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DEVELOPMENT OF A METHODOLOGY FOR THE ASSESSMENT OF POSSIBLE RESPONSES OF ECOSYSTEM SERVICES TO ANTHROPOGENIC ACTIVITIES AND CHANGES IN GEOMORPHOLOGY IN THE ETEN COASTAL WETLAND, LAMBAYEQUE

DESARROLLO DE UNA METODOLOGÍA PARA LA EVALUACIÓN DE LAS POSIBLES RESPUESTAS DE LOS SERVICIOS ECOSISTÉMICOS A LAS ACTIVIDADES ANTROPOGÉNICAS Y LOS CAMBIOS EN LA GEOMORFOLOGÍA EN EL HUMEDAL COSTERO DE ETEN, LAMBAYEQUE

Tesis para obtener el título profesional de Ingeniera Civil

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Resumen

En todo el mundo, los humedales costeros están actualmente amenazados por actividades humanas como la agricultura, el desarrollo de infraestructura, la explotación de recursos y la expansión urbana. Las presiones sobre estos ecosistemas alteran su morfología, hidrología y ciclos biogeoquímicos, lo que da como resultado la degradación de la calidad de los servicios de los ecosistemas. Sin embargo, poco se ha estudiado para comprender la respuesta de los humedales costeros, a fin de identificar la estrategia de conservación y mitigación más eficiente.

A lo largo de la costa peruana, los humedales presentan una diversidad de paisajes y características. Aunque las amenazas y presiones son similares entre ellos, la respuesta en cada entorno puede ser diferente. En este contexto, este estudio describe una metodología para evaluar los impactos ambientales sobre los servicios ecosistémicos basada en la comprensión de las características geomorfológicas y el estado actual del humedal costero de Eten, ubicado en el norte de Perú. La metodología combina la aplicación de herramientas SIG de código abierto y estudios de campo para caracterizar los entornos geomórficos y los servicios ecosistémicos proporcionados, y también para analizar los cambios en la morfología de los ríos, el uso de la tierra, la calidad del agua y la biota acuática. Luego se procesaron los datos para definir las principales amenazas y presiones sobre el humedal Eten y cómo impactan en los servicios del ecosistema, utilizando un modelo DSPIR (impulsores, presiones, estados, impactos, respuestas) de causa-efecto.

Los principales resultados indicaron que el río juega un papel vital en la definición del paisaje y las características de los humedales, como la cubierta vegetal y los hábitats. Además, la diversidad biológica de los hábitats acuáticos está influenciada por las estructuras hidráulicas y las actividades agrícolas. Asimismo, los cambios en el uso del suelo perturbaron el paisaje natural, afectando los servicios ecosistémicos como la recarga de aguas subterráneas y la regulación del agua. Al combinar aplicaciones de teledetección y estudios de campo, este estudio presenta un enfoque para mejorar el manejo de los humedales costeros a través de la identificación de las funciones y servicios más afectados.

Abstract

Worldwide, coastal wetlands are currently threatened by human activities such as agriculture, infrastructure development, resource exploitation, and urban sprawl. Pressures on these ecosystems disturb their morphology, hydrology, and biogeochemical cycles, thus resulting in the degradation of ecosystem services quality. However, little has been done to understand the coastal wetland response to identify the most efficient conservation and mitigation strategy.

Along the Peruvian coast, wetlands present a diversity of landscapes and features. Even though threats and pressures would be similar, the ecosystem response in each environment may be different. In this context, this study describes a methodology to assess the impacts of human activities on ecosystem services based on the understanding of geomorphic features and current state of the Eten coastal wetland, located in northern Peru. The methodology combines the application of open-source GIS-tools and collection of field data to characterize the geomorphic settings and the ecosystem services provided and also to analyze the changes in river morphology, land use, water quality, and aquatic biota. Data were then processed to define the main threats and pressures on the Eten wetland and how they impact on ecosystem services, using a cause-effect DSPIR (Drivers, Pressures, States, Impacts, Responses) model.

The main results indicated that the river plays a vital role in defining the landscape and wetland features such as vegetation cover and habitats. Moreover, the biological diversity of aquatic habitats is disturbed by the hydraulic structures and agricultural activities. Changes in land use modified the natural landscape, thus affecting supporting and regulation services such as groundwater recharge and water regulation. By combining remote sensing applications and field surveys, this study presents an approach to improve coastal wetlands management through the identification of the most affected functions and services.

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Chapter 1 Introduction

1.1 Background

The Convention on Wetlands in 1971 stated that the ecological function of wetlands is to regulate water regimes and support habitats for flora and fauna, and also to "play a vital role in the hydrological cycle" (Ramsar Convention Secretariat, 2010a, p. 7). The Coastal Wetlands Initiative–established by the US Environmental Protection Agency–defines coastal wetlands as saltwater and freshwater ecosystems located within coastal watersheds (Stedman & Dahl, 2008).

Coastal wetlands are characterized by their dynamic ecological conditions (e.g., vegetation succession) and their geomorphological adaptations (e.g., channel abandonment) (Maltby & Barker, 2009; Tooth et al., 2015; Tooth & Viles, 2014). These ecosystems are also highly dependent on river inflows combined with other landscape factors (e.g., geological faults, rock outcrops, swelling soils, and ponding by tributary or aeolian sediments) that reduce drainage and infiltration. Furthermore, coastal wetlands are influenced by tides, the hydrological connection of the basin with the ocean (Dahl, 2013) and the geomorphic setting linked to water flows and storage (Brinson, 1993). The open connection of freshwater to the ocean results in critical transitional zones between river and tidal that create many gradients of flow velocity, sediment type, salinity and vegetation (Leuven, 2019; Levin et al., 2001; Yang et al., 2017), thus, also considered as primary drivers of coastal ecosystem structure (Smith et al., 1992).

The interaction between the geomorphic factors described above and the local hydrology generates a variety of aquatic habitats (Cook et al., 2009; Zhang et al., 2013). Thus, any geomorphological change in coastal ecosystems can alter the biochemical circulations and ecological processes (Burnside et al., 2007; Day et al., 2008; Phillips, 2018; Viles et al., 2008).

Coastal wetland loss could also have significant implications on nutrient fluxes in transition zones between the continents and the oceans (Maltby & Barker, 2009).

1.2 Importance of the Eten wetland

The Convention on Wetlands (Ramsar, Iran, 1971) established criteria for identifying wetlands of international importance to "develop and maintain an international network of wetlands which are important for the conservation of global biological diversity and for sustaining human life through the maintenance of their ecosystem components, processes and benefits/services" (Ramsar Convention Secretariat, 2010c, p. 11). The Eten wetland is shelter for migratory birds during their breeding period, over five Peruvian endemic species has been identified, and the endangered Peruvian Tern (*Sternula lorata*) has been tracked here (Angulo-Pratolongo et al., 2010; Pulido & Tabilo-Valdivieso, 2001; Tabilo et al., 2016; Zavalaga et al., 2009). Furthermore, Eten is now considered the last coastal wetland in Lambayeque (ProNaturaleza, 2010) with a unique environment in the region (Gobierno Regional de Lambayeque, 2010). Within the wetland chain of the arid coast of the South Pacific, the Eten wetland also forms a biodiversity hotspot for migratory birds (Morrison & Ross, 1989; Myers et al., 1990; Pulido & Tabilo-Valdivieso, 2001). In 2005, through the Regional Ordinance N° 004-2005-GR.LAMB./CR., the Eten wetland was declared as an "Ecological Area of Regional Interest", due to the diversity of wildlife that harbors this ecosystem and its aesthetic landscape. This documentation also stated an extension of 1377 ha, but according to with interviews and records of the District Municipality of Ciudad Eten, it has been reduced to over 264 Ha as a result of urban and agricultural expansion. (Díaz Suárez, 2014)

Nowadays, the Eten wetland represents an important source of freshwater and raw material for local communities in the zone. Therefore, the economic activities such as handicraft and agriculture highly depend of the ecosystem services this wetland provides, thus its conservation and sustainable management should be considered under a basin-wide management (Ramsar Convention Secretariat, 2010a). Moreover, further studies are needed to demonstrate the international importance of the Eten coastal wetland (see Table 1.1).

Table 1.1

Criteria for the designation of Wetland of International Importance

Group A of the criteria Sites containing representative, rare or unique wetland types	**Criterion 1:** A wetland should be considered internationally important if it contains a representative, rare, or unique example of a natural or near-natural wetland type found within the appropriate biogeographic region.	
Group B of the criteria Sites of international Importance for conserving biodiversity	Criteria based on species and ecological communities	**Criterion 2:** A wetland should be considered internationally important if it supports vulnerable, endangered, or critically endangered species or threatened ecological communities. **Criterion 4:** A wetland should be considered internationally important if it supports plant and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions.
	Specific criteria based on waterbirds	**Criterion 5:** A wetland should be considered internationally important if it regularly supports 20,000 or more waterbirds.

Extracted from Ramsar Convention Secretariat (2010c).

1.3 Objectives of the study

The general objective aims to evaluate the possible responses of ecosystem services to anthropogenic activities of the Eten coastal wetland under the DPSIR (Drivers, Pressures, States, Impacts, Responses) framework.

The specific objectives of this work are:

- To describe the environmental characteristics of the Eten wetland, including geomorphology (river morphology and sediments) and water quality (physical-chemical parameters and aquatic biota).
- To assess the effects of anthropogenic activities in the geomorphology (river morphology and sediments) and water quality (physical-chemical parameters and aquatic biota) of the Eten wetland.
- To identify the potential impacts of the human development in the ecosystem services of the Eten wetland.

Chapter 2 Literature review

Coastal wetlands are currently considered as one of the most productive ecosystems in the world by playing an important role in the local and regional ecological environment and providing important services to human settlements (Bai et al., 2019; Camacho-Valdez et al., 2013). However, these environments are declining globally because of inadequate knowledge to manage changes in ecosystem structure and functionality of services and goods (Barbier, 2013; Li et al., 2014). To illustrate the key insights regarding the management of coastal wetlands, this chapter introduces a description of the main coastal wetland services, the natural dynamics of coastal environments and their vulnerability to external drivers, and the current status of Peruvian coastal wetlands.

2.1 Coastal wetlands classification

The Ramsar Convention defines the wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" (Ramsar Convention Secretariat, 2016). Under this definition, wetlands can be also categorized as marine (coastal wetlands), estuarine (deltas, tidal marshes, mudflats, and mangrove swamps), lacustrine (when they are associated with lakes), riverine (contained within a channel, river and streams), and palustrine (marshes, swamps, and bogs). In case of marine wetlands, the Ramsar Convention Secretariat (2014) provides the classification system described in Table 2.3 .

Table 2.1

Ramsar Classification System for Wetland Type

Wetland type	Description
Permanent shallow marine waters	most cases include less than six meters deep at low tide; includes sea bays and straits.
Marine subtidal aquatic beds	includes kelp beds, sea-grass beds, tropical marine meadows.
Coral reefs	
Rocky marine shores	includes rocky offshore islands, sea cliffs
Sand, shingle or pebble shores	includes sand bars, spits and sandy islets; includes dune systems and humid dune slacks.
Estuarine waters	permanent water of estuaries and estuarine systems of deltas.
Intertidal mud, sand or salt flats.	
Intertidal marshes	includes salt marshes, salt meadows, raised salt marshes; includes tidal brackish and freshwater marshes.
Intertidal forested wetlands	includes mangrove swamps, nipah swamps and tidal freshwater swamp forests.
Coastal brackish/saline lagoons	brackish to saline lagoons with at least one relatively narrow connection to the sea.
Coastal freshwater lagoons	includes freshwater delta lagoons.
Karst and other subterranean hydrological systems	marine/coastal.

Extracted from Ramsar Convention Secretariat (2014).

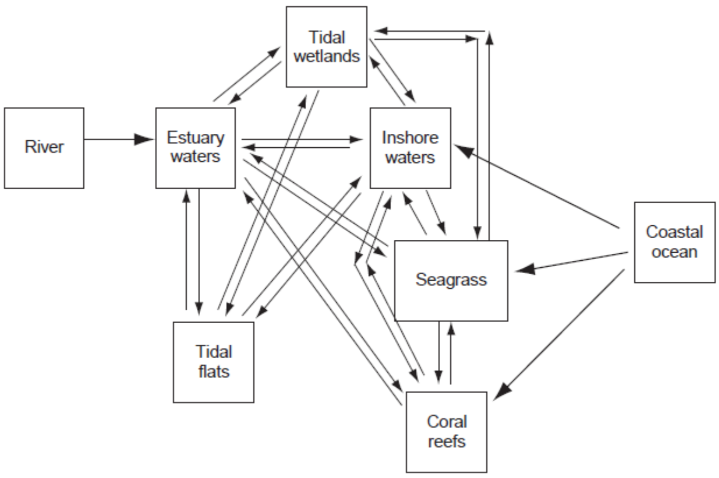

Figure 2.1 Diagram of energy and mass flows in a coastal ecosystem

Source: Wolanski et al. (2009, p. 33).

It is estimated that they cover around 6% of the Earth’s surface (An & Verhoeven, 2019; Mitsch & Gosselink, 2015). Continuously, the components of coastal systems, such us seagrass forests, mangroves, salt marshes, coral reefs, the river, and the estuarine waters exchange mass and energy with each other (Wolanski et al., 2009). Numerous ecological models suggest the connection among systems may increase the robustness to withstand some degree of human impact with minimal degradation (Jorgensen & Bendoricchio, 2001).

2.2 Ecosystem services in coastal wetlands

Some reasons why wetlands are protected can be determined by human perceptions: where the wetland is located, the anthropogenic pressures on it, and the area that the resource covers (Mitsch & Gosselink, 2015). The definition of *value* and *services* is described as something useful to humans and that adds value to society. Based on the Millennium Ecosystem Assessment (2005), ecosystem services can be classified into provisioning, regulating, cultural, and supporting services (see Table 2.2).

Table 2.2

Classification of ecosystem services

Type of service	Description
Provisioning services	This category includes products obtained directly from nature, such as water, food, wood, and other goods.
Regulating services	This category is addressed in maintaining the quality of air and water, flood control, fertilization of crops, including the regulation of climate.
Cultural services	This category consists in non-material benefits obtained from ecosystems that include aesthetic inspiration, cultural identity, tourism, recreation, and research.
Supporting services	This category is the basis of all ecosystems and include provision of living spaces and habitats for plants and animals, and the maintenance of genetic diversity

Source: Food and Agriculture Organization (2020) and Millennium Ecosystem Assessment (2005).

While ecosystem services are defined as the benefits and contributions to human well-being, ecosystem functions are the processes that provide services. For instance, coastal wetlands provide shoreline stabilization, protection against sea-level rise, sediment and nutrient retention, flood attenuation, provision of habitats and shelters for residents and migratory species, carbon sequestration, buffering on climate variability through the regulation of atmospheric carbon levels, among others (Costanza et al., 1997, 2014; Dahl, 2013; Daniels et al., 2000). The function of sediment retention and export support the deposition of sediments and nutrients carried in water inflows by slowing down the force of water and balancing coastal land loss (Perillo et al., 2009; Ramsar Convention Secretariat, 2010b), as well as storing of nutrients and organic matter in floodplains (McGuirk Flynn, 2008; Mitsch & Gosselink, 2015; Mitsch & Reeder, 1991). Moreover, the services are linked to the ecological structure and biophysical processes and functions, as shown in Table 2.3.

Table 2.3

Examples of ecological functions and ecosystem services in coastal wetlands

Ecosystem Services	Description of ecosystem functions in coastal wetlands
Gas regulation	Regulation of carbon storage
Climate regulation	Generation and maintenance of temperature, precipitation, and other processes at local conditions that influence surrounding areas
Storm protection	Attenuation and/or dissipation waves, buffers wind
Water regulation	Control and regulation of hydrological flows
Water supply	Storage and retention of freshwater
Erosion control	Provides sediment stabilization and soil retention
Flood control	Water flow regulation and control
Nutrient cycling	Nutrient and organic matter regulation, cycling, processing and acquisition. Aquatic plants acquire nitrogen and control its excess on the water column
Water pollution treatment and sediment control	Provision of nutrient and pollution uptake, as well as retention, particle deposition, and clean water
Carbon sequestration	Generation of biogeochemical activity, sedimentation, biological productivity
Pollination	Insects can transport pollen through the agricultural land
Raw material and food	Generation of biological productivity and diversity
Maintenance of fishing, hunting, and foraging activities	Provision of suitable reproductive habitat and nursery grounds, sheltered living space
Tourism recreation, education, and research	Provision of unique and aesthetic landscape, suitable habitat for diverse fauna and flora
Culture, spiritual and religious benefits, existence, and bequest values	Provision of unique and esthetic landscape of cultural, historic, or spiritual meaning

Source: Aponte (2017), Barbier (2019), and Costanza et al. (1997).

2.3 Assessing natural dynamics of coastal wetlands

Driven by changing geomorphological (sediment supply, channel abandonment) and climatic (evapotranspiration, precipitation) settings and adjustments, and ecological conditions (water quality, biota), wetlands dynamics may be complex (Day et al., 2008; Tooth et al., 2015). For instance, the hydrologic and geomorphic processes control wetlands functionality in terms of biochemical characteristics of water, habitat maintenance, and water storage and transport (Brinson, 1993; Perillo et al., 2009). Figure 2.2 illustrates the interaction between landscape processes and potential human activities within a wetland environment.

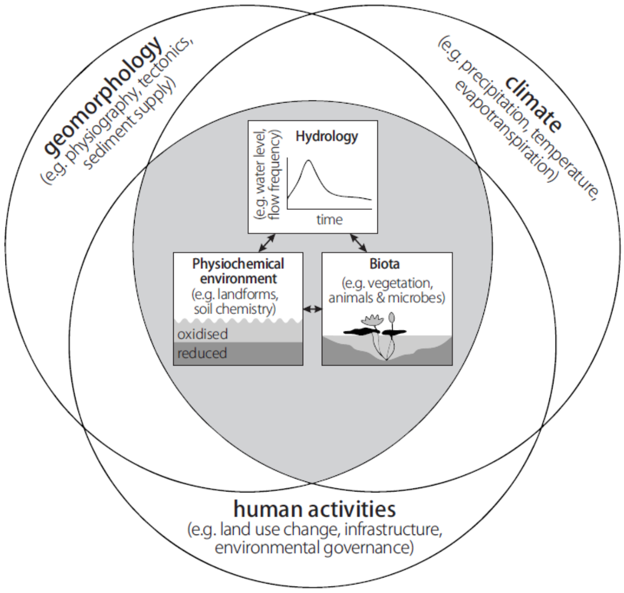

Figure 2.2 Interactions between landscape processes and potential human activities within a wetland environment Sources: Mitsch & Gosselink (2015) and Tooth et al. (2015).

The characterization of landscape includes landscape settings such as topography, geomorphology, land cover and use, and human disturbance. In order to assess how coastal wetlands varied over time, it is also important to monitor their spatio-temporal dynamics. Mapping the spatial configuration requires an adequate level of detail on the geomorphic patterns and their relationship with ecology communities (Pavri et al., 2011). Satellite remote sensing is widely used to assess human threats (Liu & Cameron, 2001) and biotic components and track changes in the surface area of wetlands over a range of timescales (Chen et al., 2018; Tian et al., 2017).

Hydrodynamics investigates the water quantity and level, fluvial and tidal characteristics based on both field measurements and modelling. Influence of wave climate is also considered. The hydrodynamic analysis is particularly important because salt and freshwater exchange (fluvial and tidal waters) determines other coastal and estuarine processes: bank erosion and sedimentation, water quality, habitat formation, and human use (Leuven, 2019; WMA Water and SCU Centre for Coastal Biogeochemistry, 2009).

The analysis of sediment dynamics characterizes sediment size, type and distribution within a coastal ecosystem, and describes how they influence the coastal processes. Sediments are vital in coastal environments because they shape landscape configuration through flow, depositional and erosional processes (Dyer, 1995; Weill & Tessier, 2016).

This characterization of water and sediment quality describes both water and sediment composition and their physio-chemical properties. The analysis of both parameters can trace the presence of contaminants and pollutants throughout the coastal wetland (Ji, 2008; Ringwood & Keppler, 2002). On the other hand, fluvial ecosystems are sensitive to the variability of the flow, sediments, and nutrients transported by the river (McCluney et al., 2014; Naiman & Décamps, 1997). This section describes the presence of biota and aquatic communities in sediment and water and examines key drivers and threats that influence the abiotic conditions of habitats, such as eutrophication, desiccation, and flooding, generated by agriculture, livestock, and channeling (Luan & Zhou, 2013).

2.4 Threats to coastal wetlands

Nowadays, a greater number of human populations are placed within river catchments along coastlines (e.g. Peru, Chile, and Australia). Human activities (e.g. changes in land use, water abstraction), climate variability and extreme events associated can affect valuable coastal environments such as estuaries, wetlands and swamps (Al-Nasrawi et al., 2016; Barbier, 2019; Day et al., 2008; Tooth et al., 2015), thus leading to habitat losses (Scholes et al., 2005). For instance, Ehrenfeld (2000) identified some effects of river regulation on wetland geomorphology: 1) decreased sinuosity of wetland/upland edge reduces the amount of ecotone habitats; 2) decreased sinuosity and river channels result in increased velocity of stream water discharge to receiving wetlands; 3) alterations in shape and slopes affects water-gathering or waste-disseminating properties; and 4) increased cross-sectional area of stream channels (due to erosional effects of increased flood peak flow) increases erosion along banks. Other examples includes the excess of pesticides and animal excreta that pollutes soils and water bodies, and the poor management of forest resources that increases soil erosion, flooding, and landslides (Food and Agriculture Organization, 2020). Table 2.4 summarizes the main threats to different types of coastal environments.

Table 2.4

Main anthropogenic and natural threats to coastal environments

Coastal wetland habitats	Estuary	Saltmarsh	Mangrove	Tidal flat	Seagrass	Coral reef	Saline Lagoon
Threats							
Climate change	X	X	X	X	X	X	
Sea level rise	X	X	X	X		X	X
Flood defenses/barrage schemes	X	X		X			X
Physical disturbance/habitat destruction	X		X		X	X	X
Land claim		X	X	X			X
Erosion		X				X	
Sedimentation		X			X	X	
Over exploitation	X		X	X		X	
Pollution	X		X		X	X	X
Eutrophication	X		X	X	X	X	
Invasive species	X	X	X	X			
Grazing		X				X	
Hypoxia	X						X
Acidification	X	X	X	X	X	X	X
Ice reduction	X	X					X
Disease					X	X	

Source: Harrison & Hester (2010)

2.5 Importance of adequate water resources management of coastal wetlands

Current policies of water resources management around the world started to implement interdisciplinary assessments to achieve an integrated, balanced, and sustainable use of coastal ecosystems. These assessments usually include a review of coastal system components, such as catchment characteristics, hydrodynamic, analysis, sediment dynamics, human interventions, water quality, water balance, and ecological studies (van der Wal, 2018). Ecogeomorphological assessments using Geographic Information Systems (GIS), remote sensing tools, field measurements, sampling, and numerical modelling also represent a valuable approach (Al-Nasrawi et al., 2016). Their main objective is to define baseline conditions of environmental processes and analyze their interaction with human activities (Day et al., 2008; WMA Water and SCU Centre for Coastal Biogeochemistry, 2009) to adopt appropriate adaptation strategies.

The valuation and conservation of coastal environments requires better informed decisions, by means of science-based evidence, thus preventing the potential impacts and evaluating the consequences. Furthermore, degradation of the ecosystem must be assessed not only by analyzing each impact separately but also considering that the majority of coastal environments have faced multiple threats simultaneously (Agardy & Alder, 2005).

2.6 Uses of water by pre-Columbian cultures in Peruvian coastal areas

Both convenient climatic conditions (i.e. moderate temperatures, low precipitations, and high humidity) and irrigation management, make soils in coastal catchments adequate for cultivation (Eguren, 2002). In this context, human development evidenced an ancient relationship with the coast. Angelakis et al. (2012) and Aponte (2017) described how Pre-Columbian cultures settled along the coastline designed water solutions for this particular environment and coexisted with the nature. The 5,000-year-old **Caral-Supe** settlements used special build terraces to cultivate in flat lands. There, water was supplied by the river and spring water through channel irrigation systems. Agriculture and fishery were both the main economic activities.

The **Mochica** or Moche harvest the land from the 3rd to the 13rd century D.C., evidenced by the extant earth-made (*adobe*) channels. Based on agriculture, more than 35% land than nowadays has been cultivated by the Mochica. Their legacy also consists in pyramidal constructions of *adobe* bricks, irrigation channels, and a regional water resource management scheme. In order to supply the water demand, the Mochica distributed water from the Chancay-Lambayeque river to croplands by using the Raca Rumi and Taymi channels (still in use but enhanced following the original channel traces). Inherited by the Mochica, the **Chimú** culture provided the foundation of the well-known irrigation systems of Tinajones (in Lambayeque) and the Chavimochic (in La Libertad). Its principal city, Chan Chan, obtained water from groundwater and transported by open channels. The Chimú also supplied their large arable lands using inter-valley channels and aqueducts.

In the central coast, **Chancay** settlements use the goods of wetlands to design handicraft, mainly made by *totora* (*Typha angustifolia*) and *junco* (*Scirpus americanus*), and as a source of food (fish) (Van Dalen Luna, 2008). Located in the dry southern coast, the **Nazca** culture also built irrigation channels and underground aqueducts (some of them still in operation). Their heritage consists in underground galleries called *puquios* made by stone and Huarango-tree trunks, which main purpose was to conduct groundwater to the arid regions. Then, water was storage in reservoirs or *cochas* to be distributed via open irrigation channels.

During the colonial times, for instance, organic matter from the marshes in the Pantanos de Villa have been used to cultivate sugarcane, cotton, and fruits as fertilizer (Aponte et al., 2018). Even though the irregular distribution of water, the Peruvian Pacific coast still remains characterized by its large agriculture development and the amount of investments for irrigation purposes due to the water scarcity, especially in the northern region (Eguren, 2002).

Growing population is directly linked to a major food demand (FAO, 2009). The inadequate water withdrawal techniques, the cultivation of products that demands large amounts of water, and the low maintenance of drainage infrastructure have led to the intrusion of saline waters in arable lands (Frenken, 1997). Eguren (2002) also indicated that, until the 70s, this phenomenon affected over two fifths of the coastal agricultural lands, but little has been done to quantify the current conditions until now.

2.7 Coastal wetlands in Peru

The Peruvian wetlands as part of the West Pacific Flyway of waterbirds (Figure 2.3) play an important role as stopover and breeding sites during their migration (Martini et al., 2009). Herein, the Humboldt current (commonly known as Peruvian current) recirculates plankton and nutrient-rich waters along the coastline (Bakun & Weeks, 2008), causing coastal areas become the hotspots of shorebirds (Butler et al., 2001).

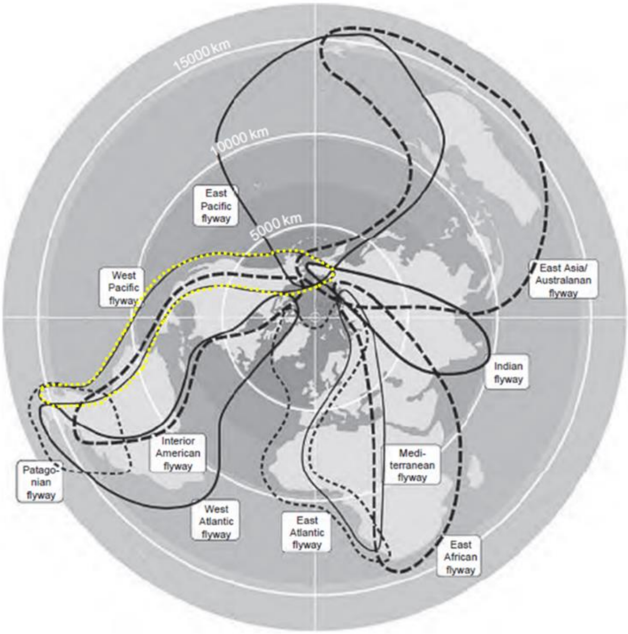

Figure 2.3 Major global shorebird flyway systems worldwide

Extracted from Perillo et al. (2009, p. 141)

Along the Peruvian Pacific coast, 92 wetlands have been identified and classified into natural (56), artificial (11), extinct (11), and river mouths (14) (ProNaturaleza, 2010). Figure 2.4 shows the location of the main coastal wetlands along the coastline. The regions of La Libertad, Ancash, and Lima host the majority of them.

Figure 2.4 Map of the main coastal wetlands along the Peruvian coast

Own elaboration, based on information from the MINAM, Moschella Miloslavich (2012), and ProNaturaleza (2010).

2.8 Conservation efforts in Peruvian coastal wetlands

Nowadays, Peruvian coastal wetlands face many threats such as sea-level rise, water and soil pollution, overexploitation of resources, and urbanization sprawl. For instance, the Ramsar-site mangroves of Tumbes, which support over 120 birds and 93 fish species, are currently threatened by the extensive aquaculture ponds (e.g. prawn and shrimp farming) and overharvesting of timber (Spalding et al., 2010). In the case of the Santa Rosa wetland, extensive water withdrawal (from surface and ground) for irrigation purposes and livestock and wastewater release are leading to the degradation of the wetlands and the loss of diversity (Aponte Ubillús & Ramírez Huaroto, 2011; Ramirez et al., 2010; Verones et al., 2012). The Ramsar-site Pantanos de Villa has been also disturbed by fires generated by open burning of trash and campfires (reducing flora and fauna communities) (Wyld et al., 2015), and the urban sprawl and uncontrolled land allocation (Aponte et al., 2018). Nowadays, both urban expansion and extensive agriculture represent the main drivers of Peruvian coastal wetlands degradation (Moschella Miloslavich, 2012).

In 2015, the Peruvian Ministry of Environment (MINAM, for its acronym in Spanish) updated the National Wetland Strategy to "foster the conservation and sustainable use of wetlands through the prevention, reduction and mitigation of ecosystem degradation" (Ministerio del Ambiente, 2015). In this document, the MINAM establish four strategic axes: 1) vulnerability reduction, 2) strengthening of the policy framework and management capacities, 3) strengthening of participatory management capacities, and 4) promotion and dissemination of cultural knowledge from indigenous communities in terms of wetland management. However, the majority of the Peruvian coastal wetlands have not any legal protection and no conservation management plans, even though some of them have been declared as conservation areas. Only few wetlands have Master Plans and programs that implemented strategies to protect these fragile environments and support their sustainable use.

For instance, the **Pantanos de Villa** was declared as a protected natural area and Ramsar site. Its master plan is oriented to conserve the biodiversity, foster institutional cooperation between stakeholders and local government, and design public spaces for educational purposes. Research studies have been also addressed to flora and fauna (including birdlife) inventory and status, uses of vegetation, and habitats degradation (Aponte et al., 2018; León et al., 1998; Pulido Capurro & Bermúdez Díaz, 2018; Wyld et al., 2015).

The **Santa Rosa wetland** has been declared as an *Área de Conservación Municipal Zona de Reserva Ecológica Intangible* by the Municipality of Chancay. They also created the Committee for Environmental Vigilance to foster wetland conservation. However, the problem of land allocation is still an ongoing issue. Previous studies include flora and vegetation inventory and monitoring (Aponte Ubillús & Ramírez Huaroto, 2011; Ramirez et al., 2010), impacts of agriculture (Verones et al., 2012) .

In 2007, the **Albufera of Medio Mundo** (*albufera* is defined as a saltwater lagoon isolated from the sea through a sandbar) was declared as a conservation area by the Regional Government of Lima to preserve its biodiversity and promote a sustainable use of services and goods. Furthermore, they published the Master Plan of the Albufera of Medio Mundo that aimed to foster an environmental awareness of habitats conservation, a sustainable natural resources management, and a participatory management to increase the income for local residents. Studies in this area entail flora inventory and monitoring (Aponte & Cano, 2013; Arana & Salinas, 2003), transmission of influenza viruses from wild birds (Ghersi et al., 2009), and economic valuations of services and goods (Aponte et al., 2014; La Chira Martínez, 2016).

The Regional Government of Callao created a Master Plan to contribute in the environmental restoration of the **Humedales de Ventanilla**, promote conservation and a wise use of natural resources, and creation of awareness of its environmental value. Research in the area include inventory of flora (Aponte & Cano, 2013; Aponte & Ramírez, 2014) and birdlife

(Alvarez Begazo, 2007; Álvarez & Iannacone, 2008), impacts in land cover due to urbanization (Moschella Miloslavich, 2012), and water quality assessments (Fajardo Vidal et al., 2017; Rodriguez et al., 2017; Vizcardo & Gil-Kodaka, 2015).

Clearly, conservation efforts are restricted to wetlands at the central coast. In other southern and northern regions, wetlands such as the Ite wetland, the Virrilá estuary, and the Eten wetland, previous studies of birdlife identified rare and endemic species (Angulo-Pratolongo et al., 2010; Pulido et al., 1996; Tabilo et al., 2016; Vizcarra et al., 2009; Williams et al., 2005; Zavalaga et al., 2009), but little has been done to create conservation strategies for these environments.

Peruvian coastal wetlands have not been fully studied and only a few sites have a base characterization and monitoring. That is why future research should be addressed on developing an updated inventory of coastal wetlands in order to conserve and restore them. Current efforts in the conservation of coastal wetlands in Peru are focused on biodiversity studies, hydrological balance and impact of human activities, flora and vegetation analysis, and in the National Wetland Strategy. Nevertheless, very little has been done to understand the physical-environmental conditions that these ecosystems form and, specifically, the environmental parameters that define the landscape and the livelihoods there.

Chapter 3 Description of the study area

3.1 The Chancay-Lambayeque basin

The Chancay-Lambayeque basin is considered one of the most important Peruvian Pacific catchments. Located across the departments of Lambayeque and Cajamarca, this bi-regional basin has a longitude of 203.93 km and an area of 5,555 km^2 (Autoridad Nacional del Agua, 2015). In order to articulate the participation of institutions and organizations within the region to implement a water resources management plan, the Ministry of Agriculture (MINAM) created the Chancay-Lambayeque Water Resources Council (*Consejo de Recursos Hídricos de Cuenca Chancay – Lambayeque*) according to the Supreme Decree N°008-2011-AG.

The Chancay-Lambayeqye river is born in the Mishacocha lake (located at 3,800 m.a.s.l.) where there is no glacier-water supply, then river receives artificial water transfer from the Chotano and Conchano river basins, both from Peruvian Atlantic catchments (Autoridad Nacional del Agua, 2010). Following its natural course, the river adopts the names of Chicos and Llantén, then, from the confluence with the San Juan river until La Puntilla water intake, the river receives the name of Chancay-Lambayeque. In La Puntilla flow divider, the river is divided in three courses: Taymi channel (to the north), Reque river (to the south), and the Lambayeque river between them. Only the Reque river discharges into the Pacific Ocean, while all Taymi and Lambayeque water supply is used for irrigation (Huertas Vallejo, 2001). Along the basin, the main river receives eventual contributions from over 24 tributaries and has an average flow of 32.2 m^3/s (Autoridad Nacional del Agua, 2015). Moreover, at a basin level, the main hydraulic projects are distributed as indicated in Table 3.1.

Table 3.1

Main hydraulic projects within the Chancay-Lambayeque basin

Structure	Description
Conchano Tunnel	Length of 4,213 m and diameter of 2.5 m. Conduction capacity of 13 m3/s.
Chotano Tunnel	Length of 4,766 km and a derivation capacity of 32 m^3/s.
Tinajones Reservoir	With a storage capacity of 320 MMC, this reservoir has an extension of 20 km^2. This structure consists of a main dam of 2,382 m long and 34 m high, and an outlet channel of 16 km long (capacity of 70 m^3/s) that supplies the reservoir with water from the Chancay Lambayeque river.
Raca Rumi Intake (Bocatoma Raca Rumi)	Intake capacity of 75 to 80 m^3/s.
La Puntilla Intake (Repartidor La Puntilla)	Maximum intake capacity of 80 m^3/s. Main source for irrigation activities in Lambayeque, Taymi, and Cachiche regions (about 82% of the total area).
Monsefú-Eten Intake (Bocatoma Monsefú-Eten)	Located in the left bank of the Chancay-Lambayeque river, its main function is to distribute water flow to the Reque river (left side) and the Monsefú channel (right side).

Source: Autoridad Nacional del Agua (2010 and 2011).

In addition, the drainage system in the Chancay-Lambayeque valley consists in seven irrigation channels and their respective secondary and tertiary drains. Each subsystem has an emitter drain that discharges into the Pacific Ocean: D-1000, D-2000, D- 3000, D-4000, D-5000, D-6000 and D-7000, together benefiting over 70,000 Ha. In total, 185 km of primary drains and 515 km of secondary drains have been built. (Autoridad Nacional del Agua, 2011)

3.2 Study area: The Eten wetland

As illustrated in Figure 3.1, The Reque river has an estimated length of 71.80 km from La Puntilla water intake until it reaches the Pacific Ocean (Instituto Nacional de Defensa Civil, 2003). The connectivity zone between the river and the ocean creates a freshwater-saline ecosystem called Eten wetland that is located in the province of Chiclayo, in the department of Lambayeque. The wetland includes a sandy strip along the Pacific Ocean, the seasonal connection between the Reque river and the ocean, small lakes, marshes, and ponds. The study area includes not only the Eten wetland but also a section the Reque river upstream (until Reque town), as indicated in dotted green lines in Figure 3.1. The area is about 29 km^2.

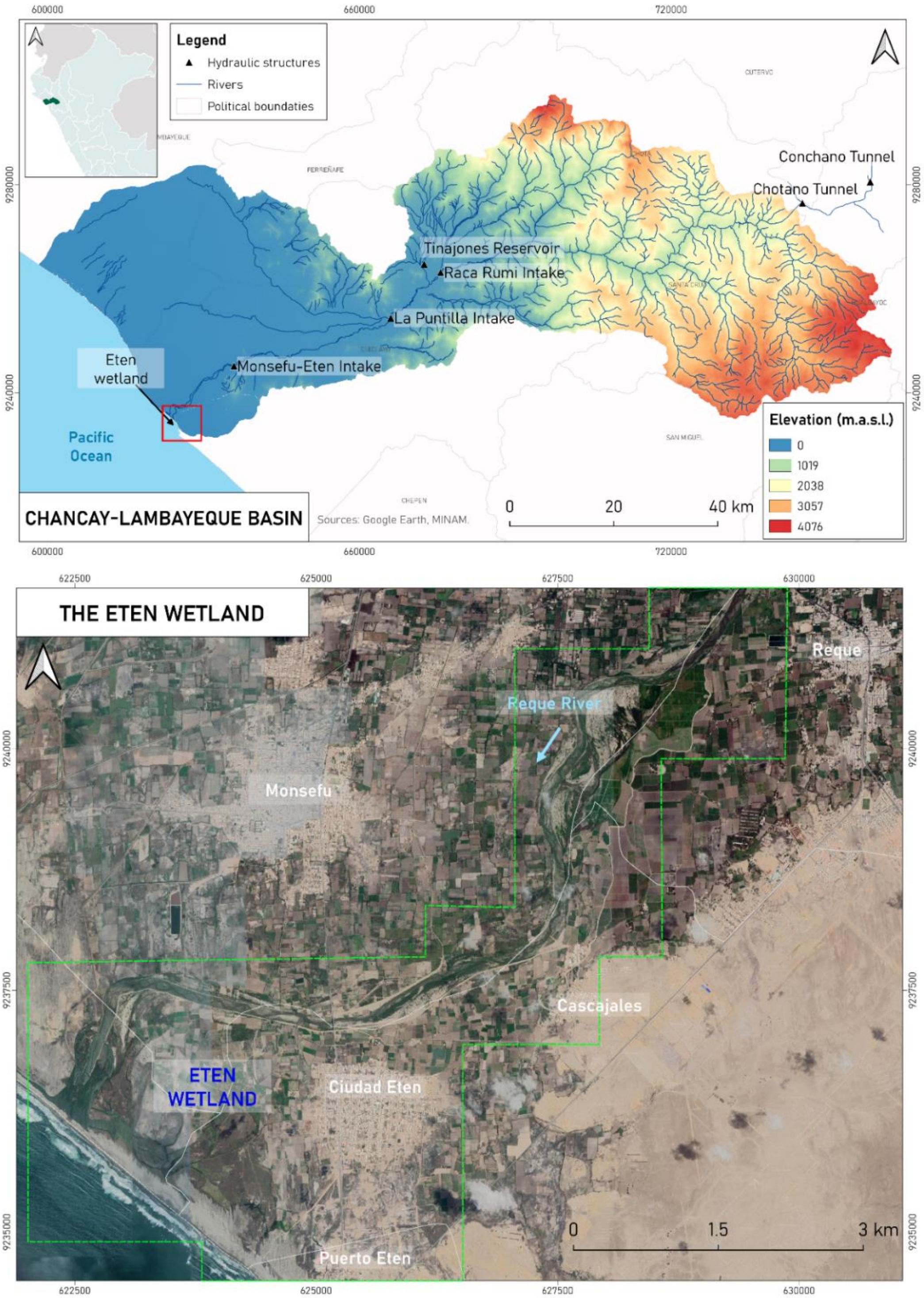

Figure 3.1 Location map of the Chancay-Lambayeque basin and the Eten wetland

Own elaboration, based on data from Google Earth, MINAM and DIVA-GIS.

3.2.1 Hydrology

Minimum values of the average annual precipitation (20.3 mm) were registered along the coastline (Lower Chancay-Lambayeque basin) while maximum values (1,678 mm) were registered in the Upper Chancay-Lambayeque basin (Andean region) (Taner et al., 2019). In the study area. In the study area, high values of precipitation are registered during February and March. The Figure 3.2 shows precipitation records in the Reque station, located 6 km upstream the Eten wetland (between Cascajales and Reque towns); there were no other stations in the study area neither climatic data. The histogram also presents extreme records in 1986/1987 (57 mm), 1997/1998 (62 mm), and 2017 (30 mm), which corresponds to the occurrence of the El Niño Phenomenon.

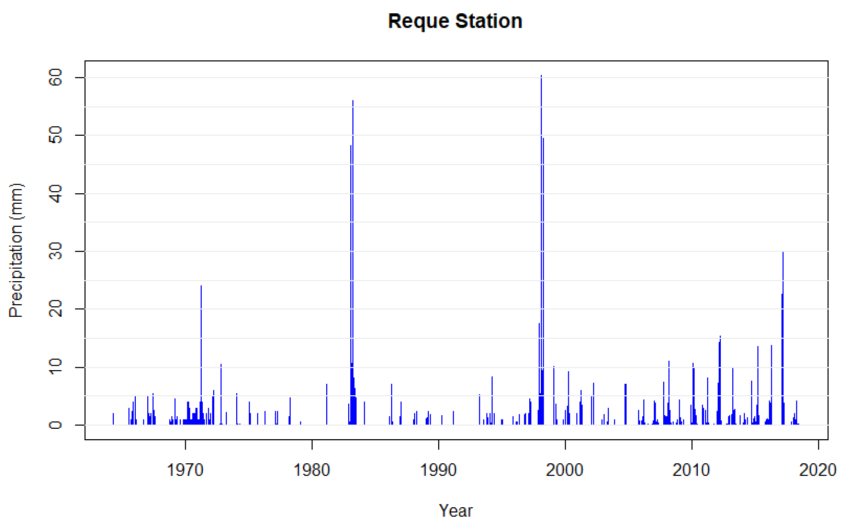

Figure 3.2 Average daily rainfall histogram from 1964 to 2018 recorded in the Reque gauge station

Own elaboration based on data from the Servicio Nacional de Meteorología e Hidrología – Senamhi from 1964 to 2018.

Figure 3.3 displays the hydrograph of the monthly average flow from 1914 to 2018 in the Raca Rumi station. The accuracy and validation of these data were in charge of the *Proyecto Especial Olmos Tinajones*, an entity in charge to manage the Tinajones reservoir and other irrigation-related infrastructure projects in the Chancay-Lambayeque basin. High water discharge is from February to May. Maximum values indicated extreme events associated with the El Niño Phenomenon: 465.13 m^3/s in 1925, 121.17 m^3/s in 1984, and 161.08 m^3/s in March of 2017.

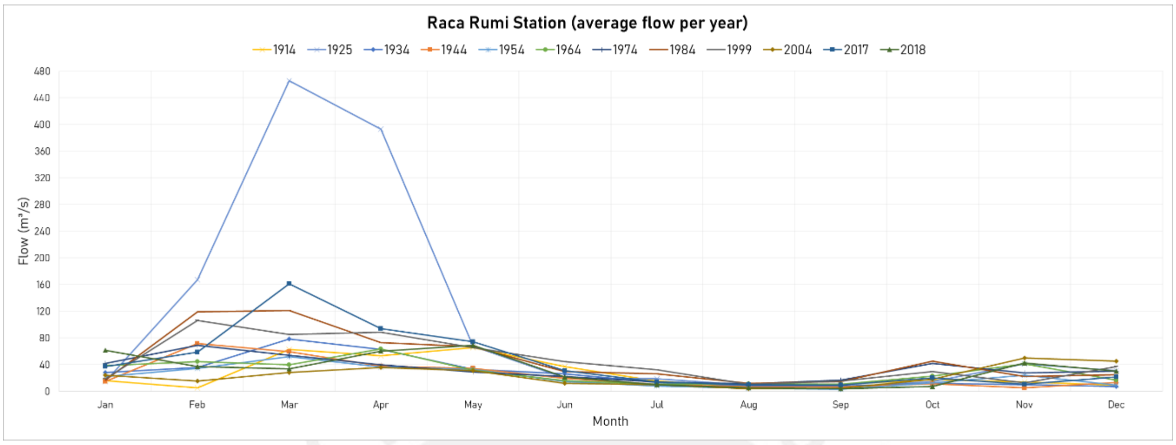

Figure 3.3 Monthly average flow from 1914 to 2018 of the Chancay-Lambayeque river in the Raca Rumi station

Own elaboration based on data from the Sistema Nacional de Información de Recursos Hídricos – SNIRH of the Autoridad Nacional del Agua (http://snirh.ana.gob.pe/consultassnirh/ConsHidrom.aspx#)

3.2.2 Hydrogeology

The aquifer of the Chancay-Lambayeque basin has an extension of 1,365 km^2, a total volume of 136,540 MMC, a depth of 100 m (Autoridad Nacional del Agua, 2011), a length of 30 m, and it is located between the Raca Rumi intake and the coast (Autoridad Nacional del Agua, 2012). In 2004, the National Institute of Natural Resources INRENA indicated the aquifer had a hydraulic gradient from 0.08% to 1.21%, and a groundwater table between 0.65 m and 13.60 m depth (INRENA, 2004).

Groundwater wells represent an important source of freshwater in the Chancay-Lambayeque basin. Main uses include irrigation, domestic, and livestock purposes. There are three types of wells used to pump: tubular, open pit, and mixed. Figure 3.4 shows the location of the existing wells in the section between the Monsefú-Eten Intake and the ocean.

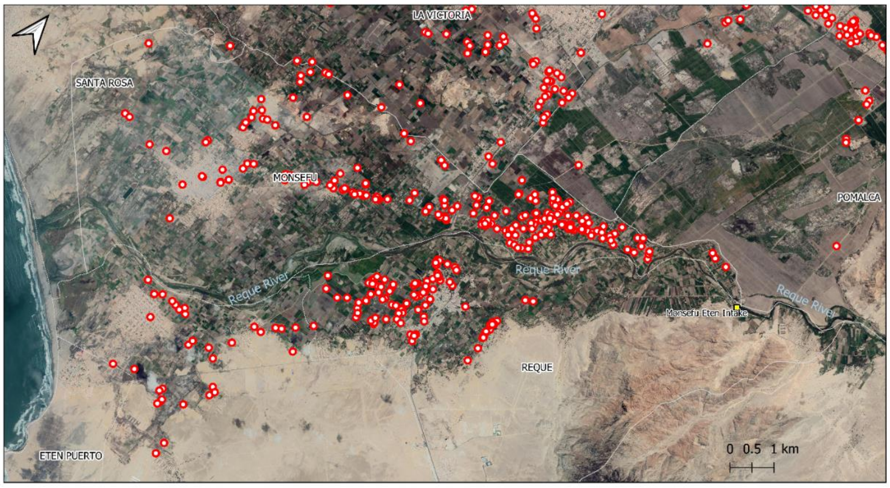

Figure 3.4 Location of the groundwater wells in the Lower Chancay-Lambayeque

Own elaboration based on data from the Peruvian National Water Authority (ANA), Senamhi, and Google Earth.

3.2.3 Topography

Starting from the Raca Rumi Intake until the Chancay-Lambayeque river reaches the ocean (160 – 0 m.a.s.l.), the Chancay-Lambayeque presents a slope less than 5° (~8%) (Núñez Juárez et al., 2006). As illustrated in Figure 3.5, the average slope in the study area is 2%. Along the coastline, there are sandbanks and other sedimentary structures (Autoridad Nacional del Agua, 2015).

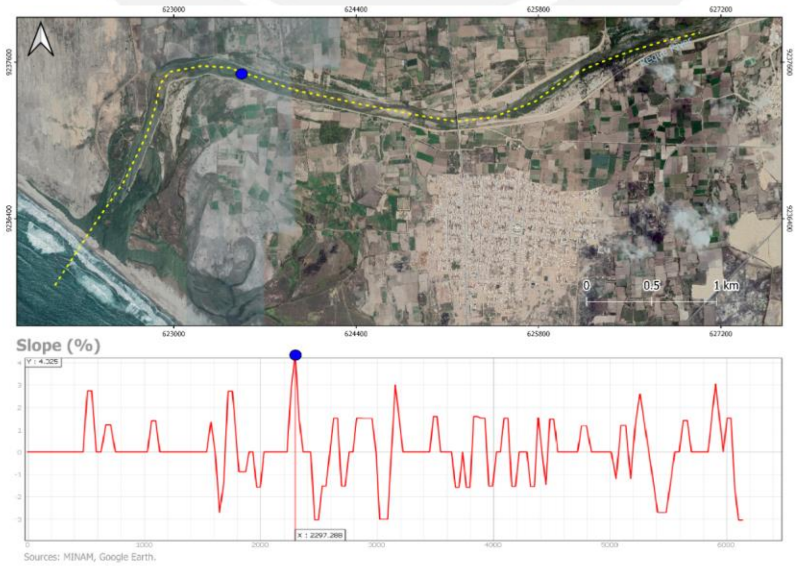

Figure 3.5 Slope profile along a sector of the Reque river

Own elaboration based on data from Google Earth.

3.2.4 Flora

Table 3.2 listed representative plant communities identified by the Gobierno Regional de Lambayeque (2010). The Eten wetland presents three main zones with typical plant associations (Figure 3.6) that have been identified based on own observations and previous research studies (Reque-Neciosup, 2008).

Table 3.2

Representative flora in the Eten wetland

Scientific name	Common name	Common name in Spanish
Bacharis augustifolia	False willow	*Chilco macho*
Bacharis saliccifolia	Mule fat	*Carrizo*
Bacopa monnieri	Water hyssop	*Bacopa*
Batis maritima	Saltwort, beachwort	*Saladillo*
Cryptocarpus pyriformis	Salt bush	*Chope*
Cynodon dactylon	Scutch grass	*Grama dulce*
Distichlis spicata	Desert saltgrass	*Grama salada*
Heliotropium curassavicum	Salt heliotrope	*Cola de alacrán*
Phragmites australis	Common red	*Chilco hembra*
Phyla nodiflotra	Turkey tangle frogfruit	*Turre hembra*
Salicornia fruticosa	Glasswort	*Pájaro bobo*
Scirpus limensis	*Junco*	*Junco*
Scirpus maritimus	Saltmarsh bulrush	*Juncia marina*
Sesuvium portulacastrum	Sea purslane	*Platanito*
Typha angustifolia	Narrowleaf cattail	*Totora*

Source: Gobierno Regional de Lambayeque (2010).

- **Foredunes and shoreline.** The desert saltgrass (*Distichlis spicata*) (Figure 3.6-A) and the scutch grass (*Cynodon dactylon*) grow in sandy and shallow soils with high salinity content. There are also beachgrass (*Ammophila*), sea purslane (*Sesuvium portulacastrum*), and saltwort (*Batis maritima*) (Figure 3.6-D) in these areas.
- **Lakes, swamps, ponds and river:** Along the river, vegetation include water hyssop or *bacopa* (*Bacopa monnieri*), shrubs, and trees. The narrowleaf cattail or *totora* (*Typha angustifolia*) and *junco* (*Scirpus limensis* and *Scirpus maritimus*) (Figure 3.6-B) grow in flooded areas in which the soil is muddy and contains large amounts of debris and organic matter.

- **Agricultural and grazing lands:** Scutch grass or *grama dulce* (*Cynodon dactylon*), salt bush or *chope* (*Cryptocarpus pyriformis*), and salt heliotrope or *cola de escorpión* (*Heliotropium curassavicum*) grow within the croplands and grazing lands, as well as the *totora* (*Typha angustifolia*) and *junco* (*Scirpus limensis* and *Scirpus maritimus*).

A. Grama salada (*Distichlis spicata*)

B. Junco (Scirpus limensis)

C. Seashore dropseed (*Sporobolus virginicus*)

D. Saltwort (*Batis maritima)*

Figure 3.6 Representative flora in the Eten wetland

Photographs by Tania Rojas.

3.2.5 Fauna

In the Eten wetland, the fauna is mainly represented by birdlife and marine animals. Habitats hosts migratory birds during their long journey from North to South and vice versa (e.g. *Leucophaeus pipixcan* or Franklin's gull who travels from Canada and USA). Furthermore, there are also resident species such as the common moorhen (*Gallinula chloropus*) and the cinnamon teal (*Anas cyanoptera*) (Angulo-Pratolongo et al., 2010; Reque-Neciosup, 2008). Birds' population are mostly congregated in ponds and lakes, and foredunes along the coastline, as illustrated in Figure 3.7.

Black-necked stilt (*Himantopus mexicanus*)

Great egret (*Ardea alba*)

Figure 3.7 Birdlife in the Eten wetland

Photographs by Tania Rojas.

Table 3.3

Record of migratory birds in the Eten wetland

Scientific name	**Common name**	**Common name in Spanish**
Actitis macularius	Spotted sandpiper	*Playero coleador*
Ardea alba	Great egret	*Garza blanca*
Calidris alba	Sanderling	*Playero arenero*
Calidris pusilla	Semipalmated sandpiper	*Playerito Semipalmado*
Calidris mauri	Western sandpiper	*Playerito Occidental*
Calidris minutilla	Least sandpiper	*Playerito Menudo*
Charadrius semipalmatus	Semipalmated plover	*Chorlo Semipalmado*
Charadrius vociferus	Killdeer	*Chorlo Gritón (Tic-til)*
Charadrius nivosus	Snowy plover	*Frailecillo blanco o chorlo nevado*
Haematopus palliatus	American oystercatcher	*Ostrero americano*
Himantopus mexicanus	Black-necked stilt	*Cigüeñuela de Cuello Negro ("Perrito")*
Leucophaeus atricilla	Laughing gull	*Gaviota Reidora*
Leucophaeus pipixcan	Franklin's gull	*Gaviota de Franklin*
Pluvialis squatarola	Grey plover	*Chorlo Gris*
Thalasseus elegans	Elegant tern	*Gaviotín Elegante*
Tringa flavipes	Lesser yellowlegs	*Playero Pata Amarilla Menor*

Source: Tabilo et al. (2016)

Angulo-Pratolongo et al. (2010) indicated that the landscape configuration of the Eten wetland (mainly surrounded by croplands and shrubs) determines the habitats for different bird communities. Their study indicated a bird diversity composed of 153 species, 17 orders and 45 families, from observations between 1978 and 2009. Tabilo et al. (2016) identified the Laughing gull (*Leucophaeus pipixcan*) as a dominant specie because over 3,000 individuals have been recorded during their survey. The grey povler (*Pluvialis squatarola*), the black-necked stilt (*Himantopus mexicanus*) and the western sandpiper (*Calidris mauri*) populations were also important: about 100 to 250 individuals of each one have been registered. Additional species are listed in Table 3.3. Additionally, the Peruvian Tern (*Sternula lorata*), classified in 2005 as an "Endangered" species by the International Union for Conservation of Nature, has been reported in the Eten wetland at least 8 times from 1978 to 2007 (Angulo-Pratolongo et al., 2010; Zavalaga et al., 2009).

The Eten wetland is notable for its birlife, but the ecosystem also harbors some mammals, reptiles, fish, crustaceans, and insects (Table 3.4). Along the shoreline, cart driver crab or *carretero* (*Ocypode gaudichaudii*) (Figure 3.8-A), Pacific mole crab or *muymuy* (*Emerita analoga*) can be found. The coastal dunes also harbors ophidians, amphibians, arachnids, saurian (Figure 3.8-B), and mammals, and the river provides aquatic habitats for fish and benthic macroinvertebrates, as illustrated in Figure 3.8-C (Rojas-Carbajal et al., 2019).

Table 3.4

List of representative fauna in the Eten wetland

Scientific name	Common name	Common name in Spanish
Callopistes Flavipunctatus	False monitor	Lagartijas
Cryphios caementarius	Freshwater shrimp	Camarón de río
Dormitator latifrons	Pacific fat sleeper	Pocoche
Lycalopex sechurae	Sechuran fox, Peruvian desert fox	Zorro de Sechura, zorro del desierto peruano
Mugil cephalus	Flathead grey mullet	Lisa
Occypode gaudichaudil	Cart driver crab, painted ghost crab	Carretero, cangrejo playero
Rattus rattus	Black rat	Ratas y ratones de campo
Stromateus brasiliensis	Butterfish Pampo Pintado	Pampanito

Source: Humedales de Eten Blog (http://humedalesdeeten.blogspot.com/p/flora-y-fauna.html)

A. Cart driver crab (*Ocypode gaudichaudii*)

B. Peru Pacific iguana (*Microlophus peruvianus*)

C. Mayflies (*Baetidae*)

Figure 3.8 Crabs, lizards, and benthic macroinvertebrates found in the Eten wetland

Photographs by Tania Rojas.

3.2.6 Human uses of the Eten wetland

Agriculture

As in many coastal areas in Peru, agriculture represents the main economic activity in the study area, followed by livestock farming (Instituto Nacional de Defensa Civil, 2003). Water for irrigation is mainly supplied by Reque river and groundwater wells in lower Chancay-Lambayeque (Table 3.5). According to the CENAGRO 2012 records, main cultivation products include flint corn or "*maíz amarillo duro*" (*Zea mays L. var. Indurata*), beet (*Beta vulgaris*), lettuce (*Lactuca sativa*), carrot (Daucus carota subsp. Sativus), sweet potato (*Ipomoea batatas*), maize (*Zea mays*), and sugarcane for alcohol (*Saccharum officinarum*).

Table 3.5

Irrigated croplands (ha) per water source

District	Well	River	Lakes	Ponds	Reservoir	Small seasonal reservoir	Other source	Well or river	Other combinations	Rainfall	Total (ha)
Eten	38.60	728.03						119.72		762.96	**1,649.31**
Reque	29.78	958.15		3.00	10.00			615.30	272.50	6,017.63	**7,906.36**
Monsefú	47.95	2,516.11	5.00	68.61	50.69	3.00	0.15	547.06	55.83	72.35	**3,366.75**
Santa Rosa		294.50								800.00	**1,094.50**
Total	**116.33**	**4,496.79**	**5.00**	**71.61**	**60.69**	**3.00**	**0.15**	**1,282.08**	**328.33**	**7,652.94**	**14,016.92**

Source: IV Censo Nacional Agropecuario 2012 – CENAGRO 2012

Handicrafts

For local people, the Eten wetland is the main source of raw material. As a heritage handed down through generations from the Mochicas, local villagers in the wetland elaborate handicrafts using local materials such as clay and vegetable fiber, particularly from the *totora* (*Typha angustifolia*), *carrizo* (*Bacharis saliccifolia*), *junco* (*Scirpus limensis*), and saltmarsh bulrush (*Scirpus maritimus*). Some products include bags, straw hats, purses, rugs, paintings, musical instruments, ceramics, jewelry, and textiles (Figure 3.9). Ciudad Eten is also well-known as the "*Capital del sombrero de paja*" (Universidad Señor de Sipán, 2019). In 2009, its local woman artisans achieved the Guiness Record of the “biggest straw hat in the world” (Constantino Lozano, 2015).

Figure 3.9 Exhibition of handicrafts in the Casa del Artesano museum in 2017 (center and left) and woman knitting fiber in 1971 (right)

Source: Municipal Library of Ciudad Eten

Birdwatching

Due to its variety of landscape settings, Peru is one of the megadiverse countries in birdlife (over 1,800 species) (Schulenberg et al., 2010). In 2005, *PromPerú* created an initiative to foster ecotourism in Peru by creating a birdwatching route called the “Northern Route for Bird Observation” (Williams et al., 2005). The route crosses throughout the arid desert, the mountains, and forests of northern Peru, to cover the main habitats of more than 1,600 species of birds, stationary and residents. Herein, the Eten wetland represents an important site in this route.

The Center of Ornithology and Biodiversity (CORBIDI) is currently organizing census and festivals of shorebirds and migratory birds for educational and conservation purposes. These events include birdwatching activities not only in the Eten wetland but also in other coastal systems (Figure 3.10). Additionally, to promote birdwatching in Eten, CORBIDI has an ongoing partnership with the Cornell Lab of Ornithology to develop a book entitled “Atlas de Aves Playeras del Perú”–in which the Eten wetland was one of the census sites along the Peruvian coast–and to develop the app eBird (https://ebird.org/) to monitor birds. eBIRD is a platform that gathers checklist of birds and allows users to explore the diversity of birds (called 'birding') within a region and track new records.

Figure 3.10 Flyers of shorebirds festivals organized by CORBIDI in 2019 and 2020

Source: "Festival de Aves Playeras" 2019 and 2020 edition, CORBIDI.

Chapter 4 Methodology of coastal wetlands assessment

Nowadays, there is an urgent need to assess the natural functioning and status of coastal systems to develop conservation and management strategies. This chapter gives an outline of methods used to assess the impacts on the ecosystem services of the Eten wetland based on a hydrogeomorphic classification and an environmental characterization (Figure 4.1). First, a hydro-geomorphic classification was applied to classify the Eten wetland under the Brinson (1993) methodology and, based on the class, to identify the expected services following the methodology described by Malekmohammadi & Jahanishakib (2017). Second, an environmental characterization is performed–using open-source tools and field measurements–to determine the current status of wetland components. Third, to assess the impacts and responses in ecosystem services, a DPSIR (Drivers, Pressures, States, Impacts, Responses) is applied.

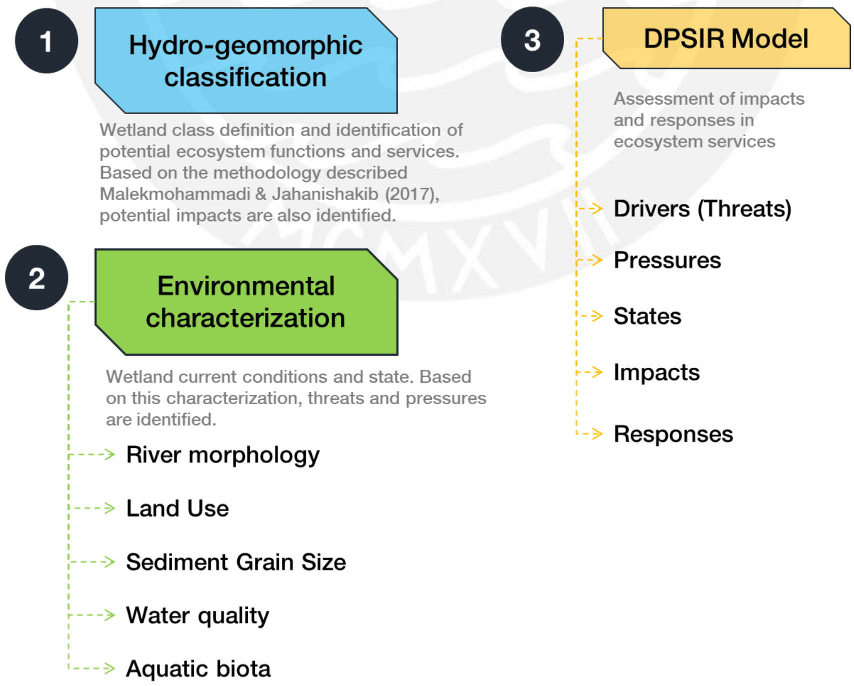

Figure 4.1 Research methodology flowchart

Own elaboration.

4.1 Hydro-geomorphic classification and identification of expected ecosystem services and human benefits

The hydro-geomorphic approach classifies the functionality of a wetland ecosystem by analyzing the physical, chemical, and biological interactions of the structural components of the ecosystem and the surrounding landscape (Engineer Research and Development Center, 2010). Brinson (1993) defines three main factors to characterize a wetland: the **geomorphic setting**, that describes the landscape evolution of the wetland; the **water sources**, that means the origin of the water that enters to the wetland such as precipitation, surface flow, and groundwater; and the **hydrodynamics**, that refers to water fluctuation, energy and direction, within a wetland. According to these three factors, wetlands can be classified as: Depressional, Riverine, Flats (mineral and organic), Fringe (tidal/estuarine and lacustrine), and Slope. The characteristics per each class are summarized in Table 4.1. This study tests the applicability of this classification to Peruvian coastal wetlands.

Table 4.1

Hydro-geomorphic classes of wetlands

Hydro-geomorphic Class (geomorphic setting)	Water source (dominant)	Hydrodynamics (dominant)
Riverine	Overbank flow from channel	Unidirectional and horizontal
Depressional	Return flow from groundwater and interflow	Vertical
Slope	Return flow from groundwater	Unidirectional, horizontal
Mineral soil flats	Precipitation	Vertical
Organic soil flats	Precipitation	Vertical
Tidal Fringe or Estuarine	Overbank flow from estuary	Bidirectional, horizontal
Lacustrine	Overbank flow from lake	Bidirectional, horizontal

Extracted from Brinson (1993) and Smith et al. (1995)

Once wetland class specified, following the methodology described by Malekmohammadi & Jahanishakib (2017), the Eten wetland ecosystem functions and services were identified based on previous research, literature reviews, and the guidelines described by the International Union for Conservation of Nature – IUCN (Dugan, 1992) and the Millennium Ecosystem Assessment (MEA, 2005) due to the lack of local data.

4.2 Environmental characterization

4.2.1 River morphology characterization

The characterization of the Reque river morphology was performed to describe the lateral connectivity with the Eten wetland. The planform morphology was described using past and recent aerial photographs, GIS-based tools such as QGIS (https://www.qgis.org/), and open-source satellite imagery of Landsat and Google Earth Pro. Past aerial photographs of 1949 were acquired from the *Servicio Aerofotográfico Nacional* (see Appendix A to visualize the full plot). Photographs were digitalized and georeferenced into the projected coordinate system WGS 64 zone 17S using QGIS. In addition, photogrammetry was applied to take aerial imagery from August 2019, using a Drone Phantom 4 Pro. Then, data was processed and georeferenced to obtain a high-resolution imagery of the Reque river (20 cm). This process was performed with the support of UTEC's research assistants.

Later, satellite data from 1949 to 2019 was compared to analyze the lateral movement of the Reque river over the years. Rivers in coastal plains are characterized by their sinuosity due to the low slope (Shafer & Yozzo, 1998). The sinuosity defines the degree of bend or meandering of a river course and quantifies how much it deviates from the shortest path (Horacio, 2014), as illustrated in Figure 4.2. Sinuosity index can be calculated by dividing the as the length of the stream divided by the length of the valley, and can be classified in four types: <1.05 (straight); 1.05-1.3 (sinuous); 1.3-1.5 (moderate meandering); and >1.5 (meandering form):

$$Sinousity = \frac{\widehat{AB}}{\overline{AB}}$$

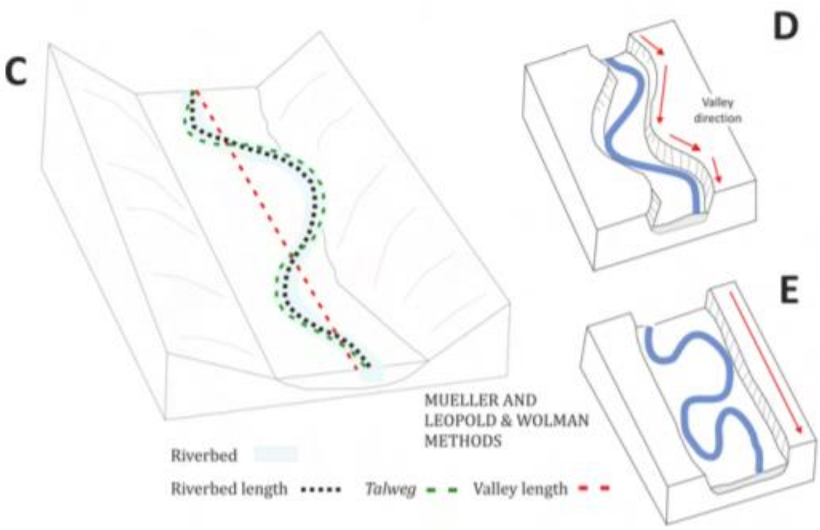

Figure 4.2 Graphical representation of river sinuosity calculation method

Extracted from Horacio (2014).

Satellite imagery from Google Earth was used to digitalize the central line of the Reque river stream. Then, centerlines were exported to QGIS and the sinuosity index for each centerline was calculated using the *Sinuosity* tool in the *Geometric Attribute* plugin. Channel width was also calculated using the *Measuring Length* tool in QGIS.

Satellite imagery was also used to characterize agricultural, urban, and dune areas. Moreover, a hillshade of azimuth 45° was obtained from the Digital Elevation Model (DEM) to characterize geomorphic characteristics such as paleochannels or "footprints" of past dynamics.

4.2.2 Land Use and Land Cover Change Analysis

To assess the changes in land use, Landsat satellite imagery of 5-m resolution from 2009, 2011, 2014, 2016, and 2019, and aerial photographs for the 1949's environment were processed using Google Earth Pro software. According to the *IV Censo Nacional Agropecuario 2012* and the Regional Government of Lambayeque records, croplands are productive at least twice a year (Gobierno Regional de Lambayeque, 2010). In this context, croplands were manually traced per year. Both, croplands and urban areas were considered only within the Eten estuary region. After delimiting crop areas, *.KML (Keyhole Markup Language, a geographic annotation format) files were exported to QGIS, and then converted into shapefiles. All data were georeferenced in the projected coordinate system WGS 64 zone 17S. Using the *Calculator>Geometry* tool in the *Attributes Table* option, the area of each class was obtained and exported to an Excel spreadsheet.

4.2.3 Sediment grain size and composition

Sediment material were sampled in July 2017 and August 2019 from the bedforms and riverbanks along the Reque River, as well as the shoreline and marshes within the Eten wetland (Figure 4.3). The objective was to characterize the sedimentary environment in the aquatic habitats and characterize land-derived inputs. The analysis also included the identification of the environmental conditions in which sediments were deposited.

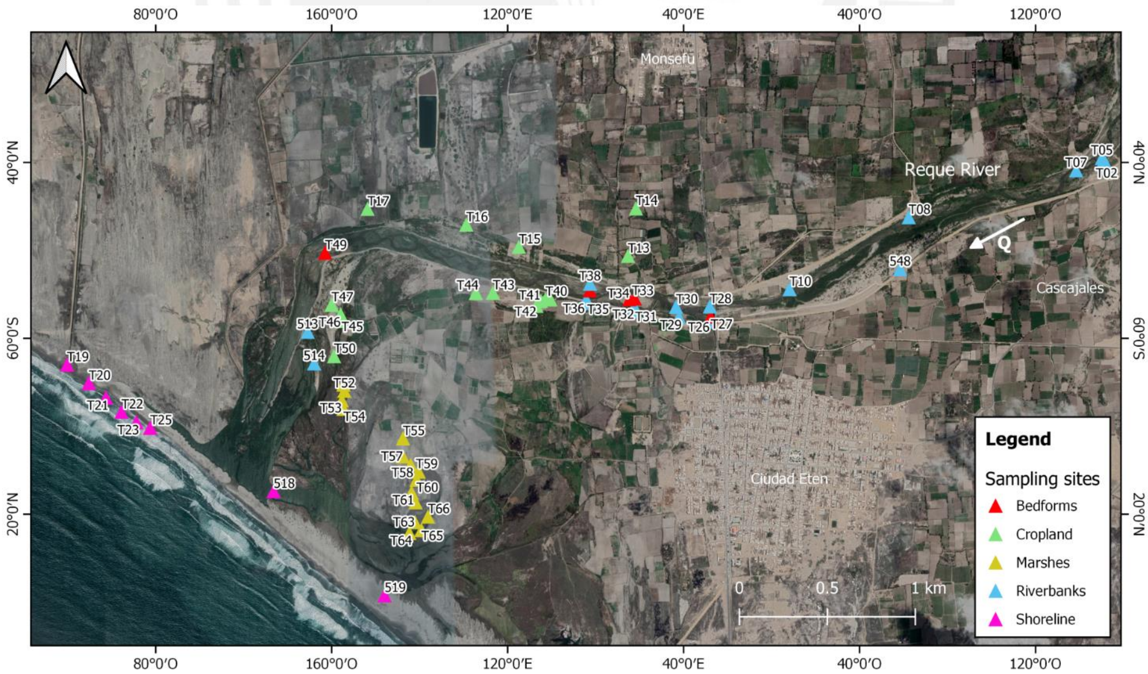

Figure 4.3 Location map of sampling sites for sediment grain size characterization

Own elaboration based on Google Earth imagery.

Sub-superficial and superficial sampling have been performed. Cores of 40 cm depth were taken from different locations (shoreline, mouth, crops, marshes, and riverbanks) while surface sediment samples of 500 g were collected from bedforms (Figure 4.4). Sampling followed the field methods for measurement of fluvial sediment (TWRI 3-C2) by the US Geological Survey (Edwards & Glysson, 1999). Then, samples were sealed in plastic bags and transported from the field site to the laboratory in Lima.

Figure 4.4 Core and regular samples, sealed in plastic-bag

Photographs by Tania Rojas.

In the laboratory, samples were mixed and quartered to uniformly distribute the sediment material following the guidelines of the ASTM C702/C702-11 "Standard Practice for Reducing Samples of Aggregate to Testing Size" (ASTM, 2018) (Figure 4.5). The processing method followed the ASTM C136/C136M-14 "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates" (ASTM, 2014). Quartered samples were weighted and then they were dried at a temperature of 110 ± 5 °C for about 12 hours. Then, they were placed in a desiccation cabinet to avoid moisture absorption. To remove air and moisture, a vacuum pump was turned on until 80kPa for half-hour. Dried samples were also weighted. Therefore, very fine sediments were separated using a #230 sieve. One more time, washed samples were dried, air and moisture removed, and weighted.

Figure 4.5 Reducing sampling process and samples distribution

Photographs by Tania Rojas.

Considering the field site presents mostly fine sediment, sieves of mesh 4.75 mm (No. 4), 2.36 mm (No. 8), 2.00 mm (No. 10), 850 µm (No. 20), 600 µm (No. 30), 425 µm (No. 40), 300 µm (No. 50), 250 µm (No. 60), 180 µm (No. 80), 150 µm (No. 100), and 75 µm (No. 200) were nested in order of decreasing size of opening from top to bottom. Each sample was placed on the top sieve, then using a mechanical sieve shaker, each one was agitated for 45 minutes. Material retained in each sieve was weighted and registered in a worksheet. Based on the information registered, percentages of both passing and retained material were estimated. Before it, weights were corrected using the before and after-shaking weights. Processing method was performed by the author of this thesis at the UTEC laboratory with the support of the research assistants in charge.

4.2.4 Physical-chemical parameters of water quality

Water samples were collected in July 2017 from the lower region of the Reque River along different points, and the lakes within the Eten wetland to understand water quality spatial variability. The purpose was to evaluate the influence of freshwater inputs in the wetland and the influence of agriculture and urban sprawl. Two points were sampled in the center of the Reque channel until Cascajales town, two in the mouth of the estuary, and three in the main lakes (Figure 4.6). Water quality parameters were defined considering the use of water and human activities in the region. Each site was georeferenced with a GPS and sampled two times.

Physical-chemical properties of water were measured following the standard methods from the Environmental Protection Agency (EPA) using a commercial laboratory. The used methods are indicated as follows:

- EPA Method 120.1: Conductance (Specific Conductance, µmhos at 25 °C)
- EPA Method 405.1: Biochemical Oxygen Demand (5 days, 20 °C)
- EPA Method 410.1: Chemical Oxygen Demand (Titrimetric, Mid-Level)
- EPA Method 360.1: Oxygen, Dissolved (Membrane Electrode)
- EPA Method 150.1: pH (Electrometric)
- EPA Method 170.1: Temperature (Thermometric)

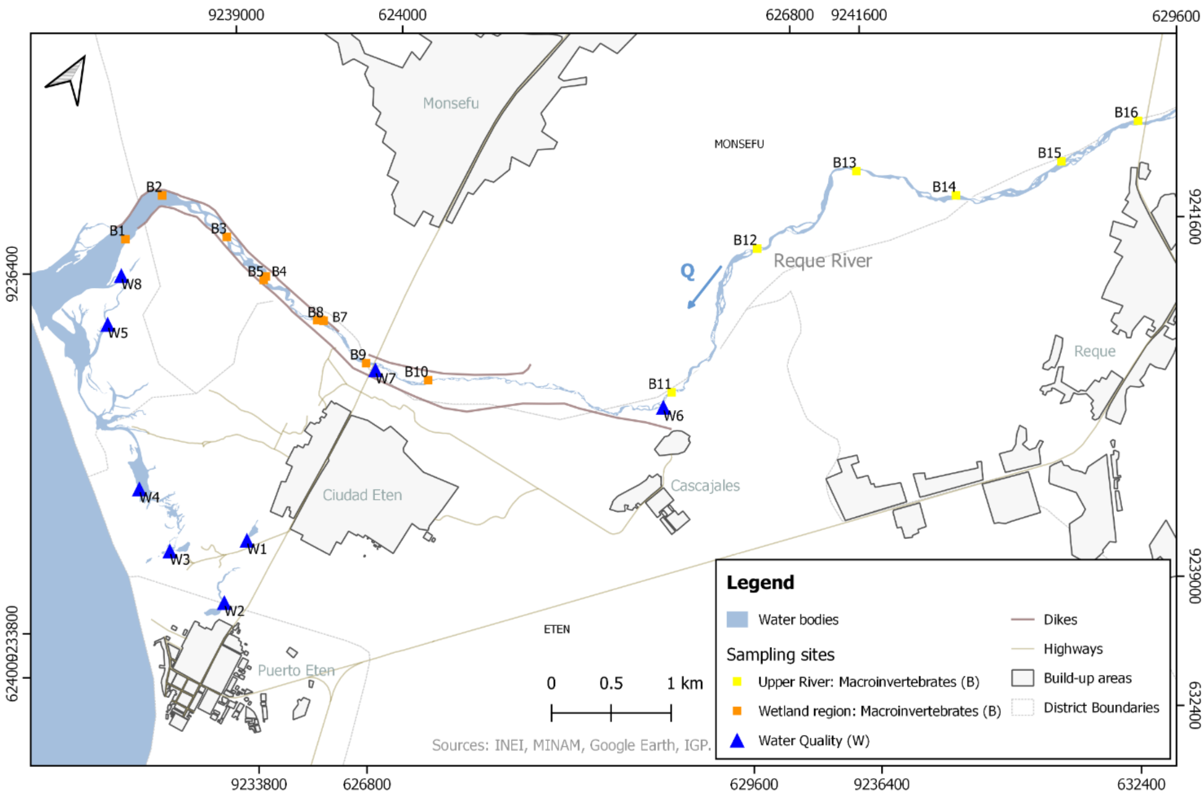

Figure 4.6 Sampling sites for water quality (blue color) and aquatic biota (orange and yellow colors) in the Eten wetland in 2017 and 2019, respectively

Own elaboration based on INEI, MINAM, IGP and Google Earth data.

4.2.5 Aquatic biota: estuarine macroinvertebrates assemblages

The objective of this section was to determine the diversity of macroinvertebrates. The macroinvertebrates were sampled in early August 2019 along the banks of the Reque channel. There were 16 sample stations starting from Reque town (upstream from the wetland) until the mouth of the estuary as shown in Figure 4.6. Sampling followed the collecting methods developed by the Museum of Natural History for the Peruvian Ministry of Environment (Samanez et al., 2014). At each sampling station, in an area of $1m^2$, bottom substrate was removed and filtered using a kick net of a mesh diameter of 300 µm (Figure 4.7). Each sample then was filtered one more time in sieves of aperture less of 425 µm to pass the coarse and fine sediment. Each macroinvertebrate individual collected were fixed in situ and preserved with 3:1 concentration of water and 96% ethanol in plastic bottles of 30 ml. In the laboratory, all specimens were identified at the families level, using available taxonomic keys (Domínguez & Fernández, 2009) and reference collections (Loayza-Muro & La Matta, 2015; Roldán, 1996) using a Q-Scope QS.20200-P Digital Hand Microscope.

Figure 4.7 Sampling process using a kick net of 300 µm mesh

Photographs by Tania Rojas.

To analyze the macroinvertebrate communities in the wetland, taxa richness *S* and abundance N indices were calculated. Richness is defined as the number of families in an assemblage (Zhao et al., 2017). Then, the Shannon-Wiener Index (H’) and the improved

Shannon-Wiener Index (B) were calculated to assess families' abundance and richness. The Shannon-Wiener Index *H'* was calculated using the following formula (Zhao et al., 2017), based on data at family level:

$$H' = -\sum_{i=1}^{S} \left({n_i}/{N}\right) \ln\left({n_i}/{N}\right)$$

Where:
S = total number of families at each site
n_i = number or individuals of the i^{th} family
N = total number of individuals at each site

The improved Shannon-Wiener Index B was estimated considering the abundance of individual per family per each site, and can be calculated as follows (Wang et al., 2009):

$$B = -\ln N \sum_{i=1}^{S} \left({n_i}/{N}\right) \ln\left({n_i}/{N}\right)$$

Equitability (evenness) of families were estimated from Shannon index H to evaluate the distribution of families in a community (Choi et al., 2010). Equitability values in the range between 0 and 1, with 1 being complete evenness (Begon et al., 1996). Pielou's evenness (J) formula is defined as (Pielou, 1996) to evaluate taxonomic dispersion of data at family level:

$$J' = \frac{H'}{\ln S}$$

4.3 DPSIR (Drivers, Pressures, States, Impacts, Responses) Model

Developed by the European Environment Agency, the DPSIR is a conceptual model that describes the relationships between the human-being and the environment. The DPSIR model consists on a chain of causal links starting with a 'driver' (a demand that influences the ecosystem, e.g. agriculture) that can cause 'pressures' (when demand can modify the ecosystem, e.g. changes in land use) on the ‘state’ of the environment (physical, chemical and biological) thus generating ‘impacts’ on ecosystems and human health. Finally, the understanding of resulting impacts leads to ‘responses’ that can be displayed in terms of decision-making, target settings, prioritization projects, and policies for risk mitigation and conservation purposes (Kristensen, 2004).

Driving forces are described as the demands that modify or influence the natural behavior of an ecosystem, and can be natural or anthropogenic (Burkhard & Müller, 2008). Some examples include population growth, transportation, energy use, implementation of infrastructure (e.g. power plants, ports), mining, agriculture, and land use. Then, when a human demand (driver) has the potential to change the environment, thus it can be classified as a **pressure**. Generally, all human activities that affect the environment are considered pressures (Burkhard & Müller, 2008). Pressures can occur at different scales in time and space, as well as be constant or infrequent. They can be classified into three types (Kristensen, 2004): 1) excessive use of environmental resources, 2) changes in land use, and 3) emissions (chemicals, waste, radiation, noise) to air, water, and soil. As a result of the occurrence of pressures, the **state** of an environment is modified (e.g. eutrophication due to wastewater release). A state can be described as the quality of a system resulting from the combination of physical, chemical, and biological conditions. States can be evaluated based on changes in the quality of air, water and oil, human health, use of natural resources, and ecosystems condition (e.g. biodiversity, vegetation, organisms).

Impacts are defined as changes in the physical, chemical or biological state of the environment (Kristensen, 2004). They can affect not only social components as welfare and well-being but also economic conditions. For instance, by reducing the provision of ecosystem services and goods. The impact depends on the magnitude of the pressure and the sensitivity of the ecosystem. In this project, the DPSIR approach is addressed to qualitative analyze the impacts under a conceptual framework that considers delays in the response of some impact indicators (Burkhard & Müller, 2008). Finally, the DPSIR framework defines **response** as the actions taken by society or policy makers to reduce or mitigate an undesired environmental impact (Kristensen, 2004). Moreover, a response can influence drivers and pressures and, consequently, improve the environmental state (Burkhard & Müller, 2008).

(Müller & Burkhard, 2012) developed an improved DPSIR model that allows to evaluate the state of biophysical processes and ecosystem functions and how changes in the environment can impact on ecosystem services and human benefits (Figure 4.8). The DPSIR model is then an analytical tool to assess the effects the anthropogenic activities into ecosystem services and also to improve decision-making.

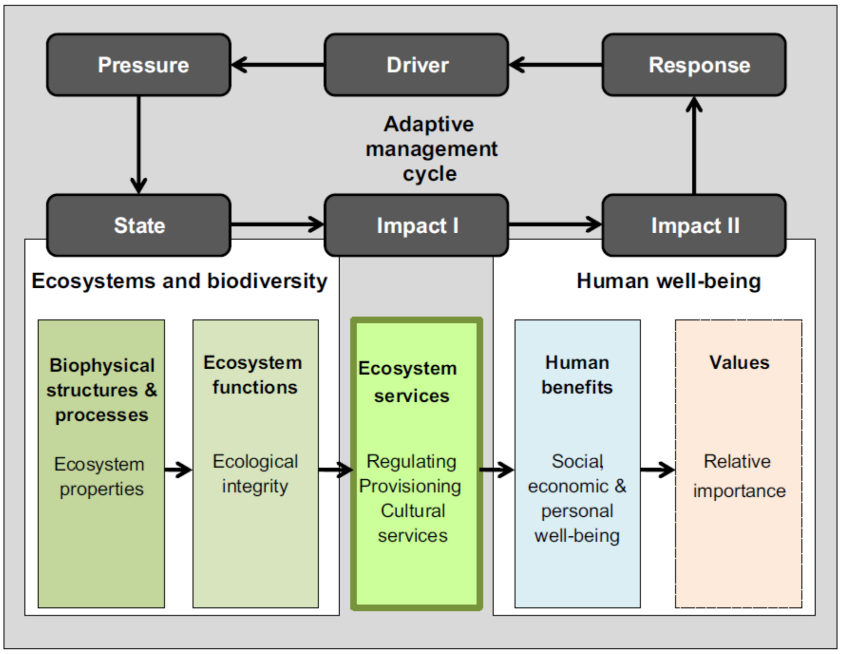

Figure 4.8 Improved DPSIR assessment framework model

Extracted from (Müller & Burkhard, 2012)

Chapter 5 Results

This section describes the application and results obtained from the previous methodology. The hydrogeomorphic characterization consist in a qualitative assessment of ecosystem functions of the Eten wetland. Then, the environmental characterization of the Eten wetland is based on collected data and GIS-based analyses. Finally, a qualitative assessment of impacts in ecosystem services and functions is performed using a DPSIR model.

5.1 Hydro-geomorphic classification and identification of expected ecosystem services of the Eten wetland

The Eten wetland is located in a coastal plain limited by the Reque river and the Pacific Ocean. The Reque river describes a delta with small streams flowing into it, forming an estuary that encloses the Eten wetland and describes a wedge-shaped section that is seasonally connected to the ocean. Therefore, the Eten wetland receives both freshwater and brackish water inputs intermittently. Here, there is a transition zone between the ocean and the river delta that harbors vegetation patterns dominated by herbaceous plants (marshes), as illustrated in Figure 5.1.

Based on the hydrogeomorphic classification established by Brinson (1993), the Eten wetland corresponds a Estuarine class, in which the dominant water source is the overbank flow from the Reque river and the hydrodynamics is dominated by bidirectional and horizontal flow. Moreover, the geomorphic setting is described as a blind estuary with a characteristic funnel shape in the river mouth, as illustrated in Figure 5.1, in which foredunes are formed along the coastline as well.

Figure 5.1 Characterization of the Eten wetland based on the local geomorphology

Source: Google Earth imagery. Photographs by Tania Rojas.

On estuarine environments, such as the Eten wetland, it is expected to find ecosystem services such as groundwater recharge, sediment retention, biological diversity, flood control, carbon sequestration, nutrient cycling, storm attenuation, sediment retention, and water regulation (Barbier, 2019; Camacho-Valdez et al., 2013; Costanza et al., 1997; Dugan, 1992; Perillo et al., 2009), as summarized in Table 5.1. Then, they were categorized in provisioning, regulating, cultural and supporting services, following the Millennium Ecosystem Assessment (MEA, 2005), as well as the type of human benefit they represent.

Table 5.1

Summary of expected ecosystem services and benefits of the Eten wetland

Classification	Ecosystem service	Human benefit
Provisioning	Raw fiber material (*junco* and *totora*) Fishery Pasture and forage Soil Water	Ecological and Economical
Regulating	Groundwater recharge Sediment retention Storm attenuation Water regulation Flood control Waste processing	Hydrological, Economic, and Ecological
Supporting	Biological diversity Genetic resources Carbon sequestration	Ecological
Cultural	Cultural heritage Education and research	Economic and Social

5.2 Environmental characterization

The environmental characterization was based on data obtained from field visits, field data collecting, and GIS-based analyses using open-source tools. The main purpose of this environmental evaluation was to identify drivers of change or threats, and the existing pressures derived.

During the field visit, as illustrated in Figure 5.2, two types of hydraulic structures have been identified: two bridges (the Reque and Eten bridges) and the dike built from the Cascajales town until half part of the wetland. Additionally, intensive agricultural activities demanded channeling riverbanks to derive water inputs for croplands. The lack of waste disposal facilities also resulted in the accumulation of liquid and solid waste within the wetland.

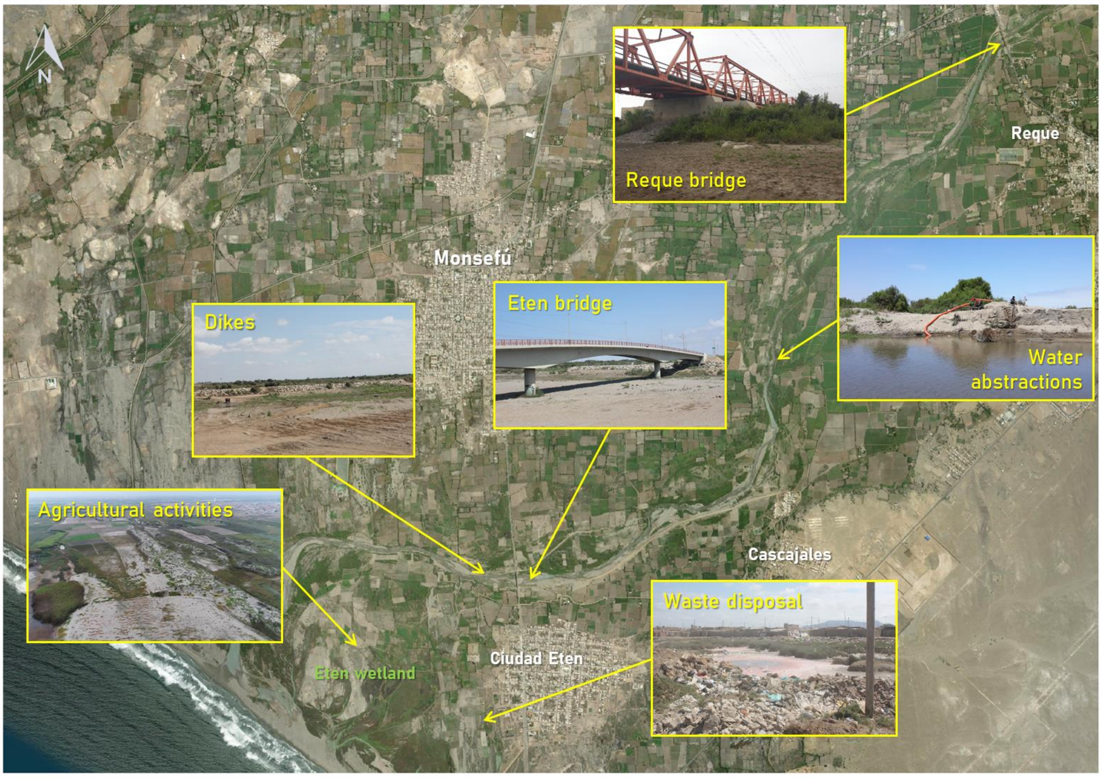

Figure 5.2 Landscape condition along the Reque River

Source: Google Earth imagery. Photographs by Tania Rojas.

5.2.1 Characterization of fluvial morphology

The river represents the main source of freshwater input and its morphology can define the wetland structure. However, the morphology of the Reque river has changed over the years. A comparison between 1949 and 2018 indicated that the Reque river used to create deltas generating a variety of landforms and ridges of water and sediment, and average sinuosity values indicated a moderate meandering form (1.20 – 1.38) (Abad et al., 2010; Odgaard & Abad, 2008), especially from the Reque to Ciudad Eten town. Figure 5.3 illustrates the sinuous watercourse that the Reque river described in this period. Average channel width was 120 m upstream while downstream was 100 m.

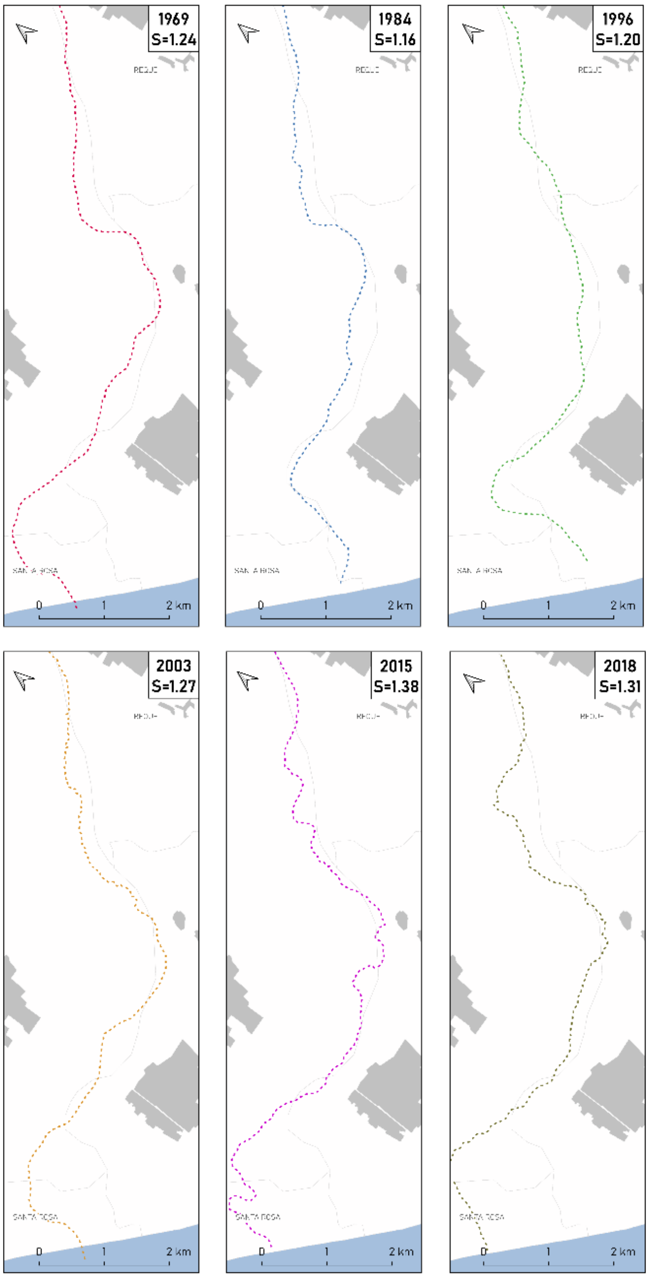

Figure 5.3 Average sinuosity index along the Reque river from 1949 to 2018

Own elaboration based on MINAM and Google Earth data.

A comparison between 1949 and 2019 indicated that the Reque river used to create deltas (Figure 5.4) generating a variety of landforms and ridges of water and sediment. The river transported the sediment load through many streams, thus providing freshwater inputs to all water bodies within the wetland. Additionally, dunes areas within the Eten wetland have been reduced by cropland occupation and changes in river morphology. From 1949 to 2019, agricultural lands also increased in 17% and urban areas in 19%.

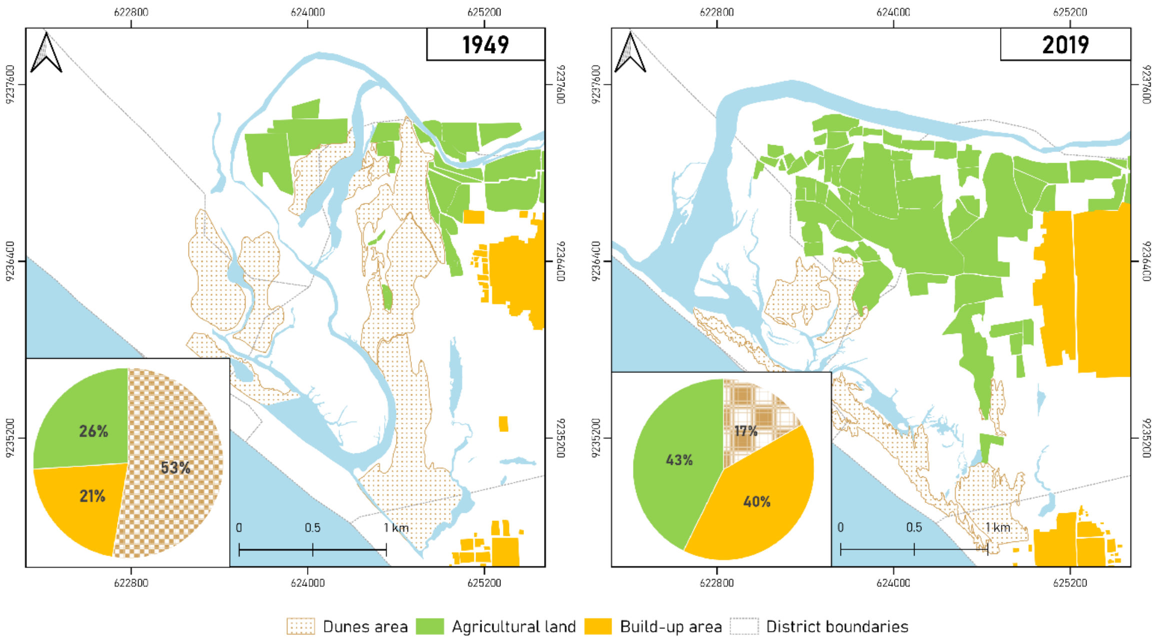

Figure 5.4 Reduction of the coastal dunes area in the Eten wetland from 1949 to 2019

Own elaboration based on MINAM, Google Earth and the Servicio Aerofotográfico Nacional data.

Aerial photographs of August 2019 illustrate the current state of the Reque river morphology, starting from the Reque bridge until the river reaches the ocean. Figure 5.5 illustrates the data obtained from the photogrammetry and the sections to be analysed: Section A consists on a section without river embankment; Section B presents river embankment on the left side; Section C describes both-sides river embankment, bridge constriction, and channeling for irrigation; and Section D shows river morphology without embankment but receiving direct saline water flow.

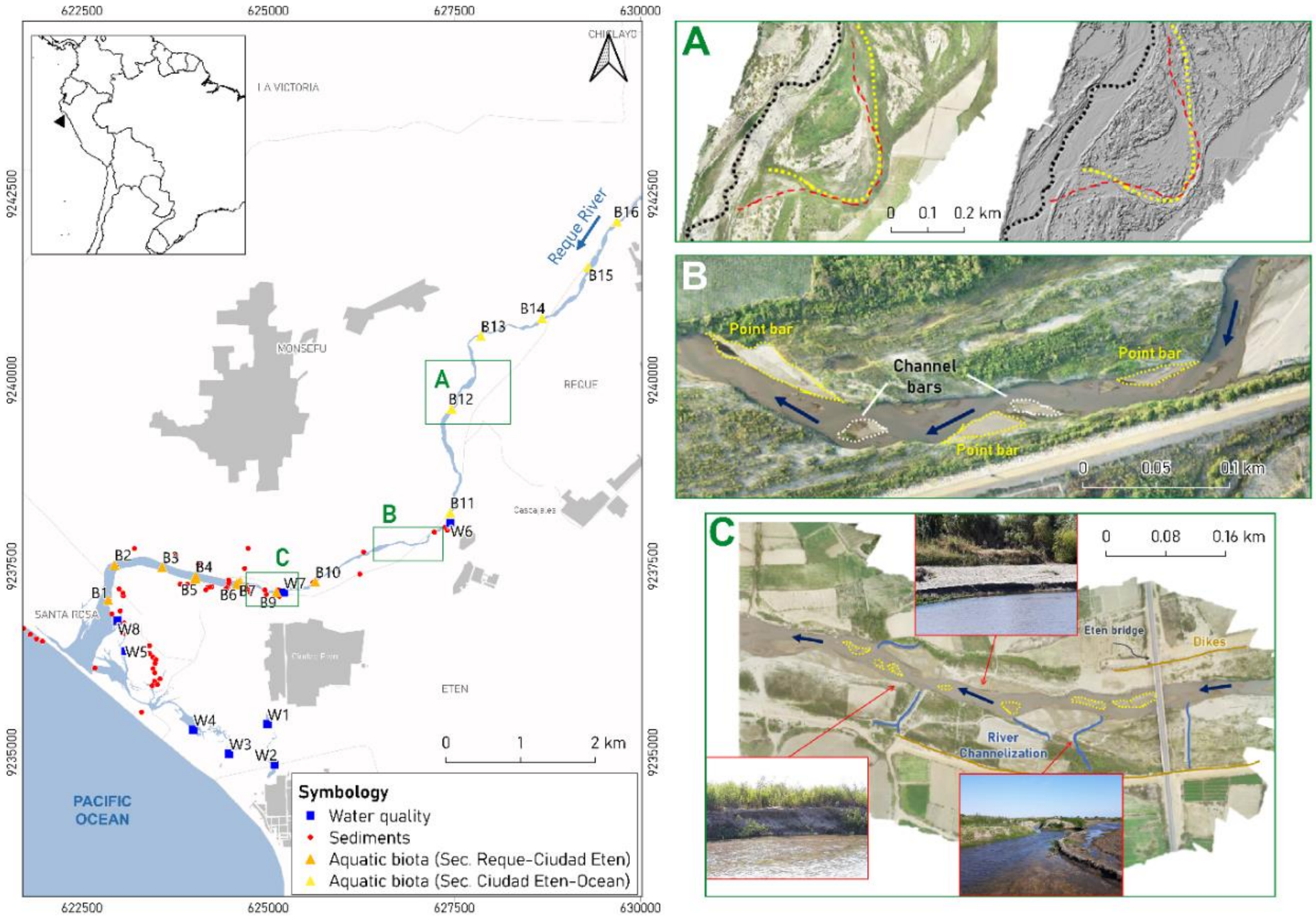

Figure 5.5 Location of aerial photographs of the Reque River taken in August 2019

Own elaboration based on MINAM and INEI data. Photographs by Tania Rojas.

In Figure 5.5-A, the Reque channel presents a wider floodplain upstream in the side in which there are less fluvial constraints (e.g. agricultural lands). Hillshades (azimuth 45°) created from the Digital Elevation Model (DEM) of aerial photographs shows a naturally meandering river morphology based on the observed paleochannel patterns (dotted yellow and orange lines). Paleochannels evidenced the natural extension of the river floodplain and sinuosity (dotted red line). As illustrated in Figure 5.5, agricultural lands covered river floodplain at different seasons.

In Figure 5.5-B, aerial photographs illustrates the types of sand bars along the Reque stream and presents the type of bars identified. The presence of point and channel bars evidenced that the river still maintains its meandering dynamics. However, the dike on the right side constrains the sinuosity of the river, in contrast to Section A.

In Figure 5.5-C, the river morphology presents a different dynamic. Figure 5.5 shows that the Reque river channel presents less curvatures and more mid-channel bars created by the new energy balance along the stream. In this section, there are more croplands that channelized the stream to abstract water for irrigation purposes. Moreover, the Eten bridge, the 3.5 km-length dike on the sides, and the debris accumulated below the bridge confines the stream, thus increasing flow velocity. As a consequence, the Reque river is clearly prone to erosion.

Spatial analysis along the Reque river indicated that embankment for flood protection influences river morphology from a meandering to almost a braided stream, in which the channel is constrained to follow only the left margin of its natural course. Braided rivers are characterized by a wide channel prone to bank erosion that can also increase turbidity. The debris accumulated also traps the sediment load and, consequently, reduces nutrient availability. It is evidenced by the low vegetation cover in section C. In one hand, constraining can directly impact the natural flow and ecology of the Reque river. On the other hand, bank erosion can also increase the maintenance cost of river infrastructure.

The Reque river represents a crucial component of the Eten wetland because it represents the main source of freshwater input and its morphology defines the wetland structure. However, lateral connectivity has been reduced due to flood protecting structures that constrain the river channel and agricultural lands occupation. Channelization also disturbed the riverbanks thus increasing bank erosion.

5.2.2 Changes in land cover and land use

Aerial photographs suggest soil salinization of agricultural lands. Figure 5.6 shows some photographs that evidenced a saline creeping into croplands and the presence of salinity tolerant plants (e.g. succulents, red color). IV CENAGRO indicated that river is the main source of water for irrigation and previous section evidenced river channelization for irrigation, thus water-added evaporates leaving behind the salt in the soil.

Figure 5.6 Brackish springs in crop yields and oxbow lakes within the Eten wetland

Photographs by Tania Rojas.

The qualitative analysis of temporal changes in land cover and land use shows an increase in crop areas from 1949 to 2014 (Figure 5.7). From 1949 to 2009, a period of 60 years, agricultural activities registered an increase of 62%. In particular, in only 2 years (from 2009 to 2011) there was an accelerated increase in crop areas of 52%. However, during the 2014-

2016 period, croplands were reduced in over 20%. The last 4 years that include 2016-2019 period shows a slight increase of croplands of 3%. Figure 5.7 also illustrates an extensive urban development in the last 70 years. Urban areas doubled sized from 1949 to 2009. Then, the increase trend barely reached the 12%. The results demonstrated that uncontrolled agricultural use (based on the records of the Municipality of Ciudad Eten), livestock farming, and the urban sprawl, reduced the natural plant composition within the Eten wetland.

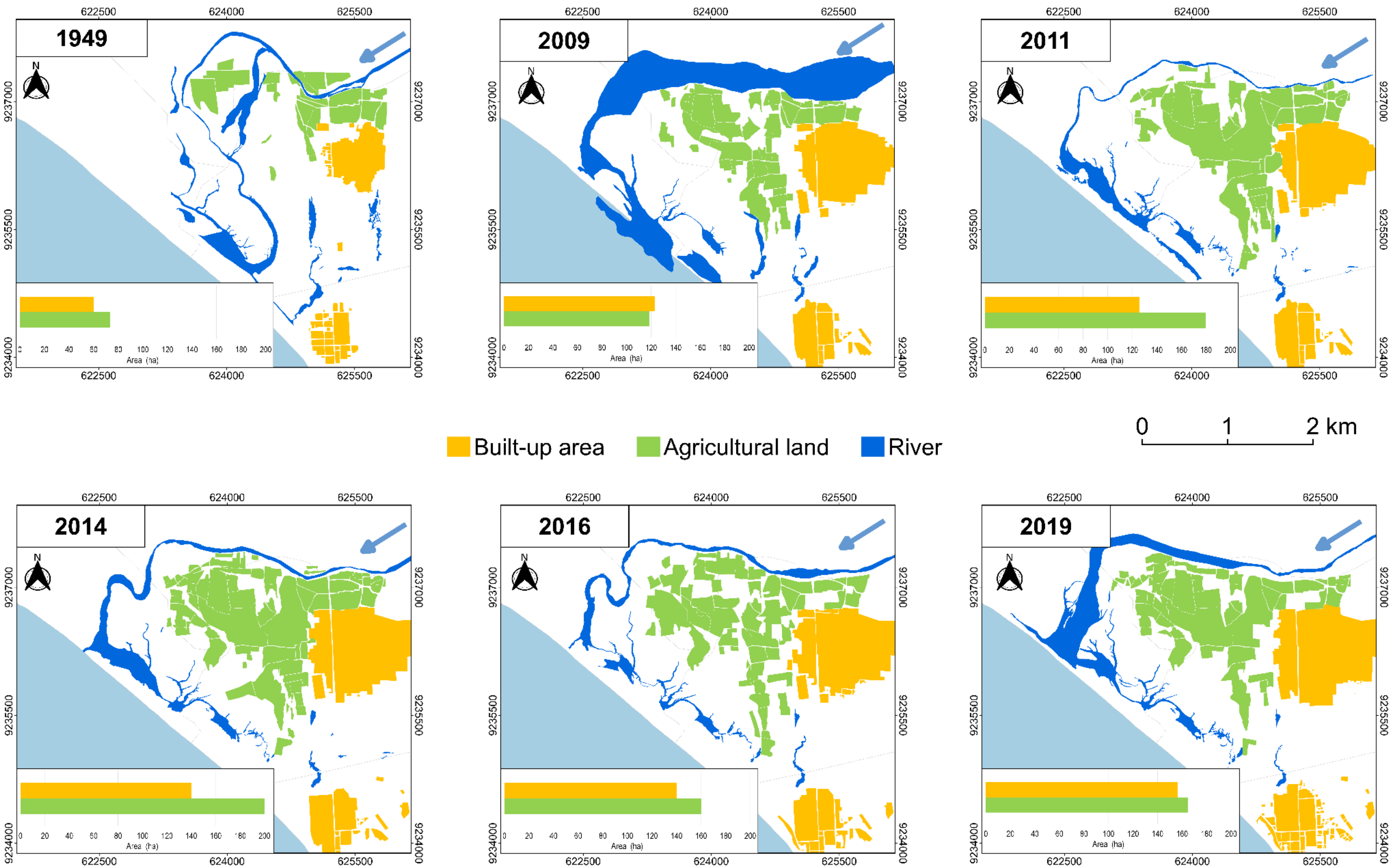

Figure 5.7 Changes in land use within the Eten wetland from 1949 to 2019

5.2.3 Granulometric and sediment composition analysis

62 sediment samples have been collected in different zones to characterize sediment composition and grain size. Figure 5.8 summarizes the mean grain size per zone as well as a field photography. Bedforms (ripples) of 2-5 cm height were identified within the Reque River channels as the dominant bedform. This size is a typical feature in fine-to-medium sand mainly carried by wind and low-velocity water flow, as illustrated in Figure 5.8 and Table 5.2. In these bedforms, the mean size grain (D50) was 247.60 μm.

Sediment texture in croplands was composed by fine sand. The average D50 found in crops was 189.1 μm which might be caused by tillage activity (removal and preparation of arable soils) and soil erosion due to river channelization. Moreover, finest material was found in the right side of the Reque river. Therefore, it is suggested that crop areas are an important source of finer sediment material in the Reque river, which is transported by irrigation-water flow.

The substrate in marshes was mainly medium and very fine sand and the D50 was similar to croplands (189.9 μm). It might be because sampling sites in marshes were located between the river and crops. Typical marshes use to have an average grain size of less than 50 μm (Bartholdy, 2012), thus the sampling area might be strongly influenced by sea-water inputs that supply coarse-grained sediments.

Regarding the granulometric composition of the riverbanks, they presented greater medium coarse and fine sand percentages. The mean grain size D50 is about 217.8 μm and slightly tended to become finer near to the river mouth in the estuary.

Finally, when the Reque river reaches the sea, it creates a barrier where sediments are deposited. Sediment texture is mainly represented by fine sand uniformly distributed along the estuary mouth. Sediment texture in the mouth mainly composed by medium-coarse to fine sand. The average D50 value is 203.4 µm along the shoreline, similar from riverbank composition. See Appendix B to visualize detailed granulometric curves per sampling zone.

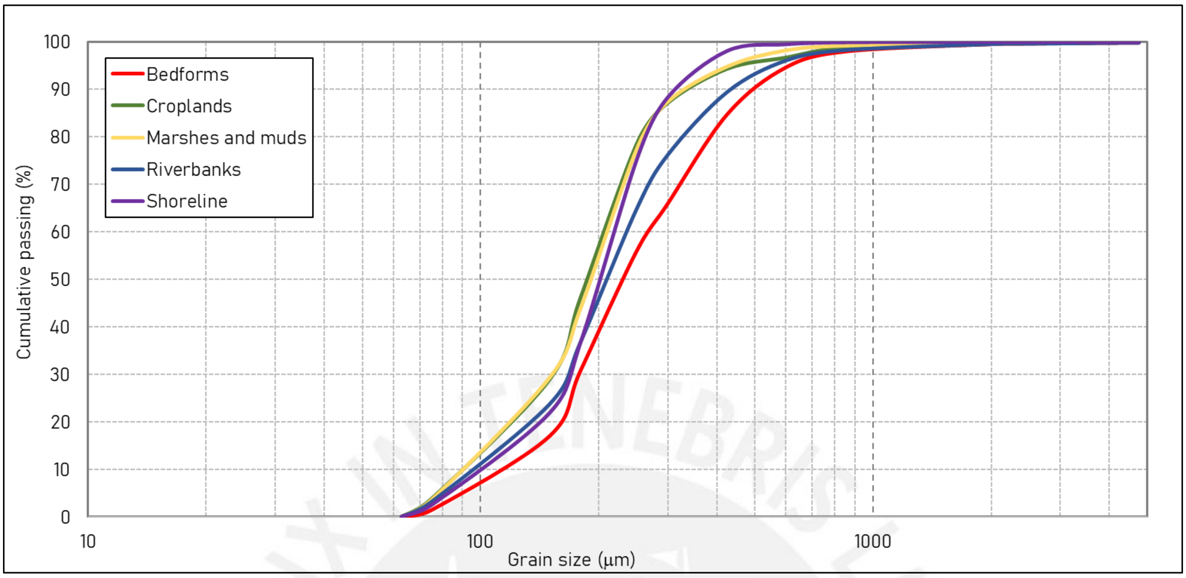

Figure 5.8 Average granulometric curve in sampling zones

Table 5.2

Mean grain size (d_50) of sediments in sampling zones

Field site photography			
Sampling zone	Bedforms	Croplands	Marshes and muds
Mean_d_{50} (µm)	247.6	189.1	189.9
Field site photography			
Sampling zone	Riverbanks	Shoreline	
Mean_d_{50} (µm)	217.8	203.4	

Photographs by Tania Rojas.

The sediment composition analysis indicated that the grain-size distribution in croplands and marshes are very similar. Riverbanks present finer sediment size than bedforms, thus indicating erosion and continual deposition. River channelization for irrigation purposes might altered the sediment distribution along the stream as well. In normal condition, fine-grained sediment tend to move landward. As a consequence, riverbanks tend to erode easily due to the presence of more fine material.

5.2.4 Physical-chemical parameters of wetland water quality

To analyze the spatial variability of water quality, physical-chemical parameters were compared from a reference point: the river mouth (when the Reque river reaches the sea). It is because both brackish and freshwater inputs influence wetland environment. As indicated in Table 5.3, the pH values of all sites were greater than 8 during the dry season, indicating a low alkaline environment. Previous studies indicated that decline of pH at some levels can disturb biological responses in the aquatic environment (Ringwood & Keppler, 2002; Wright & Worrall, 2001), therefore, pH values might be important to monitor the biological diversity of the Eten wetland.

Table 5.3

Physical-chemical parameters at the sampling stations in the Eten wetland

Sampling Station	pH	DO (mg/L)	BOD5 (mg/L)	T (C°)	Conductivity (µS/cm)	Chloride (mg/L)	COD (mg/L)	Sulfate (mg/L)	Bicarbonate (mg/L)
W1	9.8	9.0	485	24.0	43,300	10,227.43	1,020	4,817.5	4,769.7
W2	9.2	8.9	420	25.8	124,800	46,625.04	1,185	12,797.7	6,932.0
W3	8.3	8.8	74	22.2	1,996	149.40	150	206.0	60.4
W4	8.2	9.0	8	21.6	50,000	18,950.82	18	2,711.6	79.4
W5	8.8	9.1	10	20.4	30,010	9,575.68	20	1,335.0	54.9
W6	8.5	9.1	< 3	19.6	1,000	61.67	6	115.4	80.3
W7	8.5	9.0	< 3	21.0	979	63.67	6	114.6	78.4
W8	8.4	8.9	< 3	21.4	912	62.17	<6	113.8	76.1

The average value of dissolved oxygen (DO) was 8.975. Differences between oxbow lakes and the river values were very little and there was no evidence of hypoxia in water bodies (<2-3 mg/l O_2) (Diaz et al., 2019). Conductivity decreased from the mouth to upstream and increased from the mouth to the oxbow lakes. Salinity and conductivity measures are directly related because dissolved ions increase both values, thus it suggests that lakes receive more saline than freshwater inputs. Even though higher values of chloride are consequence of brackish water inputs during coastal flooding and animals and plants are commonly adapted, concentration values might be also increased by sewage and wastewater contamination (Hunt et al., 2012).

The biochemical oxygen demand (BOD) values along the Reque river were less than 2 mg/L. However, BOD increased from the mouth to the oxbow lakes. Values in farther oxbow lakes (W1 and W2) were more than 400 mg/L. BOD is influenced by the temperature, the type of organic and inorganic matter in water bodies, and the aquatic biota (US EPA, 2006), thus can be used as indicator of pollution with organic substances. Moreover, BOD has a direct relationship with DO. However, high values of DO and BOD was found in lakes W1 and W2, but low BOD concentrations in W3 even though DO was similar among them. It was expected to have lower values of DO, this it would be required to take more measurements and monitor changes in DO and BOD to understand the origin of this result.

Water temperatures have an average of 22 °C. Warmer temperatures have been registered within the boundaries of the wetland, mainly in the oxbow lakes far from the river mouth. The chemical oxygen demand (COD) along the Reque river were less than 6mg/L, while values in farther oxbow lakes (W1 and W2) were more than 1,000 mg/L. As well as the results of BOD concentrations, it can be because oxbow lakes are located near to the urban areas, thus receive more domestic wastewater inputs (Figure 5.9), that also increased the concentration of sulfate and bicarbonate in water.

Water pollution is also evidenced by the higher values in sulfate and bicarbonate. Additionally, even though higher values of chloride are consequence of brackish water inputs during coastal flooding and animals and plants are commonly adapted, concentration values could be increased by sewage and wastewater contamination.

Figure 5.9 Lakes within the Eten wetland near to Ciudad Eten and Puerto Eten

Photographs by Tania Rojas.

5.2.5 Macroinvertebrate Taxonomic Composition, Abundance and Richness

A total of 309 samples of macroinvertebrates were collected from the 16 sampling sites. They belong to 17 families distributed heterogeneously along the Reque river. Sampling sites have been characterized in two sections: from Reque to Ciudad Eten (upstream) and Ciudad Eten to the ocean (downstream). Based on their relative location from the flood protection structure, this division were considered to compare the influence of hydraulic infrastructure in aquatic biota.

Figure 5.10 indicates that taxa richness upstream was greater than downstream. Higher Shannon-Wiener index values were recorded upstream than downstream as well. In ecological studies, typical Shannon-Wiener values are between 1.5 and 3.5 (Khudhair et al., 2019) and indicate the diversity of families. It might be because of the lower disturbance in the river (i.e. embankment). The Shannon-Wiener index has also a direct relationship with richness and evenness. Evenness values suggest a constant population size of families collected downstream. Nevertheless, upstream registered a disparity between the number of individuals within each family. The results indicated that the downstream area harbors fewer families than the area above the tidal limit (upstream), but the abundance of individuals was higher (mainly tolerant families).

The alpha diversity (the average diversity in a specific area) at a single sampling location in the downstream region (Ciudad Eten-ocean) was lower than upstream (Reque-Ciudad Eten). The maximum number of families recorded at each sampling site was 8. However, the alpha diversity of families on a catchment-wide scale was 17 (considering all the 16 sampling sites). Heterogeneity in families' distribution might be due to several causes including: 1) lower temperatures upstream, 2) type of sediment material in the substrate, and 3) few riparian vegetation along the riverbanks in the wetland region (Zhao et al., 2017).

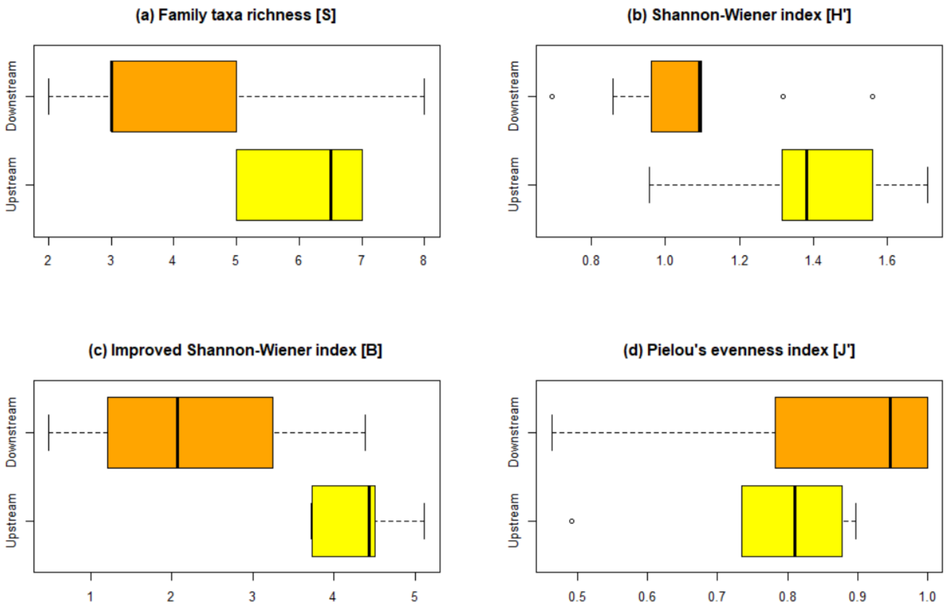

Figure 5.10 Richness indices and equitability of benthic macroinvertebrates in the Eten wetland: yellow (Reque-Ciudad Eten section) and orange (Ciudad Eten-ocean)

Figure 5.11 shows the relative abundance of macroinvertebrate families per sampling sites. *Chironomidae* and *Baetidae* represent the most abundant families, followed by the *Palaemonidae*. Both *Chironomidae* and *Baetidae* families are considered detritus feeders and during their adult phase as flies they become vectors for infectious diseases (Hall & Gerhardt, 2002). *Chironomidae* individuals are tolerant to environmental stress (Domínguez & Fernández, 2009) and their presence also indicates organic matter (Roldán, 1996), elevated salinity (Mendelssohn et al., 2014), and heavy metals (Loayza-Muro et al., 2010) concentrations in the stream. In case of the *Palaemonidae*, commonly known as freshwater shrimp or prawn, they play an important role in fishery and aquaculture. Moreover, Ephemeroptera, Plecoptera and Trichoptera (EPT) orders affects primary production positively, thus are considered to play a vital role as food for stream fishes. However, they are very sensitive to sedimentation. Upstream, individuals sampled included *Odontoceridae* taxa in the order Trichoptera upstream, and *Baetidae* taxa in the order Ephemeroptera downstream.

Results in this section indicates that the diversity of families and abundance of individuals are influenced by changes in the environment. Modifications along the river channels such as embankment and river channelization disturb the grain-size of sediments (more erosion increases finer sediments), and physical-chemical parameters such as temperature, DO, COD and BOD. Alterations in aquatic biota might affect the biological diversity in the Eten wetland.

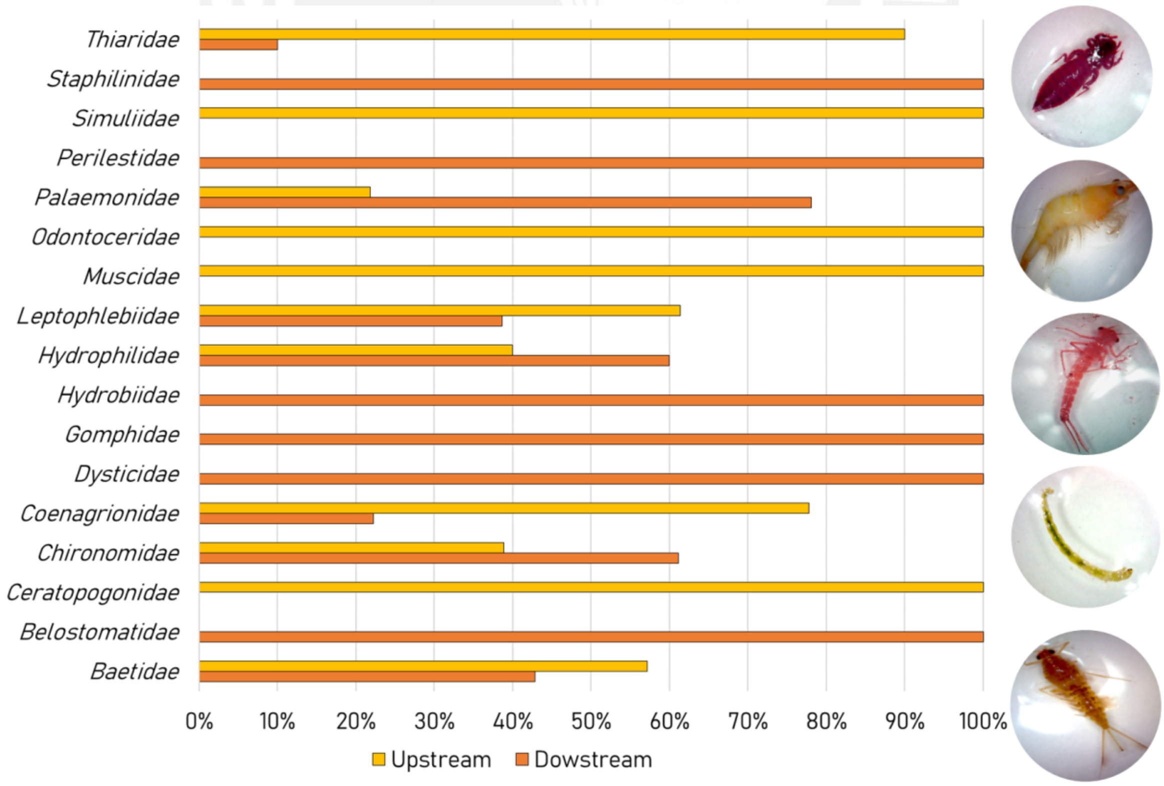

Figure 5.11 Relative abundance of the macroinvertebrate community downstream (left) and upstream (right) Photographs by Tania Rojas.

5.3 Assessment of impacts using a DPSIR model

Based on the hydro-geomorphic characterization, 13 ecosystem services that the Eten wetland provides were identified (see Table 5.4). The environmental characterization (section 4.2) identified 3 main threats (agricultural, livestock and farming activities; dikes and hydraulic infrastructure for flood protection; and population growth and rapid urbanization) that influence wetland status, generating changes in river morphology, land use, sediment grain size, water quality, and aquatic biota.

As a first step of the assessment, each wetland condition was linked with one or more threats, as illustrated in Figure 5.12. This figure shows the threats identified and how they are linked to each wetland condition (status), in terms of the environmental characterization performed. For instance, agricultural activities modify the composition of sediment transported by increasing fine material concentration due to river channeling and uncontrolled water harvesting.

Then, for each threat, we established a linkage between pressures and impacts that can be generated as a consequence, based on the information collected. Following the previous example, increasing of finer sediments in the stream might lead to the increase of turbidity and the reduction of aquatic habitats.

The last step was to correlate how the impacts affects the ecosystem services and human benefits identified. For example, the reduction of aquatic habitats can modify ecosystem services such as a reduction of wildlife and biological diversity, or the disturbance of nutrient cycling.

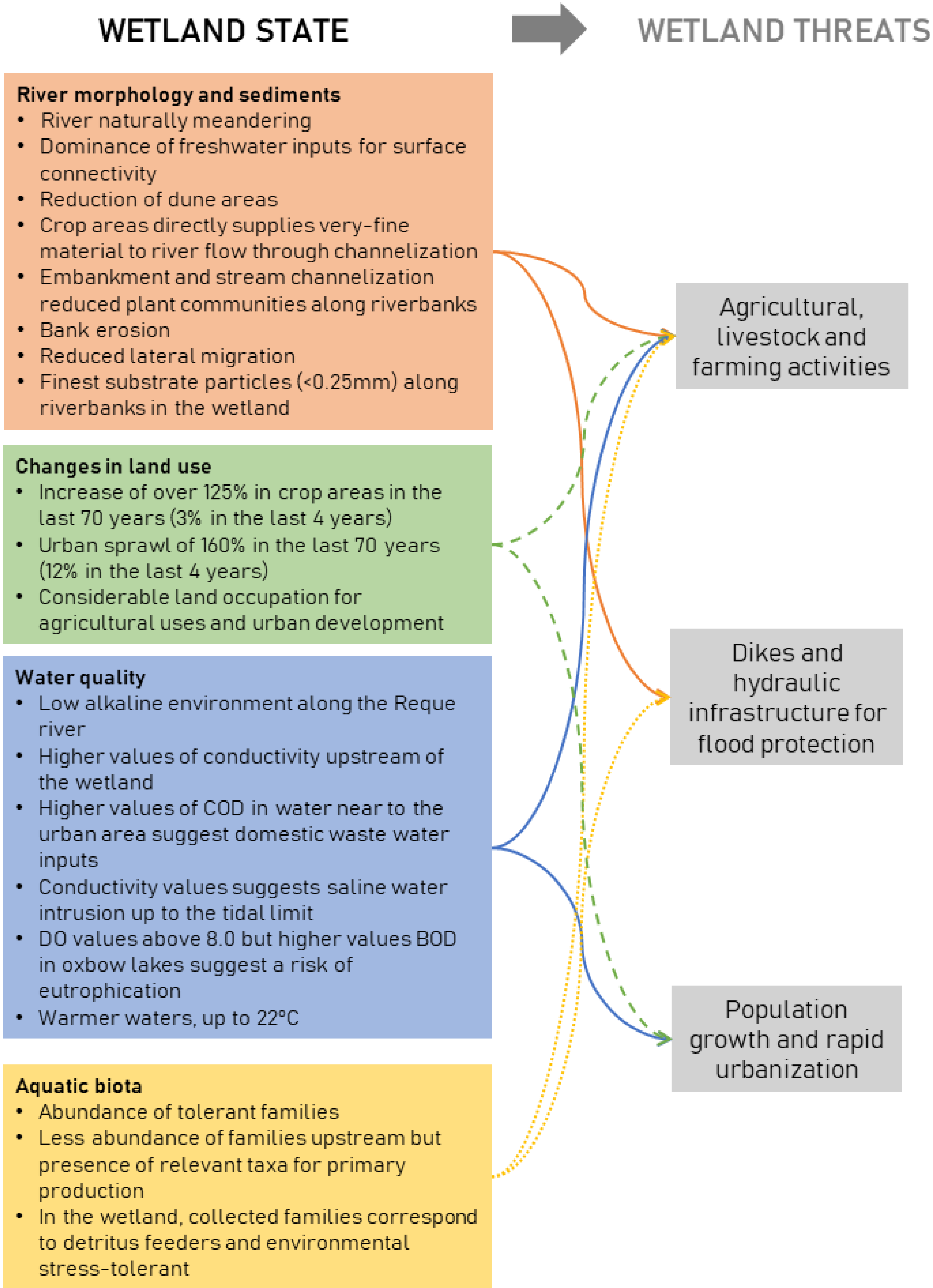

Figure 5.12 Identification of state and threats (drivers) based on the environmental characterization of the Eten wetland

Finally, the DPSIR model allowed to establish a causal linkage among drivers (threats), pressures, states, and services of the Eten wetland, resulting in a decision-making tool:

Threat 1: Agricultural, livestock, and farming activities

Pressures: Uncontrolled water harvesting, cultivation of fields and croplands, river channelization and water withdrawal

State: The results of the environmental characterization indicated that coastal dunes and the river floodplain has been heavily reduced due to changes in land use by agricultural activities. Consequently, this modified the sediment load and river morphology. Moreover, uncontrolled water harvesting demanded river channelization and the modification of riverbanks.

Impacts: Water exchange between the river flow and croplands also increased ions concentration, thus it generated water pollution and fostering the abundance of tolerant biota. These pressures resulted in the alteration of water balance, soil salinization, and disturbance of the hydrological connectivity and nutrient cycling. Affected ecosystem services included provisioning, regulating, and supporting. Based on the hydrogeomorphic classification, it is expected that these impacts could affect groundwater recharge, sediment retention, waste processing, and the biological diversity of the Eten wetland.

Threat 2: Dikes and hydraulic infrastructure for flood protection

Pressures: Construction of levees and dikes, and channel embankment

State: Results of remote sensing analysis indicated that river channeling and embankment constrained the lateral dynamics of the Reque river. When dynamics of river morphology is reduced, it causes the loss of lateral connectivity between the river and the wetland.

Impacts: Impacts on ecosystem services resulted in the alteration of water balance and the disturbance of flow regime and hydrological connectivity (possible impacts). Moreover, channel embankment can cause the capability of storm protection, thus leading to human and economic losses during flooding and extreme events. Modification in river morphology also increased the supply of very fine sediment and the velocity of river flow, thus generating bank erosion that reduced plant communities and disturbed biota and primary production population in the riverbanks. Results indicated that ecosystem values affected would be water regulation, flood control, biological diversity, and storm protection.

Threat 3: Population growth and rapid urbanization

Pressures: Waste disposal, bulldozing of marshes, land claim, and uncontrolled groundwater pumping

State: The evaluation of changes in land use and water quality indicated that the urban sprawl and rapid urbanization reduced the Eten wetland area and polluted soils and water bodies. The contamination of the Reque river and lakes within the wetland is worsening by the lack of sewage and sanitary infrastructure in the area. Uncontrolled groundwater pumping could also foster the infiltration of pollutants to the aquifer, but more measurements should be done.

Impacts: Pressures impacted the Eten wetland by reducing wetland area, plant communities, habitats, and aesthetic value. Therefore, the ecosystem services that could be affected include biological diversity; the cultural, educational, and research value; and the capability of waste processing and biomass export.

Table 5.4 shows a summary of the results obtained for the Eten wetland. All information in columns 1 to 3 were collected in the previous sections and, based on them, the expected impacts on ecosystem services (columns 4 and 5) derived from literature sources.

Table 5.4

Application of the DPSIR model to human-nature system of the Eten wetland

Threat or Driving Force (D)	Pressures (P)	State (S)	Impact 1 (I)	Impact 2 (I)		
			Ecosystem functions	Ecosystem services	Human benefits	Values
Agricultural, livestock, and farming activities	▪ Uncontrolled cultivation of fields and croplands ▪ Uncontrolled water harvesting ▪ Channeling by the edge of the river and the wetland ▪ Release of pesticides and fertilizers in soils and water ▪ Uncontrolled drilling of wells ▪ Uncontrolled water withdrawal	▪ Loss of wetland habitats ▪ Modification of sediment load and river morphology ▪ Eutrophication ▪ Drainage of agricultural wastewater that contains toxic pollutants from pesticides ▪ Reducing vegetation cover and coastal dunes ▪ Increasing nutrient runoff ▪ Decreasing of freshwater inflow ▪ Saline soils ▪ Reduction of soil recovery	▪ Reducing wildlife livelihood conditions ▪ Reducing pollution control (water purification) ▪ Disturbance of nutrient cycling ▪ Alteration of water balance ▪ Disturbance of flow regime and hydrological connectivity ▪ Soil salinization ▪ Loss of water-soluble plant nutrients	Provisioning Regulating Supporting	Ecological Hydrological	Groundwater recharge Sediment retention Waste processing Biological diversity Genetic resources
Dikes and hydraulic infrastructure for flood protection	▪ Excavation and construction of levees and dikes in the margin of wetland and along the river ▪ Channel embankment ▪ Lack of knowledge about impacts and their costs	▪ Shut off the natural floodplains from peak flows ▪ Lowering of water level in-bank flows ▪ Modification of river morphology ▪ Constrain of lateral connectivity ▪ Bank erosion	▪ Removal of the buffering effect ▪ Alteration of aquatic habitats ▪ Reducing biota and primary production population ▪ Erosion and sedimentation	Regulating Supporting	Hydrological Ecological	Water regulation Flood control Biological diversity Storm protection

Population growth and rapid urbanization	▪ Land claim ▪ Reduction of wet areas ▪ Bulldozing of marshes for the construction of housing and other buildings ▪ Sewage disposal without adequate sanitary infrastructure ▪ Municipal solid waste disposal ▪ Uncontrolled groundwater extraction	▪ Water and soil acidification ▪ Trace metal contamination ▪ Infiltration of wastewater into groundwater ▪ Lowered water table ▪ Urban effluents runoff ▪ Topographic change by eliminating vegetation ▪ Habitat loss ▪ Saline intrusion ▪ Water pollution	▪ Reducing pollution control and detoxification ability ▪ Reducing wetland extent ▪ Reducing water regulation ▪ Reducing biomass production ▪ Reducing habitats and breeding continuity ▪ Biodiversity loss ▪ Reducing educational and research opportunities ▪ Aesthetic loss	Regulation Provisioning Supporting Cultural	Ecological Hydrological Social	Biological diversity Waste processing Biomass export Cultural heritage Education and research

Chapter 6 Discussion

6.1 Geomorphic and environmental features of the Eten wetland

Results of the hydro-geomorphic and environmental characterization indicated that the Reque river plays an important role in defining the landscape of the Eten wetland. Aerial photographs illustrated the dynamism of the Reque river and its natural floodplain extension. Therefore, the meandering nature of the Reque river determined the location of agricultural lands because it transported not only water but also nutrients that fertilize soils.

In the last 70 years, the agricultural land area increased in 125% while the urban in 160%. Agricultural development increased the demand for water resources for irrigation. Because the river represents the main source of freshwater, channelization is a common practice for local farmers to redirect water for their croplands. Moreover, riverbanks are exposed to livestock. These modifications disturbed not only channel morphology but also habitats in overflow areas. Water conditions behind obstacles and riverbanks destroyed by livestock footprints (stagnation in deep pools) then offered a suitable habitat only for tolerant species associated with extreme conditions (e.g. reduced oxygen availability and warmer temperatures) such as detritus feeders. Besides, the environmental characterization indicates that urban sprawl caused the contamination and desiccation of water bodies and soil in areas near the urban areas.

The analysis using photogrammetry and GIS-tools indicated that embankment and river channelization constrained the lateral connectivity of the river, thus modifying floodplain morphology by increasing flow velocity and reducing sinuosity. While riverbanks from Reque to Ciudad Eten were prone to erosion, the region between the Ciudad Eten and the river mouth presented bank failures that led to the loss of riparian vegetation and aquatic communities. Therefore, bank erosion generated more sediment supply (mainly silt and clay) that increased turbidity.

6.2 Impacts of human activities on ecosystem services

The presence of hydraulic structures for flood protection in the Eten wetland caused the reduction of floodplain ecosystem functions such as water quality. For instance, the hydrologic connectivity within the floodplain allows the streamflow to trap sediment-associated nutrients, but in crop areas trapped material also includes agriculture-derived pollutants (Hupp et al., 2009). Also, channel constraining increase velocities, disturbs the lateral connectivity. Consequently, it might lead to the destruction of built-up structures and the reduction of the capability of storm attenuation (Hupp et al., 2009).

Benthic macroinvertebrates play an important role in supporting the food web by cycling nutrients and contributing in the productivity of higher trophic levels (Zhao et al., 2017). Riverbanks provide macroinvertebrates of ecotone habitats, but they are highly sensitive to any variability of the flow, sediment concentration, and nutrients transported. Changes in water quality were evaluated based on the type of families found and how they are distributed along the Reque river. This evaluation indicated that the presence of hydraulic structures (dikes) and agricultural activities reduced the aquatic habitats and increasing the diversity of tolerant families, thus disturbing the biological diversity. Moreover, urbanization in wetlands tends to generate negative impacts of aquatic biota, as indicated in Novoa et al. (2020) and Vizcardo & Gil-Kodaka (2015).

Results also evidenced that changes in land use disturbed the natural landscape and geomorphology, thus affecting supporting and regulation services such as groundwater recharge and water regulation. Additionally, agricultural activities caused salinization of soils and desiccation of lakes due to the disconnection of the river with the floodplain.

Based on municipality records, these problems are currently exacerbated by the lack of regulations, sanitation facilities, and culture of water.

6.3 Applicability for sustainable ecosystem management and conservation plans

Nowadays, Peruvian most coastal wetlands face similar issues (e.g. agricultural and urban development); however, the ecosystem response in each environment may be different. Therefore, understanding the natural processes and functions of a coastal wetland allows the valuation of ecosystem services, and its vulnerability and capability to respond.

First, it is important to characterize the type of coastal wetland because it determines the geomorphic settings that describe the landscape. The hydro-geomorphic characterization demonstrated the role of the Reque river in determining riverine communities along the alluvial corridor and also fertilizing the floodplain due to the lateral connectivity with the Eten wetland. For instance, another type of coastal wetlands includes depressional (*Pantanos de Villa*) and lacustrine (*Albufera de Medio Mundo*) wetlands which might be influenced by other components such as precipitation and groundwater, thus the geomorphic features and ecosystem functions will be different. Once described the type and features, potential ecosystem services of a coastal wetland can be defined. For example, depressional wetlands such as swamps and peatlands provide the service of carbon sequestration and storage. Second, an environmental characterization assesses the current status of the components of a coastal wetland. By evaluating the changes in the geomorphic features (defined in the previous step); the quality of water, soils, air, plant, and animal communities; and landscape over time, it is possible to define the main threats and pressures through a cause and effect relationship. Third, the DSPIR framework provides a wide overview of how threats and pressures can disturb the ecosystem services and the impacts generated. Based on this information, decision-makers can respond by prioritizing conservation projects, establishing regulations to reduce the pressures, and other actions to mitigate impacts. Moreover, the framework can be applied as many times as required to evaluate the implementation of actions and responses.

Chapter 7 Conclusions

This study describes a methodology to assess the impacts on ecosystem services based on the understanding of geomorphic features and current status of a Peruvian coastal wetland. By combining remote sensing applications and field surveys, this study presents an approach to improve coastal wetlands management through the identification of the most affected functions in terms of geomorphological changes and environmental parameters.

Considering the very limited local data, it was challenging to characterize the landscape features only using available literature data and open-source GIS tools and products. It can be improved by acquiring high-resolution multitemporal imagery and field surveys to map the full-extension of the wetland. For instance, land use and land cover change detection analysis can support the delimitation of the Eten wetland and the status of other geomorphic settings such as shoreline variation and river-ocean connectivity. Furthermore, the environmental characterization consisted of spatial analysis that identified the main threats and pressures in the Eten wetland. However, the accuracy of results should be complemented with more field evidence and spatio-temporal monitoring. The application of a cause-effect model DSPIR linked the analysis of the Eten wetland conditions with the impacts on ecosystem services. This information is addressed to enhance decision-making in terms of conservation and sustainability.

The proposed methodology aims to be a tool to identify the most effective responses to reduce environmental impacts in ecosystem services, with a scope that this is a cyclic process that needs to be reinforced over time. Applied to a Peruvian coastal wetland with few field data, this study provides a rapid diagnosis of ecosystem status and potential impacts on services. Moreover, the environmental characterization applied in the methodology is not limited to the areas described above, but also nutrient analysis, soil quality, water balance, sediment transport, among other disciplines. This versatile methodology, however, can be improved by increasing the time, area of study, and field data collecting. On the other hand, results are also presented in plain language for non-technical decision-makers, which helps them to easily evaluate responses and actions.

The results of this work indicates that agricultural and urban development generates critical pressures on the ecosystem services of the Eten wetland. Uncontrolled water abstractions and overbank modifications can lead to the loss of the wetland area and its ecological value (biological diversity and waste processing). Therefore, further research should be addressed to establish better assessment, monitoring and water management practices to reduce both environmental and economic impacts. Moreover, management strategies in terms of land use and waste water treatment must be improved with a sufficient capacity to cover population demand.

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Appendix

Appendix A. Aerial photography of the Eten wetland in 1949

Aerial photographs acquired from the Servicio Aerofotográfico Nacional.

Appendix B. Sediment grain size distribution in the Eten wetland

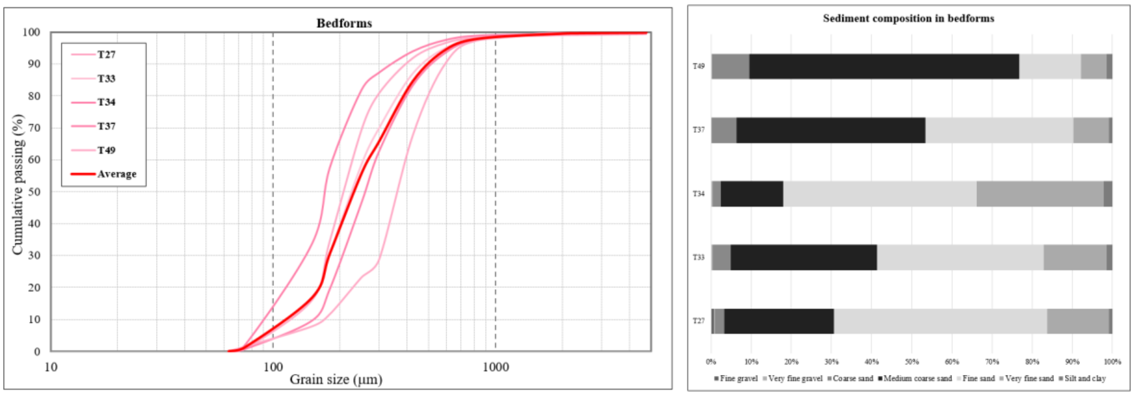

Figure B.1 Grain size distribution curve and sediment composition in bedforms

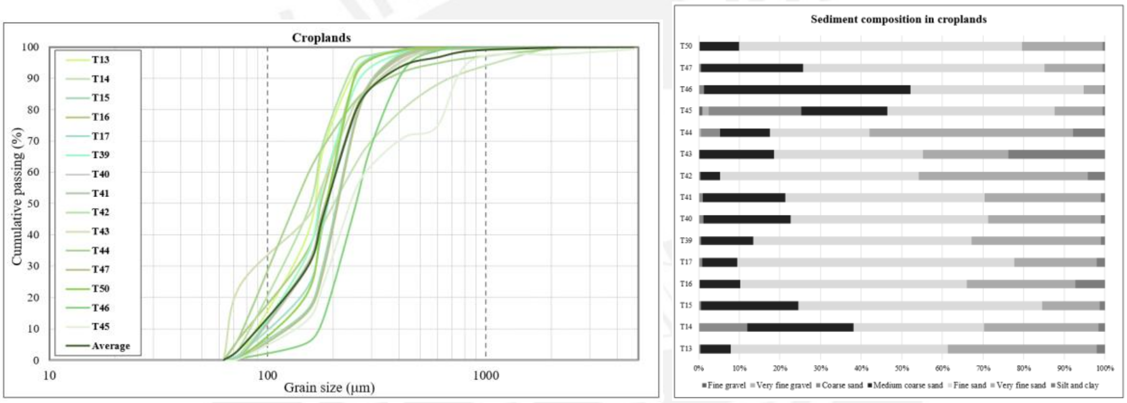

Figure B.2 Grain size distribution curve and sediment composition in croplands

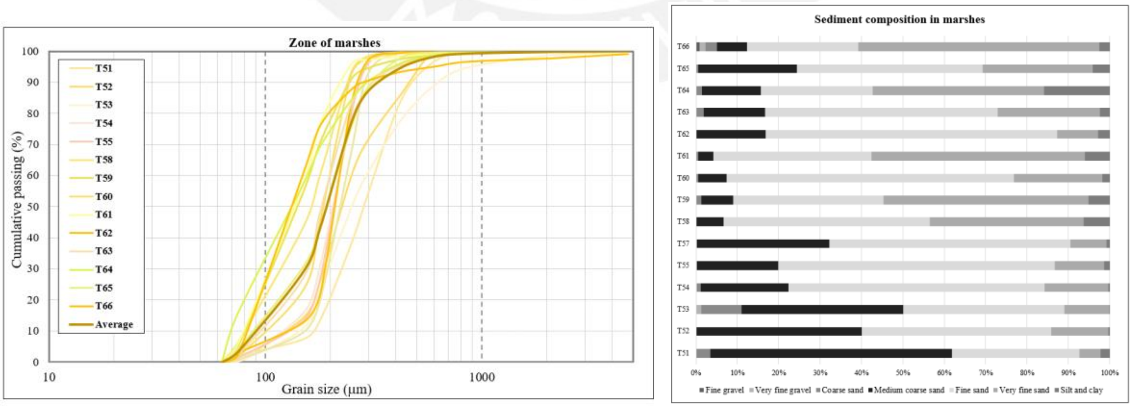

Figure B.3 Grain size distribution curve and sediment composition in marshes

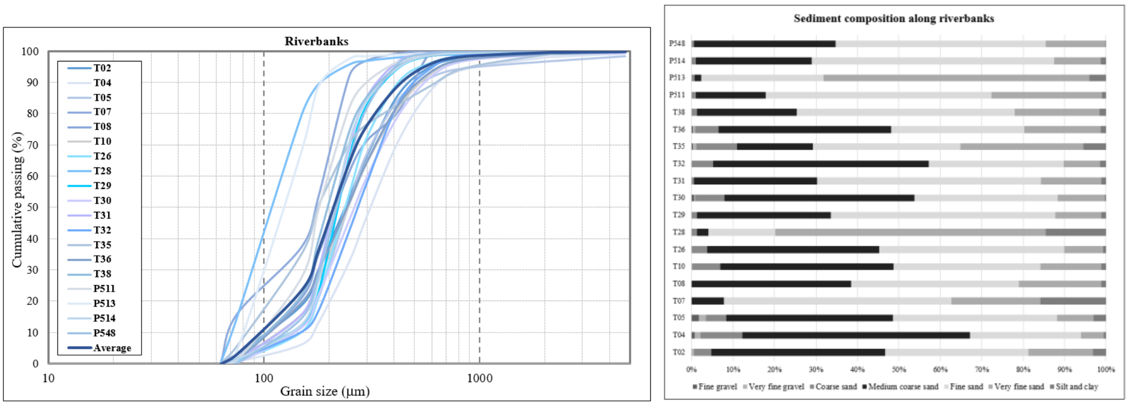

Figure B.4 Grain size distribution curve and sediment composition along riverbanks

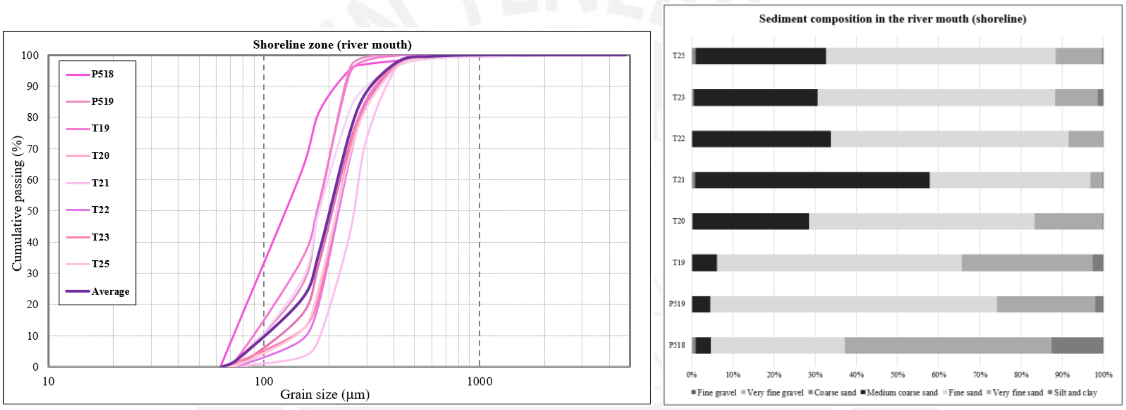

Figure B.5 Grain size distribution curve and sediment composition in the river mouth (shoreline)