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Soil Liquefaction Hazards and Ecological Impacts in Coastal Wetlands of the Pisco River, Peru

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Abstract. Coastal wetlands located in seismic regions can be highly vulnerable to soil liquefaction, a phenomenon where saturated, loosely compacted soils temporarily lose strength during earthquakes. This study investigates the relationship between soil liquefaction and the dynamics of coastal wetlands along the left bank of the Pisco River in Peru, a region affected by the 2007 Pisco earthquake. Through geotechnical field tests, satellite image analysis, and local interviews, we identified that wetlands and their adjacent areas—often with shallow groundwater and sandy soils—present high susceptibility to liquefaction. Affected wetlands showed both negative impacts, such as ground subsidence and vegetation loss, and in some cases, post-seismic ecological recovery due to groundwater rise. The results confirm that even degraded or filled wetlands retain subsurface characteristics prone to liquefaction, extending risk zones up to approximately 200 meters beyond current water boundaries. These findings highlight the dual role of wetlands as both vulnerable ecosystems and natural indicators of geotechnical risk. Future research should focus on integrating wetland conservation into seismic risk management and land-use planning. Recognizing the geotechnical memory of these ecosystems is key to avoiding infrastructure damage and promoting more resilient coastal development in earthquake-prone areas.

1 Introduction

Coastal wetlands—including mangroves, marshes, lagoons, estuaries, oases, swamps, and deltas—are habitats formed in water-saturated or inundated terrain along coastal zones. These ecosystems are critical for sustaining a wide range of plant and animal species and provide numerous ecosystem services, such as the supply of fiber, fuel, food, freshwater, and opportunities for recreation and ecotourism. Importantly, they also play a regulatory role in mitigating natural hazards by functioning as protective barriers against tsunamis and as buffers that reduce the impacts of flooding (MINAM, 2019; Falcón, 2010). Despite these multiple benefits, many of these ecosystems have been severely reduced or lost due to anthropogenic pressures, including land reclamation, drainage, vegetation burning, and pollution, aimed at converting them into urban, agricultural, or other land uses incompatible with their ecological function. As a result, their degradation remains an ongoing and critical concern (Verhoeven and Setter, 2009; ANA, 2018; RAMSAR, 2016).

Beyond anthropogenic disturbances, coastal wetlands are also susceptible to natural phenomena such as earthquakes, whose ground effects—most notably soil liquefaction—can profoundly alter their structural integrity and ecological functionality. Soil liquefaction is a geotechnical process in which saturated, loose, and often fine-grained soils experience a buildup of excess pore-water pressure under cyclic loading, typically induced by seismic shaking. As effective stress decreases toward zero, these soils undergo a sudden loss of shear strength and stiffness, leading to a temporary fluid-like response. This behavior is commonly expressed at the ground surface through sand and water ejecta, differential settlements, ground fissuring, lateral spreading, and related manifestations (Idriss and Boulanger, 2008; INGEOMINAS, 2003). Such processes are particularly critical in seismically active settings characterized by recent alluvial or deltaic deposits, shallow water tables, and unconsolidated fills, conditions frequently found in the vicinity of streams, rivers, and coastal wetlands (Lees et al., 2015; Orense, 2011).

At the international level, recent scientific studies have examined the relationship between soil liquefaction and wetlands; however, research specifically addressing this topic remains limited. Notable investigations have been conducted in certain countries. In New Zealand, for instance, the 2010 and 2011 Canterbury earthquakes prompted extensive studies of liquefaction in Christchurch, a city built on former wetlands and alluvial soils, where Orense (2011) documented that liquefaction-induced damage was concentrated in areas such as abandoned river channels, meander scars, wetlands, and ponds. Similarly, the 1964 Niigata earthquake in Japan represents one of the most extensively studied cases of liquefaction, as it affected highly saturated terrains analogous to wetlands and spurred numerous investigations into the susceptibility of different soil types to liquefaction in waterlogged environments. The observed damage confirmed that geology plays a fundamental role in controlling liquefaction behavior and associated ground failures. Furthermore, factors such as tectonic setting, depositional and reworking conditions, and anthropogenic modifications contributed to creating the conditions for the dramatic liquefaction effects observed (Kayen, 2024).

In Cuba, studies conducted in the city of Caimanera—underlain by swamp sediments composed of plastic sandy clays and fine clayey sands with low organic content and groundwater levels ranging from 0.5 to 3 m—enabled the evaluation of geotechnical conditions through measurements of liquid limit, plasticity index, liquidity index, and fines content. The results, which showed limited variability in these parameters, allowed these soils to be classified as susceptible to liquefaction (Fernández et al., 2017). In Mexico City, built on what was once a shallow lake situated in the lowest part of a volcanic basin, the subsurface consists of alternating strata of sand and sandy silt interbedded with lacustrine clay layers and volcanic deposits. These characteristics exert a strong influence on the mechanical properties of the soils and their seismic response, including susceptibility to liquefaction, subsidence, and differential settlement (Ovando-Shelley et al., 2007; Instituto de Ingeniería de la UNAM, 2020). In Washington State (USA), a study on liquefaction hazards highlighted the critical role of wetlands in influencing soil susceptibility in the Ocean Shores and Westport peninsulas. Although the peat present in these wetlands was itself non-liquefiable, it was prone to earthquake-induced deformation and settlement due to underlying liquefiable sediments.

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The study found that 42% of the area was covered by wetlands, indicating a shallow water table that heightened the risk of liquefaction in unconsolidated interdunal sands. Hazard mapping further revealed that artificial fill deposits, such as those in Westhaven Cove, are highly vulnerable (Slaughter et al., 2014). Similarly, Kusler (2009) reported that in coastal cities such as San Francisco, Oakland, Charleston, and Boston, the infilling of wetlands exacerbated liquefaction and amplified seismic wave propagation, producing secondary hazards such as flooding and erosion by obstructing natural water flows.

In South America, Chile and Peru exhibit the highest number of recorded soil liquefaction events, primarily due to their intense seismic activity. Both countries lie along the convergent boundary between the Nazca and South American plates, where subduction generates large-magnitude earthquakes capable of inducing soil liquefaction (Alva & Ortiz, 2020; SERNAGEOMIN, 2010). Liquefaction susceptibility in these regions is largely controlled by the presence of alluvial deposits and loose sands, particularly in coastal zones and fluvial valleys. In such environments, recent sediments combined with high groundwater saturation favor the loss of soil strength during seismic events, resulting in ground deformation and structural damage (González Fuentealba, 2017; Alva, 2006). Differences in the occurrence and effects of liquefaction between Chile and Peru are linked to variations in soil geology, groundwater levels, and site conditions. In Peru, liquefaction typically manifests in a localized manner, mainly in fluvial valleys and coastal areas underlain by unconsolidated soils. In contrast, in Chile, higher groundwater saturation promotes more widespread liquefaction effects (SERNAGEOMIN, 2010). Furthermore, while ground uplift is a common manifestation in Chile, subsidence and differential settlement are more prevalent in Peru (Alva & Ortiz, 2020; González Fuentealba, 2017).

In Chile, specific studies have examined the relationship between soil liquefaction and coastal wetlands. The National Geology and Mining Service (SERNAGEOMIN) has produced liquefaction hazard maps that delineate areas of highest susceptibility across the country. Several authors have further linked liquefaction to the presence or disappearance of wetlands. For example, Alfaro (2013) reported that liquefaction commonly occurred in low-compaction soils where lakes, lagoons, and wetlands had previously existed, while Falcón (2010) identified its occurrence in sandy or silty soils with shallow groundwater tables, particularly in former deltas, riverbanks, estuaries, and lagoons, as well as in urban areas developed over infilled wetlands, where severe damage to infrastructure was documented. More recently, Lagos et al. (2019) argued that natural events such as earthquakes and tsunamis can also play a critical role in reestablishing wetland dynamics, citing the example of the Malaquito River estuary, where the ecosystem demonstrated remarkable resilience, recovering within just four months after a seismic event.

In the Peruvian context, studies addressing soil liquefaction in coastal wetlands are scarce and generally gain attention only in the aftermath of seismic events, rather than being incorporated into preventive or prospective approaches. This contrasts with the international literature, where coastal wetlands are preemptively recognized as areas of high susceptibility to liquefaction. The absence of an integrated framework that connects geotechnical, ecological, and risk management perspectives has limited the understanding of how coastal wetlands respond to seismic disturbances.

Nevertheless, given that many of these ecosystems in Peru develop on alluvial or highly saturated soils, it is pertinent to regard their vulnerability to liquefaction as a relevant working hypothesis, particularly in a context marked by intense seismic activity

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resulting from the convergence of the Nazca and South American plates. This tectonic interaction produces large-magnitude earthquakes capable of triggering soil liquefaction processes (Tavera, 2014; CENEPRED, 2020). Previous studies have documented the occurrence of this phenomenon in several coastal regions, such as during the 1970 Chimbote earthquake and seismic events in the northeastern region in 1990 and 1991 (Alva, 2020). These investigations have delineated zones of high susceptibility and supported the development of hazard maps; however, the relationship between liquefaction and wetlands remains an understudied field.

A representative case is the Pisco River basin, where wetlands are located in depressed areas on terraces and gently undulating alluvial plains, with groundwater levels typically less than 2 m deep, favoring surface emergence (Instituto Geológico Minero y Metalúrgico, 1981; Baez et al., 2022). Baez et al. (2023) identified zones of high liquefaction susceptibility in areas adjacent to the principal coastal wetlands on the left bank of the Pisco River. Hazard maps generated in that study revealed a spatial correspondence between these vulnerable zones and the distribution of wetlands, allowing a preliminary association to be established between the presence of these ecosystems and the liquefaction effects observed during the August 15, 2007 earthquake. On that date, a magnitude 7.0 ML (7.9 Mw) event, known as the "Pisco earthquake" occurred with its epicenter 60 km west of the city of Pisco at a depth of 40 km, lasting approximately 210 seconds (IGP, 2007; Tavera, 2007). This event reaffirmed the recurrence of liquefaction processes in the region, manifested through subsidence, lateral spreading, and sand–water ejecta, particularly in areas underlain by saturated soils (Zavala et al., 2008; CISMID, 2012). The phenomenon severely affected urban areas and transportation infrastructure, as well as wetland-adjacent zones, including those modified by anthropogenic infilling (Tavera et al., 2007; Olcese & Zegarra, 2007).

The 2007 earthquake highlighted clear differences in liquefaction susceptibility between the two banks of the Pisco River. The left bank, underlain by sandy and silty-sand soils, experienced the greatest impacts due to its high vulnerability to liquefaction. In contrast, wetlands on the right bank, situated on alluvial deposits with higher proportions of silty claystones and diatomaceous mudstones of the Pisco Formation, exhibited lower susceptibility, a condition attributed to the greater plasticity of these soils (Lees et al., 2015; CISMID, 2012). Consequently, liquefaction events on this bank were more localized and less intense (Carrillo, 2007).

The Pisco Valley aquifer is fan-shaped and unconfined, consisting primarily of Quaternary alluvial deposits. On the left bank of the river, coarse gravels and sands predominate, imparting high permeability that facilitates groundwater storage and flow, thereby supporting the persistence of wetlands. Groundwater movement generally follows a southeast–northwest direction (Instituto Nacional de Recursos Naturales et al., 2006; Autoridad Nacional del Agua, 2018; Baez et al., 2022). However, the soils on this bank, composed mainly of sands and sandy silts, exhibit low cohesion and high saturation, making them highly susceptible to liquefaction during large-magnitude earthquakes (INGEMMET, 1981; Bernal & Gómez, 2016).

In the coastal wetlands of Pisco, adjacent areas exhibit groundwater levels ranging from 0 to 3 m in depth, with soils composed primarily of low-density sands and silty sands, varying from loose to very loose (ANA, 2020; INDECI, 2008). These geotechnical characteristics render the wetlands highly susceptible to soil liquefaction during large-magnitude seismic events, exposing them to processes such as subsidence, uplift, fissuring, and lateral displacement, all of which disrupt the ecological

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balance of the region. While liquefaction has been more extensively studied in urban settings due to its impacts on infrastructure (SERNAGEOMIN, 2010; INDECI, 2008), research specifically addressing its influence on wetlands remains limited. Nevertheless, these ecosystems play a critical role in environmental regulation and may serve as natural early-warning indicators for disaster prevention (Kusler, 2009; RAMSAR, 2016).

The objective of this study is to analyze the impact of soil liquefaction on the coastal wetlands of Pisco by identifying ecosystem changes and assessing their capacity for recovery following large-magnitude seismic events. The case study focuses on wetlands located on the left bank of the Pisco River, a region characterized by high seismic activity, documented evidence of liquefaction, and geotechnical and hydrogeological conditions indicating high susceptibility to this phenomenon. To achieve this objective: (a) liquefaction potential in areas adjacent to the wetlands was evaluated using Light Dynamic Penetration (DPL) tests and test-pit excavations; (b) an annual time-series analysis of wetland-associated vegetation was conducted through remote sensing techniques and the calculation of the Normalized Difference Vegetation Index (NDVI) to detect changes following the 2007 earthquake; and (c) qualitative information on liquefaction effects in the wetlands and surrounding areas was collected through interviews with local residents who experienced the 2007 event, in order to validate the quantitative data obtained.

2 Study area and methodology

2.1 Study area

The study area is located in the central region of Peru, within the Department of Ica, Province of Pisco, and encompasses the districts of Pisco, San Andrés, Túpac Amaru, and Humay. Geographically, it lies in the central portion of the Pacific watershed, specifically within the Pisco River basin. This zone includes a series of coastal wetlands situated on the left bank of the river, developed on plains and terraces composed of Holocene continental alluvial deposits, at elevations ranging from 0 to 250 m a.s.l. (Fig. 1). From a geological perspective, the watersheds of Peru’s central coast exhibit distinctive geomorphological features: they originate in the Andes, are elongated in form, and are characterized by deep valleys and steep gradients. In their lower reaches, slopes decrease abruptly, reducing surface runoff velocity and enhancing the deposition of alluvial sediments. This geomorphological dynamic has facilitated the formation of extensive plains, which constitute the physical setting for the coastal wetlands of the Pisco River basin (INRENA et al., 2006; INGEMMET, 1981).

From the set of wetlands located on the left bank of the Pisco River, six were selected for detailed analysis: H-01, H-02, H-03, H-04, H-05, and H-06. These correspond, respectively, to the wetlands of Pisco Playa Sur, Pampa Ocas, Laguna La Palma, Costa Rica, Laguna Morón, and the wetland adjacent to the Bernales sector—locally known as *Los Patitos* (Baez et al., 2022). Their local names are widely recognized by both the surrounding communities and the National Water Authority (ANA, 2018).

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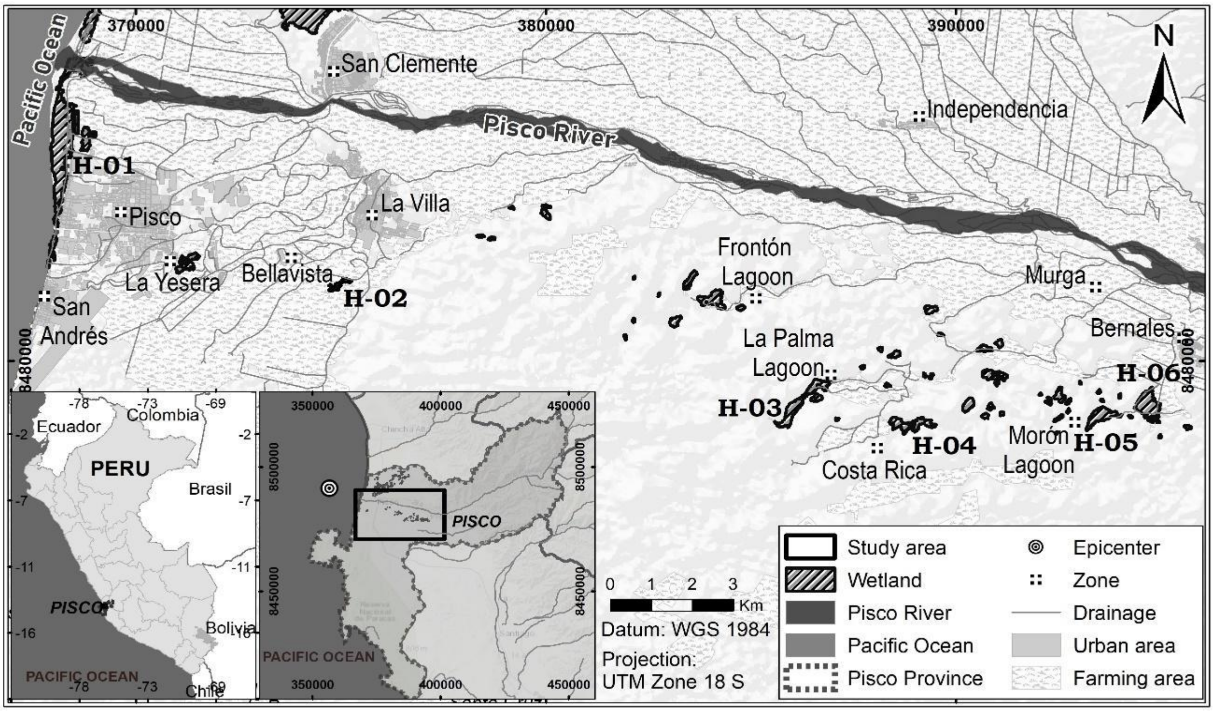

Figure 1: Location map of wetlands situated on the left bank of the Pisco River in the Peruvian Central Coast.

2.2 Methods and field study instruments

To identify areas susceptible to soil liquefaction adjacent to wetlands, a first field campaign was conducted in February 2023 (Baez et al., 2023). During this campaign, sectors previously reported to have exhibited liquefaction features during the 2007 Pisco earthquake—such as ground subsidence, fissuring, and sand–water ejecta—were surveyed. In several of these sites, clear traces of the event remain, including subsidence and differential settlement affecting infrastructure (see Fig. 2). Based on the findings of this reconnaissance, the distribution of geotechnical testing sites was proposed. A second field campaign, carried out in May 2023, included twenty-six (26) Light Dynamic Penetration (DPL) tests. This method employs a metallic apparatus composed of rods and a hammer released by gravity from a height of 0.50 m onto a driving head. The number of blows required for each 10 cm increment of soil penetration is recorded, allowing for the estimation of soil resistance in kg/cm².

In addition, five (05) test pits were excavated with a backhoe to an average depth of 3 m, which allowed for the description of soil composition, in situ density testing, and the collection of samples for laboratory analysis. To calculate liquefaction potential, the simplified method of Seed et al. (1985) was applied, based on Standard Penetration Test (SPT) data. The blow counts obtained from the Light Dynamic Penetration (DPL) tests (Ndpl) were correlated with equivalent SPT blow counts (Nspt) to derive corrected values of internal friction angle and cohesion. These parameters were then used to generate soil liquefaction potential maps for the areas surrounding the studied wetlands (Baez et al., 2023), which serve as the foundation for the analysis presented in this study.

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To complement and validate the effects of soil liquefaction during the 2007 earthquake—and its potential influence on wetland surface variation, whether positive or negative—a temporal vegetation analysis was conducted for the period 2000–2014 across six wetlands within the study area. This analysis employed remote sensing techniques using Landsat satellite imagery (30 m spatial resolution), processed in Python through the Google Earth Engine (GEE) platform, thereby optimizing the temporal calculation of the Normalized Difference Vegetation Index (NDVI). The study focused on five wetlands (H2–H6, Fig. 1) and was supplemented with data from wetland H1, previously analyzed (IGP, 2022) using the same methodology, which served as a reference for validation. Linear time-series plots of the Soil-Adjusted Vegetation Index (SAVI) were generated for different intervals, with annual averages considered to identify trends and fluctuations in vegetation cover. These results were analyzed and interpreted in relation to the timing of the seismic event, enabling a more detailed understanding of post-seismic dynamics in the studied wetlands.

Finally, as a confirmatory study of the effects of soil liquefaction on the coastal wetlands of Pisco and their surrounding areas, a third field campaign was conducted in March 2024. During this campaign, surveys and semi-structured interviews were administered to residents of the Province of Pisco who live in areas adjacent to coastal wetlands and who witnessed the 2007 earthquake. A total of 24 individuals were interviewed: 7 women and 17 men, ranging in age from 34 to 88 years, whose properties—either dwellings or agricultural lands—are located within 100 m of existing, degraded, or disappeared wetlands. To ensure anonymity, participants were coded by gender and age; further details are provided in supplementary material S1.1. The interviews were guided by open-ended questions structured into three thematic sections: (I) seismic events and their effects on the ground, including subsidence, sand–water ejecta, fissuring, flooding, drought, uplift, and lateral spreading; (II) the history of the local ecosystem, focusing on the prior existence of wetlands and changes in their extent after the earthquake; and (III) anthropogenic transformation and wetland use, addressing whether wetlands were drained, burned, infilled, or urbanized, as well as any recovery measures implemented. The semi-structured interview guide is provided in supplementary material section S1.2, while participant responses, selected testimonies, and the qualitative analysis are available in supplementary material section S1.3, ensuring methodological transparency and replicability of the study.

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Figure 2: Houses affected by soil liquefaction during the 2007 Pisco earthquake: a) Abandoned house, showing settlement with 30 cm of subsidence; located along the extension of Av. Manuel Pardo, near the Pisco Playa – Boca de Río sector, adjacent to wetland H-01. Subsidence of 1 m with walls exhibiting variable inclination. b) Settled house with 1 m of subsidence and forward tilting, now uninhabitable, where *totora* (bulrush) has grown; located on Alfonso Ugarte Street, Pisco Playa Sur, within the extended area of wetland H-01. (Baez et al., 2023)

3 Geological, hydrogeological and seismotectonic settings

As noted in the introduction, the coastal wetlands of Pisco are situated within a geologically, hydrogeologically, and seismotectonically complex setting that directly influences their formation and dynamics. The interaction of these factors is critical to role in the evolution of the Pisco wetlands, underscoring their vulnerability to natural processes such as soil liquefaction during seismic events.

From a seismotectonic perspective, the region is shaped by the subduction of the Nazca Plate beneath the South American Plate, which gives rise to major tectonic structures such as the Pisco Flexure, characterized by reverse microfaults and eastward-dipping folds (Tavera et al., 2007; Macharé, 1992). These tectonic processes have contributed to the development of

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structural depressions and the reconfiguration of the landscape, thereby creating geomorphological conditions favorable for water accumulation. Active faults and associated seismic events further heighten the risk of soil liquefaction, a phenomenon that can compromise wetland stability by inducing a temporary loss of soil strength, facilitating sediment mobilization, and disrupting aquifer structure (Seed & Idriss, 1982).

From a geological perspective (see Fig. 3 for the distribution of geomorphological units and geological features), the wetlands along the left margin of the Pisco River overlie Quaternary alluvial deposits composed of terraces and gently undulating floodplains. Their aquifer system is predominantly permeable, consisting mainly of gravels and coarse sands that facilitate infiltration and groundwater storage. These conditions sustain a shallow water table, a critical factor for the persistence of the wetlands (ANA, 2018; Hernández et al., 2013). Beneath these deposits lies the Pisco Formation, composed of diatomites and diatomaceous shales, which acts as an impermeable substrate that enhances groundwater retention (INGEMMET, 1981; Báez et al., 2022).

In hydrogeological terms, the Pisco aquifer is an unconfined system shaped by the dynamics of the Pisco River and its interaction with surrounding alluvial deposits. The high permeability of surficial materials enables continuous recharge, while underlying impermeable layers limit water loss, thereby maintaining saturation levels favorable for wetland preservation (Custodio & Llamas, 1983). In many areas, the water table lies at depths of less than 2 meters, facilitating groundwater discharge that directly sustains these ecosystems. Additionally, the presence of dunes and eolian mantles acts as a natural barrier, protecting the wetlands from both marine intrusion and anthropogenic disturbance (Monge et al., 2015). Recent studies conducted by the IGP (2022) delineated the groundwater flow direction within the Pisco Valley aquifer, as illustrated in Fig. 3.

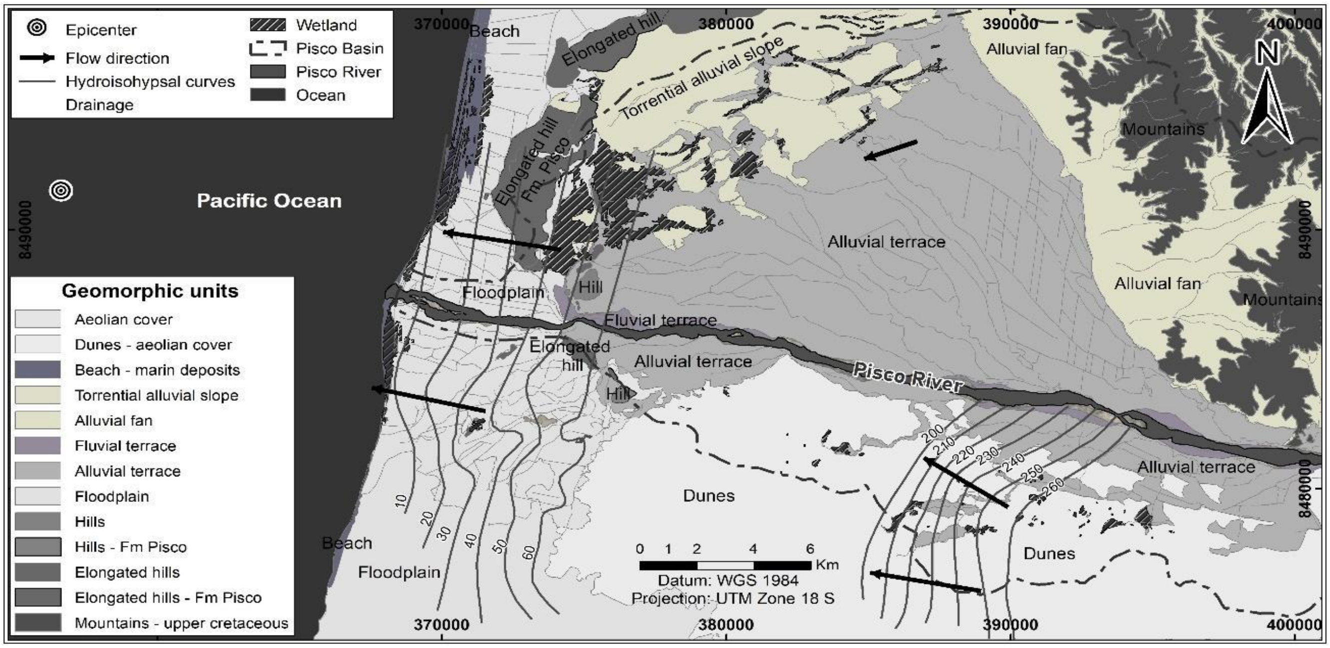

Figure 3. Geological-geomorphological and groundwater flow direction map of the Pisco drainage basin. Geomorphological units and groundwater flow direction map of the Pisco drainage basin, related to the wetlands under study. The epicenter of the 2007 Pisco earthquake is also indicated. Modified from Baez et al. (2022).

4 Results

4.1 Soil liquefaction potential and the relationship with its effects

The liquefaction potential of soils in wetlands along the left margin of the Pisco River was evaluated in areas near sites where liquefaction was previously documented during the 2007 earthquake. These events produced ground subsidence and cracking, affecting both urban and rural zones indiscriminately (Baez et al., 2023; CISMID, 2012). Results indicate that the studied wetlands—including those degraded or already lost—as well as their adjacent areas, exhibit a high susceptibility to soil liquefaction.

In the case of the Pisco wetlands, their high susceptibility to liquefaction arises from their granulometric characteristics, the presence of shallow water tables, and the region's frequent seismic activity. Liquefaction effects not only compromise the physical stability of these ecosystems but also disrupt their hydrological dynamics and biodiversity, undermining both their sustainability and their capacity to provide ecosystem services. Moreover, anthropogenic interventions—such as landfilling and urbanization—further increase liquefaction risk by altering soil properties and reducing the wetlands' capacity for water storage and regulation (Baez et al., 2022).

Hazard zoning maps reveal a clear pattern: areas with a Factor of Safety (F.S.) < 1, indicating susceptibility to liquefaction, are concentrated along the margins of existing wetlands and in terrains that previously hosted wetlands, in some cases

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extending up to approximately 200 m beyond their boundaries. This radius of influence confirms that the hazard is not confined to the wetland body itself but also encompasses the surrounding alluvial plain, along with its infrastructure and settlements. Sectors such as Bellavista and Bernales exemplify this condition, as much of their alluvial plain—likely associated with former wetlands—remains highly vulnerable.

Figure 4 illustrates this pattern in wetlands H-01 and H-02, where zones with F.S. < 1 are concentrated along the margins. In H-01, these zones extend markedly up to 200 m eastward, while in H-02 they encompass adjacent areas that were formerly wetlands and experienced liquefaction during the 2007 earthquake, thereby geographically delineating the hazard and confirming its impact beyond the lagoon body. Figure 5 reinforces this trend for wetlands H-03, H-04, H-05, and H-06, showing that susceptibility is accentuated along the margins and in areas previously filled or urbanized; in H-06, a pronounced risk zone extends eastward, consistent with the results of this study and with information obtained from local interviews. Taken together, the evidence confirms that anthropogenic interventions have altered soil properties, increased liquefaction potential, and disrupted the hydrological dynamics of these ecosystems.

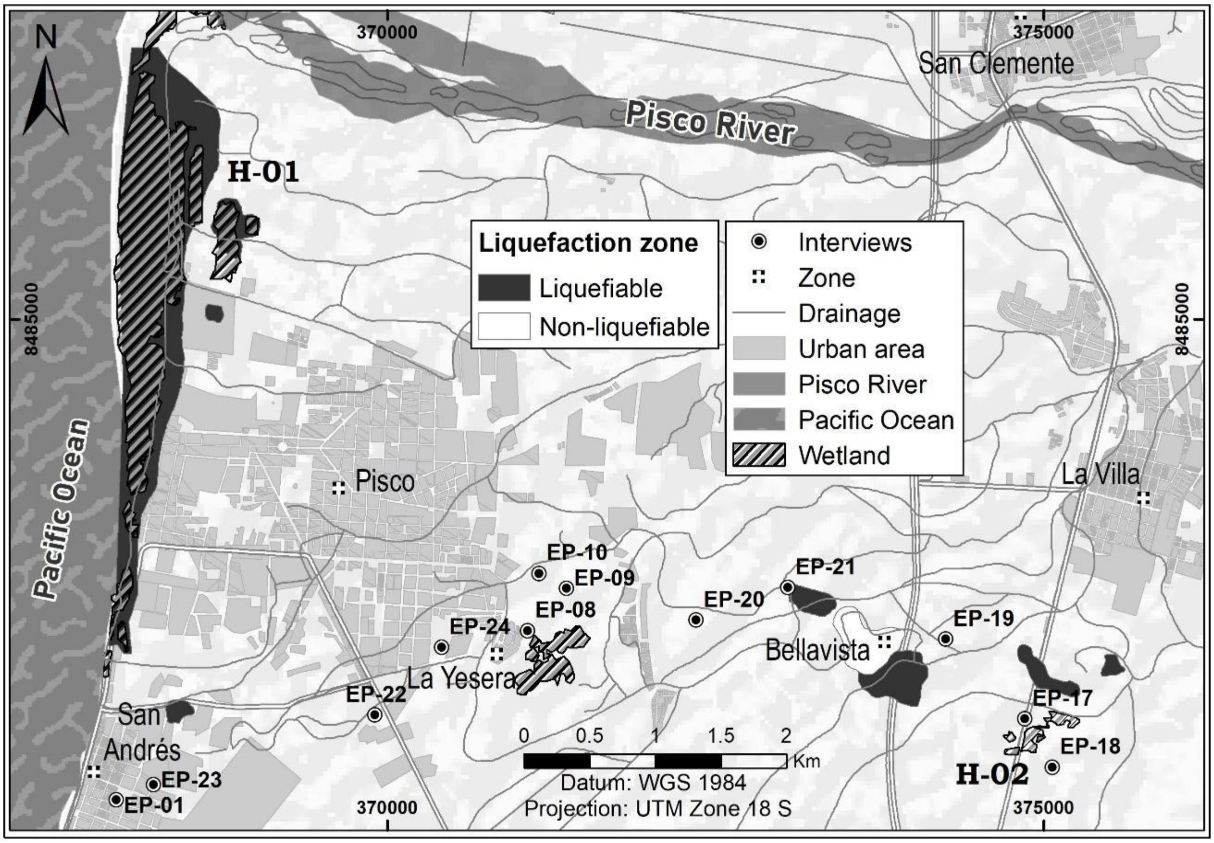

Figure 4. Liquefaction Potential Map for the Pisco Playa Sur and Bellavista (Pampa Ocas) area, associated with wetlands H-01 and H-02. Interviews conducted in March 2024 are also indicated. Based on Baez et al. (2023).

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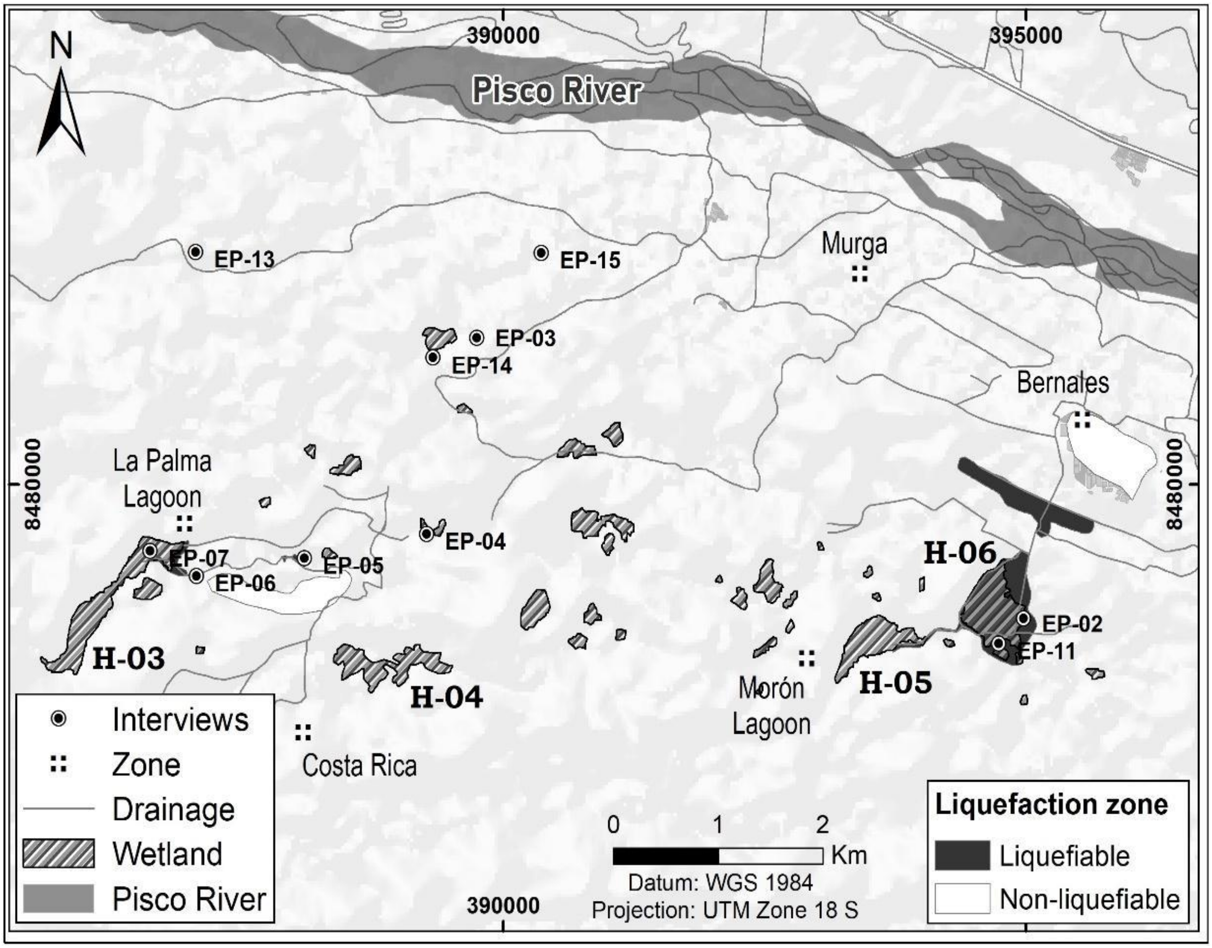

Figure 5. Liquefaction Potential Map for the district of Humay, covering the Laguna La Palma, Costa Rica, Laguna Morón, and Bernales areas, associated with wetlands H-03, H-04, H-05, and H-06. Interviews conducted in March 2024 are also indicated. Based on Baez et al. (2023).

4.2 Temporal Trends and Attribution Analysis of Vegetation

Six sectors were analyzed, encompassing wetlands H-01, H-02, H-03, H-04, H-05, and H-06, located in the areas of Bellavista (Pampa Ocas), La Palma Lagoon, Costa Rica, Morón Lagoon, and Bernales (Los Patitos), respectively, as shown in Fig. 1. The temporal analysis focused on the central portion of each wetland and included a 100-meter buffer around their perimeters in order to assess whether changes had occurred within the wetland boundaries and to evaluate potential links to the 2007 Pisco earthquake. The study period extended from 2000 to 2014.

Normalized Difference Vegetation Index (NDVI) values reveal a significant anomaly following the 2007 Pisco earthquake, indicating an abrupt alteration in vegetation conditions. This response varied spatially across the different wetlands. In wetland H-02, a decline in vegetation health was observed, likely associated with soil desiccation and subsequent degradation. In

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contrast, wetlands H-01, H-03, H-04, H-05, and H-06 exhibited an increase in vegetation cover, although the increase in H-04 was comparatively modest. NDVI calculation details are provided in supplementary material section S2.

The seismic event had a predominantly positive impact on the coastal wetlands of Pisco, with the exception of H-02. Soil liquefaction processes—such as sudden flooding, ground fissuring, and subsidence—likely contributed to a rise in the water table, creating wetter conditions that promoted vegetation growth and regeneration across several sites.

In contrast, H-02 exhibited adverse effects, with a sustained reduction in vegetation cover. This decline is plausibly linked to localized desiccation and conditions unfavorable for natural recovery. The lack of regeneration may also be explained by anthropogenic disturbances, as the wetland has been modified for agricultural use, including the recurrent burning of vegetation, a practice that continues to the present day. This differentiated spatial pattern may be explained by the indirect effects of liquefaction, such as groundwater injection and soil reorganization, which likely created wetter conditions in some areas while generating hostile environments in others. These findings are consistent with previous studies on the ecohydrological response of wetlands to seismic disturbances (Brand et al.; Miyamoto et al.).

The results suggest that the post-seismic dynamics of coastal wetlands are governed by a complex interplay between natural factors (e.g., soil liquefaction) and human activities (e.g., land-use change), underscoring the need to account for both in future monitoring and conservation strategies.

4.3 Surveys and interviews

The study employed semi-structured interviews conducted in March 2024 with 24 eyewitnesses of the Pisco earthquake (August 15, 2007, 18:41 local time). Participants were selected based on two criteria: (1) direct presence during the event or on the following day, and (2) the location of their homes or agricultural fields in areas adjacent to wetlands, some of which had prior reports of liquefaction. Interviewees, situated in peri-wetland zones (Figs. 4 and 5), described geotechnical phenomena associated with liquefaction, which were classified into six categories: ground fissures, subsidence, sand boils, uplift, flooding, and drought (Table 1).

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Table 1. Soil liquefaction effects observed by residents homes adjacent to the wetlands.

Interview	Cracking	Subsidence	Sand Boils	Uplift	Floods	Drought
EP-01	X	X	X	X	X	
EP-02	X		X			
EP-03	X	X		X	X	
EP-04	X	X	X			
EP-05	X	X	X	X	X	
EP-06	X	X				
EP-07	X		X	X	X	
EP-08	X					
EP-09	X	X				
EP-10	X					
EP-11	X	X		X	X	
EP-12	X	X	X	X	X	
EP-13	X	X	X			X
EP-14	X	X		X		
EP-15	X	X	X	X		
EP-16	X					
EP-17	X	X				X
EP-18	X					X
EP-19	X					X
EP-20	X					
EP-21	X		X			
EP-22	X					
EP-23	X	X		X		X
EP-24	X					

Summary	
Event	**No. Interviewed**
Cracking	24
Subsidence	13
Sand boils	9
Uplift	9
Floods	6
Drought	5

The results revealed that all interviewees observed ground fissuring, characterized by cracks measuring several centimeters in width and extending for several meters in length. Subsidence—the second most frequently reported effect (13 of 24 cases)—displayed variable depths ranging from a few centimeters to approximately 1 m. Both sand boils and ground uplift were documented at 9 of the 24 sites. Flooding was reported in 6 cases, involving the expansion of wetland water bodies, in contrast to drought observed in an equal number of cases (6/24). The co-occurrence of multiple effects was recurrent: 6 cases exhibited a single phenomenon, 5 cases recorded two, and 7 cases documented four or five effects simultaneously.

Interviewees reported that most of the wetlands studied were affected during the earthquake by various processes associated with soil liquefaction. As a result, biodiversity—particularly fauna and vegetation—experienced a partial and temporary decline. However, because the local population was primarily occupied with repairing their homes damaged by the seismic

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event, human intervention in the wetlands was minimal. This circumstance, combined with flooding and a rise in the groundwater table, helped maintain relatively stable vegetation cover, preventing permanent degradation of the wetlands and, in fact, promoting a visible process of ecological recovery.

The interviews provided additional valuable insights. Testimonies confirmed that wetlands in the study area had undergone various transformations over time, including drainage, drying, infilling, and conversion for agricultural or aquaculture purposes. Some of these changes were intentional—for example, the establishment of tilapia farms or infilling during droughts—whereas others occurred naturally through seepage or gradual desiccation. Even where wetlands disappeared at the surface, soils with high liquefaction susceptibility remained as evidence of the original ecosystem dynamics.

The interviews also underscored the resilience of wetlands, as reflected in their capacity for rapid recovery. For instance, residents reported that the wetlands in the Bernales sector, surrounding Laguna Morón—a site of touristic interest—were significantly affected by soil liquefaction during the 2007 Pisco earthquake. The event caused subsidence, ground fissuring, and flooding that temporarily reduced their extent. Nonetheless, the wetlands recovered within a few months. Local totora harvesters, who directly witnessed the phenomenon, emphasized that vegetation around the wetlands increased after the earthquake, allowing for greater extraction of this resource. These observations align with technical reports from the area, which documented a rise in the groundwater table at multiple sites, as well as the broader effects of soil liquefaction.

The testimonies also provided insights into local perceptions of the persistence of risk. Despite the transformations wetlands have undergone—whether through drainage, infilling, or agricultural use—residents perceive that the subsurface retains a high susceptibility to processes such as subsidence and liquefaction. This perception is grounded in lived experience, including accidents such as falls into ground fissures or soil deformation during past earthquakes. Even in areas now occupied by urban or agricultural developments, the community recognizes that vulnerability remains, underscoring the importance of incorporating the historical presence of wetlands as a critical criterion in land-use planning and disaster risk management.

Finally, the accounts of respondents regarding the post-earthquake period were characterized by partial and heterogeneous responses. In some cases, local authorities intervened with heavy machinery or institutions such as the Red Cross provided assistance; however, the majority of testimonies emphasized the absence of formal support. Most repairs were carried out independently, using plows, privately hired backhoes, or rudimentary manual leveling of the ground. In several areas, the terrain gradually stabilized through natural processes, highlighting the absence of systematic mechanisms for coordinated management and recovery.

5 Discussion

At the international level, it has been demonstrated that coastal wetlands underlain by soils susceptible to liquefaction exhibit a high probability of failure when impacted by large-magnitude earthquakes. Such events typically generate ground subsidence, surface fissuring, and sand–water ejection, producing consequences that compromise both ecosystem integrity and environmental safety. Nevertheless, these wetlands often display a capacity for post-seismic recovery, as subsidence elevates the water table and, over time, may even promote wetland expansion. The present study examines the impacts of soil

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liquefaction on coastal wetlands located along the left margin of the Pisco River. This area was selected due to its sandy deposits and shallow water table, conditions that render it highly vulnerable to liquefaction and supported by previous evidence of the phenomenon. In contrast, the river's right margin—although containing more extensive wetlands—consists primarily of fine, plastic soils, rocky formations, and a limited record of liquefaction, factors that collectively reduce its susceptibility.

For the analysis, we integrated results from soil liquefaction susceptibility maps, time-series remote sensing data, and qualitative local knowledge obtained through semi-structured interviews. The convergence of these three lines of evidence provides a robust framework for discussing not only susceptibility and immediate impacts but also the ecological resilience of these ecosystems to seismic events, as well as their critical implications for risk management. Findings from this study confirm that the wetlands analyzed—including those degraded or lost due to anthropogenic infilling—and their adjacent areas exhibit a high propensity for soil liquefaction. This elevated susceptibility is intrinsically linked to their geological and hydrogeological context within the Quaternary alluvial plain of the Pisco River, characterized by sandy to silty-sand soils of loose to very loose compaction and a consistently shallow water table (0–3 m depth) (Baez et al., 2023; INDECI, 2008). These conditions are fully consistent with the well-established geotechnical criteria for liquefaction triggering (Seed & Idriss, 1982; Idriss & Boulanger, 2008).

The liquefaction potential maps generated in this study revealed a distinctive and significant pattern: areas with a Factor of Safety (F.S.) < 1 are concentrated primarily along the margins of existing wetlands and in zones historically occupied by wetlands, forming a susceptible field that extends up to approximately 200 meters beyond their visible boundaries. This spatial correlation indicates that the very presence of a wetland serves as a strong geomorphological proxy for subsurface conditions prone to liquefaction. Such a finding carries critical implications for land-use planning, as the hazard zone is not confined to the wetland body itself but encompasses a much broader perimeter, placing any infrastructure or settlements within this fringe at high risk during a major seismic event. The delineated area of liquefaction influence (Torres & Lel, 2022) offers valuable predictive insight for identifying vulnerable zones in other coastal settings along central Peru, where numerous wetlands share comparable geological and geotechnical attributes, including high seismicity, Quaternary alluvial deposits, and shallow aquifers.

The analysis of Normalized Difference Vegetation Index (NDVI) time series, combined with testimonies from local residents, provides a nuanced understanding of the ecological impacts of liquefaction. In the short term, the 2007 earthquake produced severe negative effects, as confirmed by interview data: subsidence, sand–water ejecta, ground fissuring, and localized flooding or desiccation were widely observed, altering both topography and local hydrology. Paradoxically, the medium-term ecological response, captured through NDVI trends, highlights a remarkable resilience across most of the wetlands studied (H-01, H-03, H-04, H-05, H-06). Following an initial decline, these ecosystems demonstrated significant recovery and, in some cases, even increases in vegetation health and cover during the years immediately after the seismic event (2008–2009). This post-seismic resurgence is likely attributable to secondary effects of liquefaction: elevated groundwater levels, terrain subsidence, and the reorganization of subsurface sediments appear to have created wetter conditions and renewed hydrological connectivity, fostering the expansion of hydrophilic vegetation, as noted in particular by reed harvesters around Laguna Morón (H-05).

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This suggests that although liquefaction is a severe disruptive agent, it can also function as a natural mechanism of ecosystem rejuvenation and expansion, effectively reestablishing hydrological dynamics that may have been altered or constrained by anthropogenic activity. The case of H-02 (Pampa Ocas), which exhibited a sustained decline in vegetation, serves as a critical counterpoint. Here, the lack of recovery cannot be attributed to the seismic event itself but rather to persistent anthropogenic pressures—agricultural conversion and recurrent burning—that have overridden the ecosystem's inherent regenerative capacity in this particular area. This contrast underscores that the long-term trajectory of a wetland following disturbance is shaped by the complex interplay between natural recovery processes and human intervention.

A central finding is that the primary threat is not the natural phenomenon of liquefaction itself, but rather the human occupation and modification of zones identified as high risk. Evidence of liquefaction in infilled wetlands (e.g., portions of Pisco Playa Sur corresponding to wetland H-01) demonstrates that anthropogenic alteration does not eliminate the underlying geotechnical hazard; it merely masks it, often redirecting the manifestation of liquefaction effects to nearby areas or amplifying the risk for structures built on non-engineered fill. Such practices create a false sense of security and directly endanger human populations settled in these areas, as has been tragically documented in other global contexts (Kusler, 2009; Cavada, 2023).

The interviews confirm that liquefaction occurred not only in existing wetlands but also in areas where wetlands had previously been infilled for urban or agricultural use. This finding underscores that susceptibility is a property of the subsurface "geological memory"; altering the surface landscape does not change the inherent grain size distribution, saturation, or density of the underlying sediments. Consequently, former wetland areas must be treated with the same level of precaution as current wetlands.

In Peru, stringent regulations are in place to ensure structural safety against earthquakes, most notably the seismic design code (D.S. N° 003-2016-Vivienda), which divides the country into four seismic zones and mandates detailed geotechnical investigations in areas with special conditions. A critical component of this framework is soil liquefaction: the code requires site-specific investigations and the definition of appropriate engineering solutions prior to final design approval. Complementing this, the regulations on soils and foundations (R.M. N° 406-2018-Vivienda) mandate soil mechanics studies for nearly all construction projects and establish standardized procedures for identifying soils with liquefaction potential. The regulation explicitly prohibits foundation placement on sites with a liquefaction probability greater than 10%, unless ground improvement measures are implemented or foundations are transferred to deeper, more competent strata. Collectively, this regulatory framework ensures that, in a highly seismic country such as Peru, rigorous engineering measures are systematically adopted to mitigate the risks of liquefaction and safeguard structural integrity.

However, compliance with seismic-resistant construction regulations in Peru remains largely ineffective, primarily due to the widespread expansion of self-construction—that is, building practices carried out without adherence to technical or engineering standards. Between 2007 and 2024, approximately 1.6 million informal dwellings were built, representing 63% of all construction during that period. The vast majority of these structures were erected without property titles, professional supervision, or municipal permits (IPE, 2025). As a result, nearly half of these dwellings have precarious roofs, and approximately 30% are built with low–seismic-resistance materials such as adobe or wattle and daub, significantly increasing

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their vulnerability to earthquakes. Currently, it is estimated that around 70% of all housing nationwide is informal, much of it constructed in unsuitable areas using substandard materials (CAPECO, 2025). This issue is also reflected in broader urban development trends: Peru ranks second in Latin America in informal urban land occupation, with 93% of urban expansion occurring without planning or regulation (Espinoza & Fort, 2020). The scale of informal housing underscores the severe lack of urban planning and weak territorial governance, with direct implications for public safety and the long-term sustainability of cities.

In the Peruvian context—where the high prevalence of informal construction severely limits the effective enforcement of stringent seismic-resistant building codes—it may be more practical to advance toward broader territorial planning instruments that establish clear restrictions on where construction should not occur, rather than focusing solely on how it is carried out. A key priority would be to prohibit construction within fragile ecosystems, such as coastal wetlands, not only due to their high susceptibility to soil liquefaction and other seismic effects, but also because their conservation provides critical co-benefits, including serving as natural buffers against extreme rainfall, flooding, and tsunamis, thereby reducing risks to surrounding populations.

In the same vein, restricting high-impact activities within these areas is essential for effective disaster risk reduction. To achieve this, it is crucial that liquefaction hazard maps be integrated into urban planning instruments, ensuring that former wetland zones are clearly delineated and their development strictly regulated. In this way, a preventive, land-use–oriented regulatory framework would simultaneously enhance seismic and climate resilience while safeguarding the ecological integrity of these strategic ecosystems.

An additional and equally critical measure is to ensure the legal protection and strict conservation of these areas. In Peru, wetlands are formally recognized under environmental law as “fragile ecosystems” requiring the State to adopt special measures for their preservation (Law No. 32099). Several territorial protection mechanisms can be applied to achieve this objective: incorporating former wetlands into the National System of Protected Natural Areas—through their designation as reserves, sanctuaries, or wildlife refuges—; establishing Regional Conservation Areas managed by subnational governments; or zoning these sites as untouchable areas within urban development plans, thereby prohibiting their urbanization.

Such protection mechanisms are already being implemented in certain cases. For instance, the Los Pantanos de Villa Wildlife Refuge in Lima—the country’s only protected urban wetland—was designated as a National Protected Area (NPA) in 2006 and later recognized as a Ramsar Site. Owing to this legal protection, it now provides critical ecosystem services to the city, including water storage, flood and tsunami mitigation, and coastal erosion control. This example clearly demonstrates that protecting these ecosystems not only significantly reduces disaster risk for nearby populations but also preserves their biodiversity and the valuable climatic benefits they provide.

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6 Conclusions

The results confirm that the coastal wetlands located on the left bank of the Pisco River—including those that have been degraded or have disappeared—exhibit a high susceptibility to soil liquefaction. This condition arises from the presence of loosely compacted sandy and silty-sandy deposits, a shallow groundwater table, and young Quaternary-age soils. Geotechnical tests (DPL and test pits) corroborate this susceptibility, revealing that the areas at risk extend beyond the visible limits of the wetlands, forming a liquefaction influence zone reaching up to approximately 200 meters beyond their boundaries.

The 2007 earthquake revealed the full extent of liquefaction-related impacts, including ground subsidence, cracking, sand and water ejection, and damage to infrastructure built on infilled wetlands. This event demonstrated the critical vulnerability of these areas and underscores the urgent need to establish clear delineation criteria and buffer zones to protect both the ecosystems and the surrounding communities from the effects of future large-magnitude earthquakes.

The recurrence of the phenomenon—known as reliquefaction—has also been documented in areas previously affected, demonstrating that subsurface susceptibility persists even after wetlands have been modified or converted into agricultural or urban land. Therefore, the original nature and location of these ecosystems should be regarded as key indicators for disaster risk management and for informing land-use planning and territorial development decisions.

Despite the immediate negative impacts, the wetlands exhibited a remarkable capacity for resilience. Analysis of NDVI data and local testimonies indicates that within one to two years after the earthquake, many wetlands had recovered their vegetation cover and even expanded their extent, driven by groundwater table rise and enhanced hydrologic recharge. This evidence offers a valuable perspective on the dual nature of wetlands—highly vulnerable to severe disturbances, yet capable of regeneration and reinforcement of their ecological functions.

Wetlands also serve as natural indicators of areas with high liquefaction potential. Their conservation is essential not only for the ecosystem services they provide, but also because they signal the geotechnical hazards inherent in the subsurface. Altering or infilling these environments increases the vulnerability of infrastructure and nearby populations, underscoring the importance of integrating wetlands into seismic microzonation studies and land-use planning frameworks.

The integrated methodological approach—combining geotechnical studies, satellite image analysis, and interviews with local residents—proved to be a robust framework for understanding the interaction between seismic dynamics, ecosystem functioning, and social perception. This multidisciplinary approach is replicable in other coastal basins of Peru and across Latin America with similar settings, enabling the development of a regional perspective on the interrelationships among geodynamics, land use, and ecosystem resilience.

In summary, the coastal wetlands of Pisco exist in a dynamic equilibrium with seismic activity. Their high susceptibility to liquefaction, coupled with their remarkable resilience, makes them strategic ecosystems for both environmental conservation and disaster risk management. Recognizing their dual role—as vulnerable environments and natural sentinels of seismic hazards—is essential for fostering a safer and more sustainable coexistence between society and the landscape in this highly seismic region.

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In this regard, the present study seeks to move beyond the traditional Peruvian approach to liquefaction studies, which has focused primarily on urban infrastructure, by characterizing ecologically and geotechnically sensitive zones. Our findings advocate for a paradigm shift in risk management and spatial planning. Wetlands should not be regarded as vacant lands for infill, but rather as valuable ecosystems that also function as natural indicators of subsurface liquefaction risk. The formal delineation and protection of wetlands—along with the establishment of buffer zones that account for the influence of the liquefaction field—should be viewed not merely as conservation measures, but as essential strategies for risk mitigation.

Code availability. No new software was developed for this study. All analyses were conducted using existing, publicly available tools and packages as cited in the 2.2 subsection Methods and field study instruments.

Data availability. The data collected during the survey contains information that might allow to identify some of the respondents, and cannot be shared publicly. Access to the anonymized version of the data set but can be made available upon request.

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