2010, Rapel River was not dammed yet and therefore the beach and dunes recovered as rapidly as other similar systems, as Mataquito river, did after the earthquake of 2010. In 1985, a new tsunami occurred in this area and produced a 50 cm vertical co-seismic raising (Quezada et al. 2012b). Somehow, this co-seismic raising, unlike the sinking observed in 2010, mitigated the lack of sedimentary material discharged by Rapel River. On the other hand, due to the high precipitations occurred before and after 1985, the dam gates were opened in several occasions (Fig. 8.12.)

It is presumed that the poor recovery of the coastal dune and beach that used to protect the wetland is related to the closure of the dam gates since 2009 (Fig. 8.12). On the contrary, the recent recovery of this waterbody seems to respond to the opening of the dam gates, allowing supply of sedimentary material. The monthly evolution of Matanza lagoon and the Albufera surfaces is shown in Fig. 8.13.

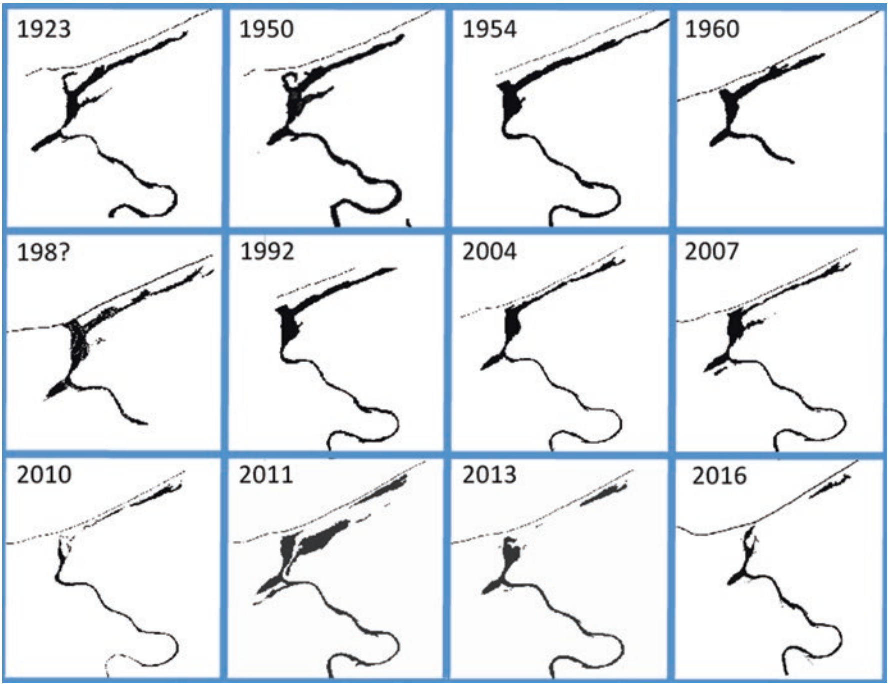

Fig. 8.11 Morphological evolution of El Yali brook mouth and the Albufera (1923–2016). Important changes are observed during the 1960s, after the 80 decade and during 2010

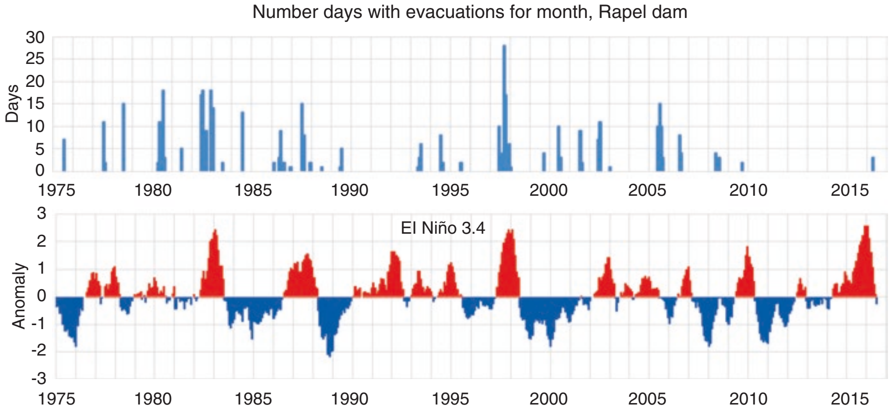

Fig. 8.12 Number of days by month when Rapel dam gates were opened, allowing the supply of sediment to the beach of El Yali wetland. ENOS 3.4 index is also shown and it is observed that, especially in the past century, there used to be a correlation between the opening of the dam gates and the index that indicates the anomalous increase of temperature in the 5°N–5°S, 120°–170° W region

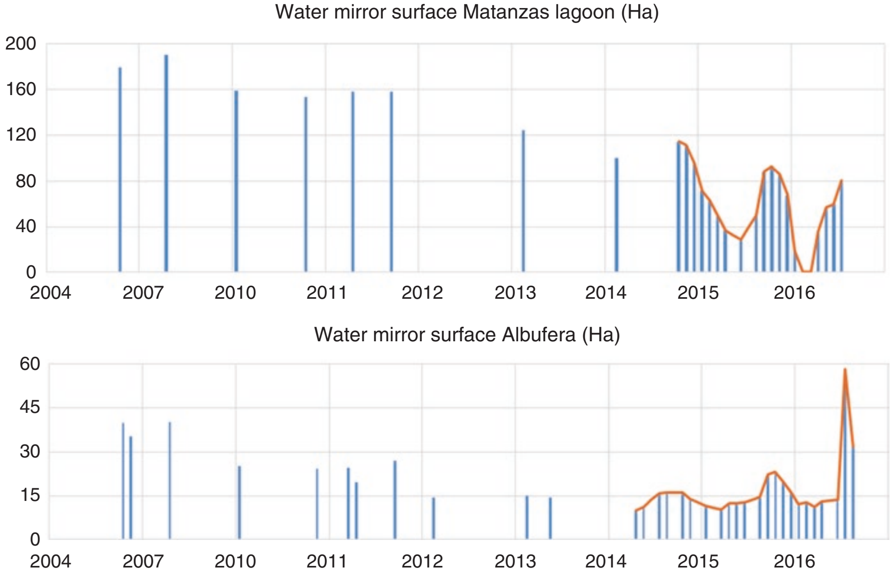

Fig. 8.13 Monthly evolution of Matanzas lagoon and the Albufera surfaces. The Surface extension is estimated from tracks along the border of the waterbodies with a GPS. It is observed that Matanzas lagoon has reached historical minimal levels, whereas the Albufera has experienced a decrease after 2010 and has shown a slight recovery only during the last months

In Fig. 8.13 is possible to observe how the Albufera experienced a reduction in its size after the tsunami 2010, which is explained by the segmentation and desiccation of the lagoon. A peak is observed during the last months, which corresponded to a flooding of the lagoon after the ocean swell. However, unlike past events, the recent opening of the dam gates (Fig. 8.12) seems to have delivered enough material to retain more water in the Albufera. A recovery of the old desiccated segment has been observed during these months.

8.6 Proposal of Ecological Restoration

As it is known, a proposal of ecological restoration must begin by defining the object on which the restoration will be focused. This is particularly difficult in coastal wetlands like El Yali, located in one of the zones most intervened by the man in the littoral of central Chile. There are antecedents about how different pre-Hispanic cultures, including Inca, Aconcagua and Llolleo cultures (Falabella and Planella 1980, 1985), have altered these waterbodies. Afterwards, with arrival of Spaniards, the first farms were established in this area. Matanzas ("slaughters") lagoon owes its name because it used to be the place where many heads of cattle were sacrificed to produce salad meat to be sent to Lima, Peru (Brito 2009).

However, the wetland system continued playing a fundamental role for migratory birds and endemic biodiversity of central Chile until the beginning of the twenty-first century. With the tsunami in 2010, it was clear that the construction of Rapel dam was a serious disturb because it cut off the sediment supply that sustained beaches and the dunes that protected this wetland. In many opportunities, this wetland was affected by quakes and tsunamis, intense ocean swell and ENSO, all phenomena able to dissipate their energy by destroying that natural barriers represented by the dunes. Before the dam construction, the continuous sediment supply was able to rapidly reconstruct the beach, sandbar and dunes, as was observed, for instance, in Mataquito river mouth.

When the sedimentary supply was cutoff, the dunes still had enough material to sustain the system equilibrium for some decades but when tsunami waves destroyed these dunes, there was no material to recover neither the beach nor dunes. This generated a substantial change in the system, turning it more vulnerable to other (even smaller) tsunamis, ocean swell, sea level rise associated to ENSO Kelvin waves, and climate change. For this reason, the first proposed restoring action is to reconstruct the dunes and reinforce them with a vegetal cover composed by native species, which used to cover the dunes destroyed by the tsunami (Caldichoury 2002). The other two steps are: (1) management of exotic forest species located around Matanzas lagoon and that appear to increase the sensibility to water scarcity and (2) planting native vegetal species around the waterbodies, as green fences that contribute to generate buffer areas in the wetland complex.

8.7 Discussion

As observed in records from around El Yali wetland, coastal wetlands in central Chile are facing pressure from the contemporary climate change: Besides the rising of the ambient temperature, the decrease of precipitations and the sea level rise, it possible to observe an increase of the sea surface temperature, a decrease of nearby rivers discharge, and a modification of the incident wave direction and significant wave height. These effects are proved by fitting a linear trend with positive or negative slopes, depending on the particular variable (Figs. 8.3, 8.4, 8.5, 8.6, 8.7, and 8.8). However, due to the occurrence of ENSO, it is possible to distinguish an important intra-annual climatic variability in those series. Years of intense precipitations are followed by years of hydric scarcity, due to the warm and cold ENSO phases, respectively. However, this typical behavior has deviated during the present century, where a strong El Niño occurred but has not been accompanied by intense rainfall around El Yali. This explains the continuous decrease of the water surface observed in the inner Matanzas lagoon (Fig. 8.13).

The delicate equilibrium at the Albufera was severely affected in two situations: (a) the cutoff of the sedimentary supply after the damming of Rapel River in 1968 and (b) the removal of sediments from beach, sandbar and coastal dunes of El Yali after the tsunami 2010. Thus a combination of anthropic alteration along with the occurrence of a natural phenomenon was able to neutralize the natural mechanism of protection and dissipation of energy that El Yali wetlands system used to have.

As result of climate change, it is possible to infer that another important alteration is occurring: From El Yali River northward, the beach is oriented from SSW to NNE and the littoral border runs parallel to the incident direction of waves from SW, increasing the attenuation of wave energy. As the marine terrace is very wide, it provides space to create an extended system of dunes cordons, transversal free dunes, dunes restrained by vegetation, along with coastal dunes on depressions and wetlands around the Albufera. However, if there is a change in the incident waves (Fig. 8.8), the beach orientation will lose this characteristic, implying a change in the costal morphology. This way, there is a natural experimental design: the system was completely reset after the earthquake and tsunami 2010, there are no continuous sediment discharges since 1968 but the only occur when the dam gates are open and consequently it is possible to know the exact moment when new sedimentary material is delivered to the system. Finally, the direction of the incident waves is gradually changing.

It is important to observe that sea-level raising in central Chile coasts seems to be no relevant as threat to coastal wetlands, considering the alterations represented by co-seismic vertical movements associated to earthquakes occurring in this region. As observed in Table 8.2, the 1985 earthquake meant a rising of 50 cm in San Antonio port. When comparing this elevation with the actual increment rate of the sea-level, about 3 mm/year, it means that the earthquake made the sea-level rise to retrogress the equivalent to 167 years. On the other hand, the descent of 35 cm during the earthquake in 2010 implied an advance equivalent to about 100 years.

Finally, besides climate change, ENSO, tsunamis and earthquakes, it must be considered the intense anthropic pressure that seeks the accelerated conversion of these wetland systems to real estate, agriculture and recreational systems. In central Chile, wetlands are the subject of anthropic perturbations due to the land use (e.g. exotic forest plantations, specific and diffuse contamination, etc.), resulting in alterations of their structure and functionality (Muñoz-Pedreros and Merino 2014).

According to Fariña et al. (2012), currently, in spite of management plans (CONAF 2009), El Yali wetland is under a series of menaces that put its biodiversity in risk: extraction of groundwater, deviation of water streams for agriculture or industry, urban expansion, contamination and eutrophication of streams, lagoons and wetlands, reduction of native vegetation by fires, agriculture, livestock and forestry activities, furtive hunters, 4WD vehicles, powered parachute disturbing birds, and electric cables causing birds dead.

8.8 Conclusions

The natural history of the wetlands complex in El Yali basin suggests that the equilibrium of this system is sensitive to the occurrence of natural phenomena like the tsunami in 2010, ENSO and climatic variations in general. It is expectable, therefore, that contemporary climate change produces alterations due to the change in the hydric regime forced by precipitations, modifications of ambient temperature and alterations in the coastal zone by the elevations of the MSL, what, added to anthropic pressure, put the wetland sustainability in risk in the long term.

Previous lagoons were also coastal lagoons but due to displacements and co - seismic raising, they are in their current location (10 or more meters above sea level and some km inland). However, they still conserve the saline characteristics that support the abundance and biodiversity of animals and plants.

El Yali was severely affected by the earthquake and tsunami in 2010, destroying 800 ha of beaches that used to be protected by a dune now disappeared (Contreras 2014). The absence of thus dune has turned the system more vulnerable before any ocean swell, as those occurred in August 2015 (Winckler et al. 2015). The recent earthquake and tsunami of 16 September 2015 also flooded about 280 ha in this area (Contreras-López et al. 2016), showing once more the vulnerability of the system.

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