*Review*

# Landscape Modifications ascribed to El Niño Events in Late pre-Hispanic Coastal Peru

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**Abstract:** The coastal Peru, one of the driest deserts in the world, has recently experienced dramatic landscape changes and asset destruction during precipitation events due to El Niño. Nevertheless, catastrophic explanations for landscape variations and human responses to the so-called "Super" or "Mega" El Niños are recurrent in pre-Hispanic time, even if alternative hypotheses were provided in literature. A deeper understanding of the geological and archaeological record can improve the knowledge on the relationship between such a coupled atmosphere-ocean phenomenon and landscape processes. The bibliographic sources required for this purpose are scattered throughout various disciplines ranging from physical to human sciences, thus comprehensive databases were used to identify and screen the relevant studies. The results provide knowledge synthesis in order to identify critical gaps and suggest specific research goals. Inferred episodes of landscape change due to severe precipitations in late pre-Hispanic time are discussed and consistencies and inconsistencies exposed. Examples of variation in landscape response due to extensive human intervention are reported.

**Keywords:** Desert landscape; Coastal plain; Paleoflood record; El Niño proxies; Debris flow; Slack-water deposit; Braided streams; Desert pavement; Regolith denudation

## 1. Introduction

Due to the dynamic of the El Niño-Southern Oscillation (ENSO), the coastal Peru is a key region to investigate the connections between climate processes and Earth surface responses [1–3]. El Niño precipitation events cause abrupt and rapid landscape modifications in stark contrast to the extremely slow changes affecting the deserts of the central Pacific coast of South America throughout long periods of time (millennia and more) [4,5]. Widespread landslides and extensive floods are the more relevant hydrogeomorphic signatures [6–10].

Several archaeological and geological studies in pre-Hispanic coastal Peru have focused on the impact on settlements and irrigation systems of severe precipitation events named "Super" and "Mega" El Niños [11–16]. This perspective has suggested major landscape modifications and community catastrophes, including the collapse of centuries-old cultures [17–20]. However, alternative interpretations involving gradual evolution of landscape and adaptation of the communities have been also provided in literature [21–23]. Due to the above, it is hard to define the temporal and spatial trend of the landscape effects of El Niño events on the coastal Peru during the last millennia [24,25].

A careful examination of data allows to explore the strengths and weaknesses of authors' hypothesis on landscape effects of El Niño events. The bibliographic sources required for this purpose are scattered throughout the literature of various disciplines ranging from physical to human sciences. Thus, the identification and screening of pertinent documents have been performed by the citation databases of Web of Science (WoS) and Scopus, in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (PRISMA) [26,27]. The overarching aim of this review is the identification of critical knowledge gaps in order to motivate additional study on targeted

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research objectives. Significant landscape changes as well as positive effects on human communities and water resources due to severe precipitations are finally noted, and possible inconsistencies exposed.

## 2. Background knowledge about the topic

Due to the interdisciplinary nature of the subject matter, some basic concepts must be given before addressing Materials and Methods (Section 3).

### *2.1. Physical setting*

The landscape of coastal Peru (Figure 1) is characterized by hill ridges - the western Andean offshoots named *lomas* - made up by pre-Tertiary carbonate, igneous, and metamorphic rocks, and flat areas crossed by rivers - the *pampas* - made up by Tertiary-Quaternary clastic rocks produced from the dismantling of the Andes during the orogenesis. Both are devoid of soil and vegetation and partially covered by deposits produced by eolian processes (dunes, desert pavements, reg soils). Typical landforms are the *quebradas*, dry braided stream and ravine systems mainly located at the Andean footzone (over alluvial fans) or next to the coast.

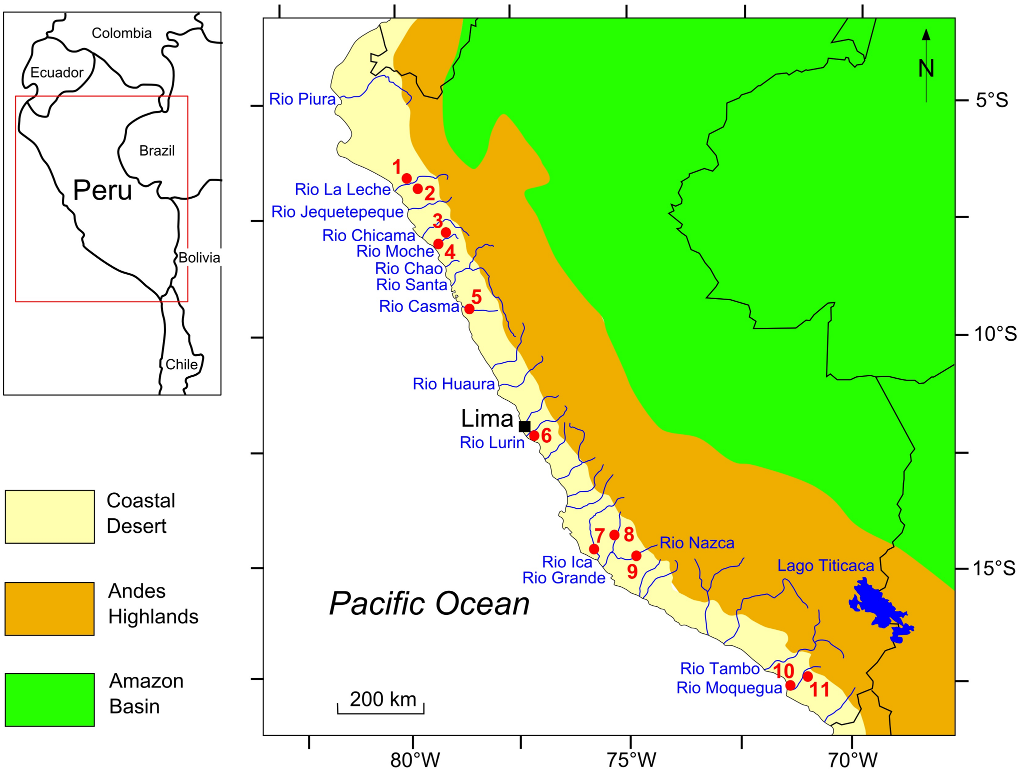


**Figure 1.** Main geographical regions of Peru. Numbers indicate the location of the cases discussed in the text; 1, Batan Grande; 2, Racarumi; 3, Caballo Muerto and Quebrada de los Chinos; 4, Huacas de Moche; 5, Casma and Cerro Sechin; 6, Pachacamac and Urpi Kocha; 7, Samaca; 8, Palpa; 9, Cahuachi; 10, Quebrada Miraflores; 11, Rio Muerto.

The coastal Peru (3°30′–18°30′S, 81°30′–70°30′W) is one of the driest region in the world. Such a desert environment results from the SE Pacific anticyclone and the Humboldt Current coming from the Antarctic Sea, because they both prevent rain [28,29]. Annual precipitation values are rather uniform along the entire coast, averaging 10 - 25 mm per year. The desert along the Pacific is narrow, only about 120 kilometers wide before the land rises into the Andes Highlands, where precipitation increases with elevation. Tens of perennial or seasonal rivers, coming down from the Andes, pass through the desert on the way to the ocean (Figure 1). They allow both biological life and human settlement

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within and in the surrounding of riparian oases. Once every 7–15 years, an El Niño brings warm sea surface temperatures and torrential rainfall on the coastal region, breaking the hyperarid state. With reference to the last century, severe El Niño events occurred during the years 1925/26, 1940/41, 1957/58, 1972/73, 1982/83, 1997/98, and 2015/16, this latter with an extraordinary prolongation in 2017 [8,25,30–32].

### *2.2. El Niño event and landscape response*

The term El Niño was initially applied to a weak warm ocean current that runs southward along the Ecuador and Peru coastline around Christmastime. It is the warm phase of the El Niño-Southern Oscillation (ENSO), an interannual fluctuation in sea surface temperature and air pressure across the equatorial Pacific Ocean [33–36]. The cold phase is called La Niña; neutral phase the intermediate one. Such coupled atmosphere-ocean phenomena dominate the interannual variability of planetary climate system and cause strong drought and flood around the world [37,38]. ENSO has dramatically changed in occurrence and magnitude during the Holocene, increasing in frequency to reach its current features about 3.0 Ka [39–41], roughly corresponding with the beginning of the Early Horizon Period.

The coastal Peru is responsible for a direct correspondence among El Niño severity, flooding, and landscape modifications. During El Niño, the South Pacific anticyclone weakens while the northern boundary of the Humboldt current migrates southward. In such a condition, significant precipitation is able to reach the coastal desert, where it reinforce due to the rain-shadow effect of the Andes [14]. However, the flood magnitude did not affect the different desert areas equally [30–32]. Latitude 12°S roughly divides north-central coastal Peru, which is hardest hit by El Niño events, from southern coastal Peru, which is usually less affected [42]. Nevertheless, large events, such as that in 1925/26, can extend much farther south [43].

Severe precipitation and flooding may be also produced by other atmospheric patterns. The eastern desert margin is involved in the monsoonal fluctuations, thus thunderstorms can occasionally reach it and cause convective precipitation especially over the southern Peru [44,45]. Again, enhanced precipitation across the Andes highlands during La Niña event may produce flooding on main valleys [46,47]. In perspective of paleoflood analysis, such processes make more challenging the detection of the triggering cause of hydrogeomorphic events preserved in geoarchaeological sequences [4,7].

The strength of ENSO events is measured by conventional physical indices. Regional Sea Surface Temperature (SST) indices and the surface atmospheric pressure-based Southern Oscillation index (SOI) are the most widely used to classify ENSO events. However, there is no agreement among scholars about which index best defines ENSO strength, timing, and duration, and fits severe precipitations satisfactorily well [33,37,48–50]. To address the change in frequency and intensity of events ascribed to El Niño that hit the central Pacific coast of South America in pre-instrumental time, various approaches have been used, including geoarchaeological studies [8,51]. After the event of 1982/83, scholars focused on the power and occurrence of extremely strong events. Events with recurrence interval up to 400 years were labelled as Super El Niño, while the ones which happens once every 1000 years as Mega El Niño [16,52].

The frequency and spatial variability of El Niño events is very difficult to establish and predict. Historical climatic and hydrological records may reflect specific atmospheric conditions of each valley and parts of them. To give some examples, the Lower Chicama Valley (northern Peru, Figure 1) saw extensive flooding as a result of the 1997/98 El Niño event but none for the 2015/16 one. Instead, the upper Moquegua Valley (southern Peru, Figure 1) experienced torrential rain and flood during the 1982/83 El Niño event but no significant surface process occurred 15 years later [19,25,43].

In arid regions, landscape response to rainfall events is typical. In fact, severe precipitations "*are more likely to cause landform change than are floods of similar magnitude elsewhere*" [53]. However, weathering and erosion rates are orders of magnitude lower than in less

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dry environments, and soil development processes differ markedly from those found on the vast majority of the Earth's surface [5,54,55]. As a result, in coastal Peru landscape modifications are slow compared to non-desert regions, except for the occurrence of high magnitude events [56,57]. With a multi-century recurrence interval for precipitation event, exceptional debris flows are reported in dry landscapes [58,59]. Under favorable conditions, layers deposited as a result of high magnitude flood events can be used as horizon markers in ancient landscape reconstruction. Slack-water deposits are significant examples of such useful beds [60]. In the last century, an event that produced notable landscape impact in the valleys of northern Peru was El Niño of 1925/26. For what concerns Moche Valley (see Figure 1 for location), the river spilled over vast tracts of alluvial plain, destroying bridges and irrigation systems and threatened the stability of *Huaca del Sol*, the great archaeological monument of the Early Intermediate Period [11].

## 3. Materials and Methods

The screening of the documents relevant to this review was conducted according to the PRISMA statement [26,27]. It assists reviewers and meta-analysts in transparently reporting why the review was conducted, what the authors did, and what they discovered. To identify and select the documents, Scopus and WoS databases were processed [61–63]. To increase the chances to find useful documents, topics "Ecuador" and "Chile" were added in the search modes. Moreover, tag "*" was used in the search phrases to cover as many keyword combination as possible (Table 1). The databases were last consulted on August 30, 2022.

**Table 1.** Wos / Scopus database search modes.

| | Search Field | Search Phrase | Document Type |
|---|---|---|---|
| WoS | TS = Topic (Title, Abstract, Author Keywords, and Keyword Plus) | (((TS=("El Nino*" OR Nino* OR ENSO OR "El Nino Southern Oscillation")) AND TS=(Peru OR Ecuador OR Chile)) AND TS=(landscape* OR settlement* OR site* OR archaeolog*)) | Articles, Review Articles, Proceedings Papers, Early Access, Book Chapters |
| Scopus | TITLE-ABS-KEY (Article Title, Abstract, and Keywords) | (TITLE-ABS-KEY (El Nino* OR Nino* OR ENSO OR El Nino Southern Oscillation) AND TITLE-ABS-KEY (Peru OR Ecuador OR Chile)) AND TITLE-ABS-KEY (landscape* OR settlement* OR site* OR archaeolog*)) | Article, Conference Paper, Conference Review, Review, Book Chapter |

Despite their great advantages, Scopus and WoS platforms may introduced biases that favor Natural Sciences, Engineering, and Biomedical Research at the expense of Social Sciences, Arts, and Humanities. In a similar manner, documents written in English predominate over those written in other languages [62]. Anyway, to found further articles and other works pertinent to the review, a careful examination of the reference list of the selected documents was made. For the full-text analysis, to establish how consistently geoarchaeological data support the occurrence of El Niño events, the following criteria were used: (a) geomorphological and stratigraphic features of the related deposits; (b) relationships between deposits and archaeological remains; (c) method of dating used to determine the age; (d) presence or absence of converging evidence; (e) consistency with data from other studies. These criteria were fixed based on the epistemological features of geology [64–66] and archaeology [67–69].

## 4. Screening Results

Among the documents mined from the databases, only one duplicate was found, thus 458 works were identified in total (Table 2).

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**Table 2.** Summary of identification, selection, and full-text examination stages.

| | Wos | | Scopus |
|---|---|---|---|
| Database mined documents | 383 | | 306 |
| After duplicate check | 383 | | 305 |
| Documents found in both databases | | 230 | |
| Identified documents | | 458 | |
| Excluded after abstract evaluation | 337 | 402 | 261 |
| Selected documents | 46 | 56 | 44 |
| From bibliography of selected works | | 14 | |
| Reviewed documents | | 70 | |

Then, carefully abstract evaluation allowed the selection of 56 documents. 402 documents were disregarded because they dealt with topics of other subject areas (i.e. medicine, public health, sustainability, ethnology, anthropology, oceanography, tectonic, geochemistry, psychic atmosphere, meteorology, glaciology, dendroclimatology, palynology, biology, zoology, botany, ecology, astronomy, history, economy, sociology) or were irrelevant to the review's objective in space and/or in time (i.e. study cases not on the central Pacific coast of South America or outside the considered time). 14 documents identified by examination of the bibliography of the selected works have been added for the review analysis (Table 2), thus, a total of 70 documents were finally reviewed (Tables 3, 4).

**Table 3.** Summary of reviewed documents. BSD = Bibliography of Selected document.

| Author(s) and Year | Source | Sites/Study Areas |
|---|---|---|
| Nials et al. (1979 a, b) [11,12] | BSD | Huaca del Sol and other 2 sites (Moche Valley) |
| Samaniego et al. (1985) [70] | BSD | Cerro Sechin (Casma Valley) |
| Craig and Shimada (1986) [13] | Scopus | Batan Grande (La Leche Valley) |
| Sandweiss (1986) [71] | Scopus | Las Salinas (North coast of Santa mouth) |
| Rollins et al. (1986) [72] | Scopus | Las Salinas (North coast of Santa mouth) |
| DeVries (1987) [73] | BSD | *Review article* |
| Wells (1987) [74] | BSD | 7 sites (Casma Valley) |
| Wells (1990) [14] | BSD | 7 sites (Casma Valley) |
| Grodzicki (1992) [17] | BSD | Pampa de Nazca (Nazca Valley) |
| Moseley and Richardson (1992) [75] | BSD | Huaca del Sol (Moche Valley) |
| Moseley et al. (1992) [76] | BSD | Las Salinas (North coast of Santa mouth) |
| Ortlieb and Machare (1993) [77] | WoS, Scopus | *Review article* |
| Uceda and Canziani Amico (1993) [78] | BSD | Huaca de la Luna (Moche Valley) |
| Grodzicki (1994) [18] | BSD | Cahuachi and other 3 sites (Nazca Valley) |
| Keefer et al. (1998) [79] | BSD | Quebrada Tacahuay (Moquegua Valley) |
| Wells and Noller (1999) [80] | Scopus | *Review article* |
| Veit (2000) [81] | Scopus | *Review article* |
| Franco and Paredes (2000) [82] | BSD | Pachacamac (Lurin Valley) |
| Satterlee et al. (2000) [19] | BSD | Quebrada Miraflores (North coast of Moquegua mouth) |
| Magilligan and Goldstein (2001) [21] | WoS, Scopus | Rio Muerto (Moquegua Valley) |
| Sandweiss et al. (2001) [51] | WoS, Scopus | *Review article* |
| Van Buren (2001) [83] | WoS | *Review article* |
| Calderoni et al. (2002) [56] | Scopus | Mejia (Tambo Valley) |
| Huckleberry and Billman (2003) [84] | WoS, Scopus | Quebrada de los Chinos (Moche Valley) |
| Keefer et al. (2003) [85] | Wos, Scopus | *Review article* |
| Dillehay et al. (2004) [86] | WoS, Scopus | Los Mochicas del Norte Valleys |
| Federici and Rodolfi (2004) [87] | WoS, Scopus | Ensenada de Atacames, *Ecuador* |
| Keefer and Moseley (2004) [88] | WoS, Scopus | lower Moquegua Valley |
| Brooks et al. (2005) [89] | WoS, Scopus | Santa Rita (Chao Valley) |
| deFrance and Keefer (2005) [90] | WoS, Scopus | Quebrada Tacahuay (South coast of Moquegua mouth) |
| Eitel et al. (2005) [4] | WoS, Scopus | Quebrada Palpa (Grande Valley) |
| Zaro and Alvarez (2005) [91] | WoS, Scopus | Moquegua Valley and North coast of Moquegua mouth |

**Table 4.** Summary of reviewed works. This table continues from Table 3.

| Author(s) and Year | Source | Sites/Study Areas |
|---|---|---|
| Fabre et al. (2006) [92] | WoS, Scopus | Mollendo (North coast of Tambo mouth) |
| Machtle et al. (2006) [93] | WoS, Scopus | upper and middle Grande Valley |
| Manners et al. (2007) [46] | WoS | middle Moquegua Valley |
| Andrus et al. (2008) [94] | WoS, Scopus | *Review article* |
| Magilligan et al. (2008) [47] | WoS | 3 sites (Moquegua Valley) |
| Beresford-Jones et al. (2009a) [95] | Wos, Scopus | Samaca (Ica Valley) |
| Beresford-Jones et al. (2009b) [96] | Scopus | Samaca (Ica Valley) |
| deFrance et al. (2009) [97] | WoS | North and south coast of Moquegua mouth |
| Eitel and Machtle (2009) [98] | WoS | upper and middle Grande Valley |
| Mettier et al. (2009) [1] | WoS, Scopus | middle Piura Valley |
| Reindel and Wagner (2009) [99] | WoS | upper Grande Valley |
| Abbuhl et al. (2010) [100] | WoS, Scopus | middle Piura Valley |
| Beresford-Jones (2011) [101] | Scopus | Samaca (Ica Valley) |
| Bernal et al. (2011) [102] | WoS | Pastaza Valley, *Ecuador-Peru area of Amazon Basin* |
| Goldstein and Magilligan (2011) [103] | WoS, Scopus | upper and middle Moquegua Valley |
| Gayo et al. (2012) [104] | WoS, Scopus | Pampa del Tamarugal, *Chile* |
| Huckleberry et al. (2012) [105] | WoS, Scopus | middle La Leche Valley |
| Sandweiss and Kelley (2012) [106] | WoS, Scopus | *Review article* |
| Sandweiss and Quilter (2012) [107] | WoS | *Review article* |
| Winsborough et al. (2012) [20] | WoS, Scopus | Urpi Kocha Lagoon (Rio Lurin) |
| Etayo-Cadavid et al. (2013) [108] | WoS, Scopus | North and south coast of Moche mouth |
| Hanzalova and Pavelka (2013) [109] | Scopus | Ciudad Perdida de Huayuri (upper Grande Valley) |
| Macthle and Eitel (2013) [110] | WoS, Scopus | upper Grance Valley and middle Nazca Valley |
| Kalicki et al. (2014) [111] | Scopus | Lomas de Lachay (South of middle Huaura Valley) |
| Nesbitt (2016) [112] | WoS | Caballo Muerto Archaeological Complex (middle Moche Valley) |
| Caramanica and Koons (2016) [113] | WoS, Scopus | Pampa de Mocan (middle Jequetepeque Valley) |
| Pavelka et al. (2016) [114] | WoS | Cantalloc (upper Nazca Valley) |
| Christol et al. (2017) [115] | WoS, Scopus | West coast of La Leche mouth |
| Wang et al. (2017) [116] | WoS | Salar Grande, *Chile* |
| Kalicki et al. (2018) [117] | WoS, Scopus | Lomas de Lachay (South of middle Huaura Valley) |
| Delle Rose et al. (2019) [23] | WoS, Scopus | Cahuachi (middle Nazca Valley) |
| Caramanica et al. (2020) [118] | WoS, Scopus | Pampa de Mocan (middle Jequetepeque Valley) |
| Kalicki and Kalicki (2020) [119] | WoS | Lomas de Lachay (South of middle Huaura Valley) |
| Sandweiss et al. (2020) [120] | WoS, Scopus | *Review article* |
| Uceda et al. (2021) [121] | WoS, Scopus | *Review article* |
| Sandweiss and Maasch (2022) [122] | WoS, Scopus | *Review article* |
| Rubinatto Serrano et al. (2022) [123] | WoS, Scopus | Rio Muerto and 3 other sites (Moquegua Valley) |

13 review articles are present among the full-text analyzed documents (Tables 3, 4). None of these are focused on landscape modifications due to El Niño events along the whole coastal Peru. Moreover, no useful data for this review was found in 20 reviewed works, including three articles on Ecuador and Chile case studies (Table A1). To expose and discuss the findings, data on landscape changes extracted from the reviewed documents were grouped and related according to main study areas (Section 5).

## 5. Main Study Areas for Landscape Changes

### *5.1. Los Mochicas del Norte Valleys*

This area includes the valleys between Rio La Leche and Rio Juequetepeque and has an ethno-historical significance [124]. The earliest work identified by citation database queries is the one of Craig and Shimada [13] on the Batan Grande archaeological complex (see Figure 1 for location). Recent Quaternary stratigraphy, analysed along a modern hydraulic excavation, suggests to the authors that few deposits survive from the 1925/26 El Niño event, except for slack-water beds roughly dated between 650 and 1000 CE by associated funerary pottery. Such deposits accumulate in areas of reduced velocity during flood flows and may be related to episodes of fluvial morphological adjustment and reshaping channel morphology [60]. Unluckily, the contained archaeological finds does not allow more precise dating and thus the use of the above deposit as horizon marker is prevented. Such a gap in knowledge should be filled by absolute dating.

South of Batan Grande, along the Jequetepeque Valley (Figure 1), Dillehay et al. [86] documented several sediment release signatures of slack-water deposits containing Late Moche and Chimu ceramics and $^{14}$C dated between 415 and 1420 CE. These authors documented also different debris flow deposits as well as erosional truncation of floors at several archaeological sites, all likely associated with El Niño events. The multidisciplinary character of this study and the numerous radiocarbon dating of organic material extracted from alluvial deposits make the findings reliable. A long-term landscape shaping due to severe ENSO-related floods has characterized the northern coastal desert before the arrival of the Spanish conquistadors. The human responses to the destructive effects of El Niño events are evaluated as "*highly sophisticated*" by the authors. Large rebuilding activities on damaged hydraulic structures, inferred by stratigraphic analysis at different archaeological sites, seem in fact to have allowed communities to avoid socio-economic repercussions of the hydrogeomorphic calamities. Similar results are obtained by Huckleberry et al. [105] for the inter-valley canal system named Racamuri (upper La Leche Valley, Figure 1), a millennial construction that reached their maximum extension between 900 and 1470 CE. Despite ENSO-driven floods and droughts such a hydraulic opera would continue to work for centuries likely even after the beginning of the colonial occupation. As a whole, for the northernmost valleys of coastal Peru, the selected literature data does not suggest drastic landscape changes or dramatic human responses to strong hydrogeomorphic episodes. Only the ca. 775 CE episode of abandonment of Pampa Grande site (45 km southeast of Batan Grande) may be associated to a strong El Niño with good confidence [122]. It must be highlighted that this date is comprises between the interval time of the event postulated in Ref. [13]. Thus, a detailed geoarchaeological study on this case is suggested.

### *5.2. Huacas de Moche (Lower Moche Valley)*

The settlement of Huacas de Moche is an early capital of the Moche state. It is located in the lower Moche Valley and includes the well-known buildings named Huaca del Sol and Huaca de la Luna (Figure 2). In their pioneering works, Nials et al. (a) [11] report "*the discovery of an El Niño catastrophe of a magnitude far greater and more devastating than all other such natural disasters striking the coast since the conquistadors first arrived in 1532. Transpiring about 1100 A.D., this prehistoric Niño was of unprecedented magnitude, and the devastation it wrought taxes the imagination of geologists and archaeologists alike*". Since about 1000 CE, the Chimu Culture had completely transformed the desert landscape, building a complex irrigation system of reclamation channels over an area of tens of square kilometers. According to the authors (they have surveyed hundreds of kilometers of ancient waterways), all the channels experienced massive erosion and has dropped from use before the begin of successive sub-cultural phase (a few tens of years later). This allowed an approximate dating of the hydrogeomorphic disaster, which was consequently called Chimu Flood. Later, much of the reclaimed area would revert to desert in short time. The lack of absolute dating makes, however, this reconstruction questionable. It is an example of critical knowledge gap.

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**Figure 2.** Huacas de Moche; 2004 satellite image (8°07′25″–8°08′22″S, 79°00′17″–78°58′35″W). Huaca del Sol and Huaca de la Luna are marked by red circle and blue circle, respectively. The depositional origin of late Holocene layers covering the plain between the monumental buildings should be ascertained taking into account the landscape processes argued by the authors [11,75,121].

The water level of the Chimu Flood would be still recognizable on the western side of the adobe brick pyramid *Huaca del Sol* (see Figure 7 at page 12 of Nials et al. (a) [11]), marked by a notch some 10-15 m above the present Rio Moche level. However, according to the geomorphological reconstruction of the authors, the major landscape change happened at the middle Moche Valley, 5-10 km upstream Huaca del Sol, with the lowering of the alluvial plain due to erosion estimated in ca. 5 m [12] (see 5.3). Moreover, the authors stated that "*a very conservative estimate would be flood waters at least 2 to 4 times the size of the 1925*[/26] *floods, the worst in the last 400 years*" [12].

Several works selected from Scopus and WoS databases by the metod described in Section 3 cite the works of the reseaerch group of Nials. Craig and Shimada [13] hint to a possible regional correlation with the slack-water deposit they found along the Rio La Leche Valley (see 5.1), thus laying the groundwork for the conceptualization of a 11$^{th}$ century El Niño event. Wells [14] suggests the possible coincidence of the Chimu Flood with the so-called Naymlap Flood, an ethno-historical records of a hydrological disaster associated with the name of a culture hero [25,125]. Again, Wells and Noller [80] use the Chimu Flood to explicate the recurrence interval of the "Mega" El Niños in northern coastal Peru. Finally, Van Buren [83], Nesbitt [112], Huckleberry et al. [105], and Caramanica et al. [118] cite Nials et al. simply to describe the destructive effects of the major El Niño events on the ancient irrigation systems and the consequences on the human communities. None of these studies deal with the reliability of the reconstruction provided by Nials et al..

By archaeological excavations on *Huaca de la Luna*, Uceda and Canziani Amico [78] argued the occurence of moderate El Niño events previous the Chimu Flood. They interpreted three layers of sediment with remnants of paint washed off walls, found on successive floors of the temple, as evidence of intense precipitation and runoff processes, the most recent dated around 600 CE. This latter should have produced significant flow within the braided streams of the Moche Valley without, however, causing changes in the landscape nor the abandonment of the settlement as asserted by Moseley and Richardson [75]. Instead, according to these authors, between 500 and 600 CE "*flood water brought by El Niño struck the Moche capital, they leveled much of the city, stripping as much as 15 feet*" (about 4.6 m) "*off some areas. It is unclear if the magnitude of destruction reflects more than one El Niño events, perhaps exacerbated by an earthquake. The survivors rebuilt their city only to see it gradually inundated by sand dunes that swept inland after forming on the beach at the mouth of the Moche River*". It is apparent how the interpretation of geoarchaeological data coming from the same site, can even lead to conflicting hypotheses [121]. Thus, the impact of the around

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600 CE El Niño event on settlement and landscape at Haucas de Moche must be further investigated especially with the aim to fill possible gaps in knowledge.

### 5.3. Caballo Muerto and Quebrada de los Chinos (Middle Moche Valley)

Caballo Muerto Archaeological Complex and Quebrada de los Chinos are located in the middle valley of Rio Moche (Figure 1). The first includes the building named Huaca Cortada, from which data on the effects of El Niño events on settlement and landscape have recently been collected by Nesbitt [112]. According to this author, the whole archaeological complex "*is situated within an environment susceptible to El Niño flooding*". Archaeological excavations at Huaca Cortada documented the occurrence of four El Niño events throughout the second half of second millennium BCE. The identified El Niño proxies are laminated muddy layers which deposited from runoff water. They contain thin laminas of white paint, which formed as the rain washed off the painted, plastered surfaces of the temple walls. These layers are sandwiched between pre- and post-event structures and were exposed to weathering for a short time as inferred from their sedimentological features. By $^{14}$C method, a date of of 1600 - 1450 BCE is established for the earliest El Niño proxy of Huaca Cortada. The age of the subsequent events are comprise between 1100 and 900 BCE, as inferred from pottery finds. Finally, it must be noted that, as Caballo Muerto is surrounding by *quebradas*, changes in the shape of the braided streams for each event may be supposed, that would be significant modifications for a desert environment. Nevertheless, according to Nesbitt [112], the communities of the Initial Period were able to rapidly reconstruct and enlarge buildings, thus "*the social, religious and economic mechanisms that allowed for the mobilisation of labour [...] were not negatively impacted by El Niño*".


**Figure 3.** Caballo Muerto Archaeological Complex; 2021 satellite image (8°03′59″–8°04′53″S, 78°55′19″–78°53′44″W). The alluvial fan on which lies the main settlement of the complex is marked by red line. Its stratigraphy should contain a wealth of data regarding El Niño events (see text).

The geoarchaeological record of the middle Moche Valley preserves a frequent recurrence of El Niño also for the two millennia of the Common Era. Huckleberry and Billman [84] describe 13 ENSO-related flood and debris flow deposits beneath the present floodplain surface of Quebrada de los Chinos, that are younger than 2000 cal y BP. The findings of these authors seem to confirm the inference of Nials et al. [12] on apparent fluvial landscape changes due to severe precipitations (see 5.2), and reflect the late Holocene increases in El Niño activity [8,51].

### 5.4. Casma and Cerro Sechin (Lower Casma Valley)

With reference to radiocarbon dating, Wells [14,74] analysed in detail the alluvial terraces system which characterizes the lower Rio Casma Valley (Figure 1). The system

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presents three floodplain surfaces whose ages of formation are comprised between 3000 and 200 cal y BP (see Table 1 and Figure 4 of Ref. [14], pages 1135-1136) thus suggesting significant geomorphological changes during the late pre-Hispanic time driven by river sediment transport and tectonic uplift. These results are consistent with data on the beach ridge accretion of the Pampas Las Salinas [71,72], about 50 km northwest of the Rio Casma mouth. From a geological point of view, such a landscape dynamics is not surprising for valleys and coasts of the Peruvian desert. Late Pleistocene and Lower Holocene were, as example, earlier periods throughout which El Niños severely impacted coastal Peru, leaving signatures on ancient landscapes (see e.g. Refs. [16,77,85]).

13 flood deposits younger than 3.2 ka are recorded along the stratigraphic section of Wells [14,74], 6 of which deposited before the conquistadors first arrived in 1532. The upper two and the lower two of these latter are $^{14}C$ dated by means of incorporated organic material. The author, however, does not recognize the ca. 1100 event (i.e. the Chimu Flood) defined by Nials et al. [11] in the Moche Valley (see 5.2). She focus mainly on the recurrence of the hydrogeomorphic events rather than their strength and suggests, for the considered time interval, the increase in frequency of flooding and the occurrence of an event "*much larger than that which occurred during 1982-1983*" at least once every 1000 years. This hypothesis can be explained as follows: a) the Mega El Niño events [16,72] actually exist and cause flood disasters in coastal Peru and possibly extreme climatic anomalies worldwide; or b) the rainfall associated with the El Niño event is distributed such that extraordinary floods occur near Casma once every 1000 years [14].

Complementary evidences on the paleoflood record of the Casma district can provide by archaeological data from Cerro Sechin site (Figure 1). However, only one laminated mud deposit ascribed to runoff water has been archaeologically dated (see Samaniego et al. [70]) and may be correlate to a terraced alluvial deposit $^{14}C$ dated at 1200 BCE by Wells [74]. Likely, new geoarchaeological research in this area would help provide significant data on landscape change due to El Niño events.

### *5.5. Old Temple of Pachacamac and Urpi Kocha Lagoon (Lower Lurin Valley)*

According to Franco and Paredes, the Old Temple of Pachacamac was abandoned around 600 CE due to heavy rains that washed away and damaged the adobe walls of the building while runoff water deposited around thick layers of mud [82]. These authors argue that an unusual climate event triggered temple modifications, and led to the development of new social trends and the introduction of architectural elements from the Andes Highlands. Later, Franco stated "*there is no doubt that the rains that caused this event correspond to a Mega Niño*" [126], which is now referred to also as the 6$^{th}$ century El Niño event. The sedimentological and palynological study of Winsborough et al. on the near Urpi Kocha Lagoon (located 0.4 km W of Pachacamac) confirm such a suggestion [20]. These last authors found, in cores extracted from the bottom of the pool, evidences of three major floods associated with El Niño events in late pre-Hispanic time, the middle event dated between 436 and 651 CE (see Table 5 of Winsborough et al., page 611).

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**Figure 4.** Pachacamac archaeological site; 2016 satellite image (12°15′08″–12°16′02″S, 76°55′08″–76°53′31″W). Old Temple and Urpi Kocha Lagoon are marked by red circle and blue circle, respectively. Archaeological and geological inferences on El Niño events were argued by the authors [20,82,126].

The El Niño signature left at Pachacamac as recognized and interpreted by Franco and Paredes [82] is similar to the ones described by Samaniego et al. [70] and Wells [74] at Cerro Sechin (see 5.4), and by Nesbitt [112] at Caballo Muerto (see 5.3), respectively. It is apparent that, in late pre-Hispanic settlements, El Niño events may have left traces in the geoarchaeological record likely corresponding to landscape changes. Nevertheless, as carried out from further archaeological excavation, the adobe constructions of Pachacamac were seriously affected by repeated torrential rains up to the twentieth century, and especially by the 1925/26 El Niño event [127]. The erosive processes caused by these rains have partially erased the traces of the most ancient events, making more difficult the reconstruction of the paleoflood record at the lower Lurin Valley.

The validity of the hypothesis that one, or even two, El Niño events affected the central coastal Peru around 600 CE is confirmed by the findings of Mauricio [128] at the Maranga archaeological complex (lower Rimac Valley, 30 km north-west of Pachacamac). Within such a site, now incorporated into the southern suburbs of Lima, the author describes two destructive floods separated by a phase of reconstruction during the Middle Horizon ($^{14}$C dated between 550-690 CE). Despite the limited size of the site, several geoarchaeological sections showing the above sequence are reported as basic data.

### *5.6. Pampa de Palpa (valleys of Rio Ica and Rio Grande)*

The *pampa* southwest of Palpa (Figure 1) constitutes the northern margin of the Atacama desert, and was inhabited by several cultures during the pre-Hispanic time. It has been object of different studies on the development of loess deposits, paleosoils, and alluvial terraces that provide insights about the long-term relationship between climate processes and desert landscape changes [4,93,98,110]. Moreover, this hyper-arid region includes relevant sites of interest for the present review, and is next to the ceremonial center of Cahuachi (that will be discussed separately, see 5.7).

Located at the lower valley of Rio Ica, the Samaca fluvial plain (Figure 1) currently is a riparian oasis that hosts numerous archaeological and paleobotanic remains. The latter are mainly constituted by partially fossilized trunks of the phreatophyte *Prosopis*, as established by Beresford-Jones et al. [95,96]. The geomorphological, archaeological and paleoenvironmental evidences gathered by these authors, allow them to state the occurrence of a major El Niño events "*at some time toward the end of the Early Intermediate Period, which spread a deep fluvial layer across the upper Samaca Basin, caused the river to cut some 5 m down into its floodplain, and had catastrophic effects upon [a] canal system*" [95]. Such a result is consistent with the conclusions of other studies made in northern and central

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Peru [20,76,78]. However, it explicates part of the above landscape modification as well as of the decline of the settlement. In fact, according to [95,96,101], human-induced gradual destruction of *Prosopis* forest in pre-Hispanic time would have considerably increased the exposure to the flood hazard of landscape and settlement, making them more vulnerable to severe events. The deforestation process would be culminate during the Middle Horizon, causing the final abandonment of the settlement [96].

Later, large urban settlements developed in the Late Intermediate Period (1000–1400 CE) within the *pampa* of Palpa, the most prominent example of which is the so-called *Ciudad Perdida de Huayuri* that, according to Hanzalova and Pavelka [109], was destroyed by an El Niño event. However, no indications or evidence of such an episode were found in other articles identified by citation database queries (Section 4, Tables 3, 4). It must be observed that Eitel and his colleagues [4,98] posit an abandonment of such a "lost city" as a consequence of the depletion of water reserve, likely related to a climate change. The above questionable information in Ref. [109] may be due to a gap in literature knowledge.

### *5.7. Cahuachi Ceremonial Center (Middle Nazca Valley)*

According to Grodzicki [18,129] the archaeological site of Cahuachi was affected by three catastrophic floods caused by El Niño between 2100 and 1000 BP. These studies support the major landscape changes ascribed to El Niño events in late pre-Hispanic time for the whole coastal desert of Peru. The second event would have even caused the collapse of the Nasca Culture (around 600 CE) while the third completely buried the ceremonial center [17,18]. In support of his hypothesis, the author describes conglomerate deposits that would result from deposition of exceptionally large, fluid debris flows. Finally, the landscape of Cahuachi would be re-shaped (and the monumental building unearthed) throughout the last millennium. A necessary assumption for this argument is that abandonment and burial of the ceremonial center preceded the construction of the Nazca Lines [17]. However, such geoglyphs, created on the desert pavement by removing colored pebbles and leaving the underlying reg soil exposed, are mainly dated from 400 BCE to 600 CE [130–133].

Dealing with the second catastrophic flood inferred by Grodzicki [129], Silverman [24] observes that around 600 CE "*Cahuachi had ceased to function as the great early Nasca ceremonial center*". In their review on the occurrence of El Niño events, Machare and Ortlieb [52] consider the hydrogeomorphic events posited in Ref. [17,18] no more than possible local climate change indicators. Nevertheless, the main criticisms to the reliability of the Grodzicki's hypothesis come from the research group headed by Eitel and Machtle [4,93,98]. Starting from the observation of "*the good state of preservation of geoglyphs, even where they cross valleys or erosion rills*", such authors "*disagree with ideas that catastrophic El Niño events destroyed the Nasca Civilization*" [4]. Again, as a result of extensive field surveys, they remark how the integrity "*of the line exemplarily illustrates that the valley floor has never been flooded since the Nasca period. Only a small channel in the foreground provides evidence for weak episodic runoff events during the past two millennia*" [98]. Finally, these authors extend their conclusion also to the contiguous *pampa* of Palpa (see 5.6).

To further test the consistency of the hypothesis of Grodzicki, stratigraphic and petrographic analyses of upper bedrock and surficial cover of the ceremonial center were carried out by Delle Rose et al. [23]. The results of this study show that the conglomerate deposits interpreted by Grodzicki as signatures of El Niño events, belonging instead to the Tertiary-Quaternary clastic succession that forms the regional substratum. Such coarse-size sediments are, moreover, a source of pebbles and cobbles which form the desert pavement. The inconsistency of the Grodzicki's hypothesis was likely due to knowledge gap in geological stratigraphy [23].

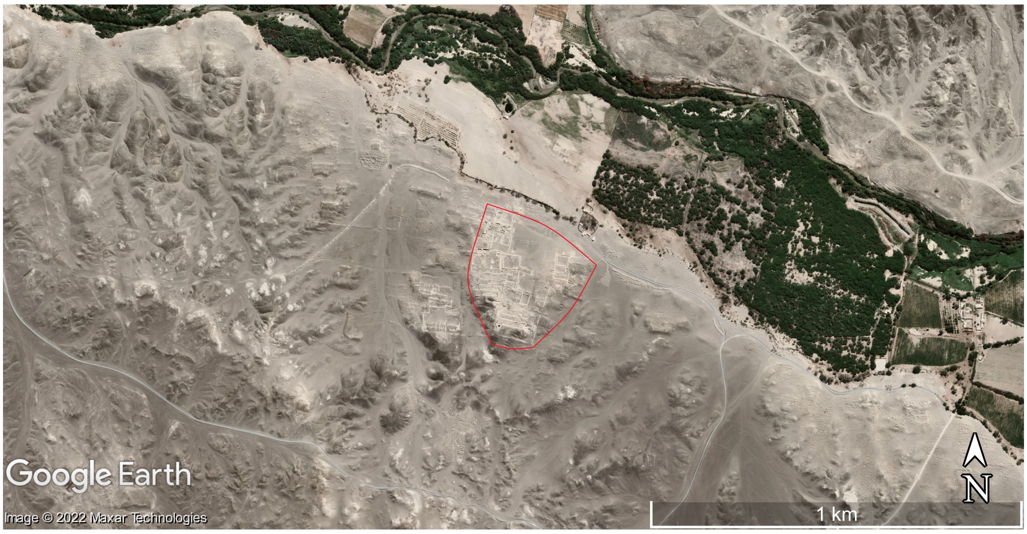


**Figure 5.** Cahuachi ceremonial center; 2022 satellite image (14°48′41″–14°49′30″S, 75°07′45″–75°06′11″W). The monumental building area investigated by Grodzicki [17,18], Orefici [134] and Delle Rose et al. [23] is marked by red line.

Recent archaeological excavations on *Templo Sur* have shed new light on hydrogeomorphic events that damaged the adobe brick buildings at Cahuachi during the development of the Nasca Culture. In fact, the inferences of Orefici [134] about two torrential rains that partially destroyed roof and walls of the temple next to the end of the fourth century CE, a time with no El Niño events is reported in the reviewed literature, lead to reconsider both the climatic pattern responsible for the events and the type of Earth surface response expected for the coastal desert. It must be noted that samples gathered at Cantalloc (20 km east of Cahuachi) by Pavelka et al. [114], considered by these authors remains of an ancient flood, are $^{14}$C dated between 47 and 480 CE.

### *5.8. Moquegua Valley and Quebrada Miraflores*

Geoarchaeological studies throughout Moquegua Valley and surrounding areas [19,21,47,76] were mainly aimed to argue the relationships between El Niño events and human responses rather than possible landscape processes [83]. Nevertheless, data exposed in the reviewed works allow to argue abrupt geomorphological changes for desert environment. As a matter of fact, already thirty years ago, Moseley et al. [76] stated that "*serious landscape modification should indicate extreme ENSO conditions or ancient "Mega-Niño" phenomena*".

Three main depositional units confidently ascribed to El Niño events have been identified and dated by the authors. 2 of them have a late pre-Hispanic age while the third (named Chuza Unit) is dated at 1607-1608 CE [88]). The oldest $^{14}$C dated unit (730-690 CE) is formed by debris flow deposits (identified within the dry Rio Muerto sub-basin [21], see Figure 6), and flood deposits recognized elsewhere [47]. As it signed fast and extensive regolith mobilization, such unit constitutes an evidence of a singular hydrogeomorphic event. For what concerns the regolith production, in a highly seismic region like the coastal Peru, it is increased by the shattering of the landscape during the frequent earthquakes that produce pervasive ground cracking and microfracturing of hillslope materials [76,88].

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**Figure 6.** Rio Muerto sub-basin; 2020 satellite image (17°17′58″–17°18′45″S, 70°59′11″–70°57′34″W). The samples point of Miraflores Unit [47] is indicated by red arrow (see text). Upstream, the cracked hillslope area of regolith production may be observed.

The second depositional unit of interest for this review is a horizon marker referred to the Miraflores Flood event [76]. It is formed by debris flow deposits and flood deposits indirectly dated between 1350 and 1370 CE by ice cores data of the Quelccaya Ice Cap [19,135,136]. Such an age is confirmed by radiocarbon dates of samples taken at Rio Muerto [47] (Figure 6). At Quebrada Miraflores (Figure 7), the thickness of the marker reach 1.2 m, which is a higher order of magnitude compared with any other flood deposits preserved in the geological record, including the Chuza Unit.

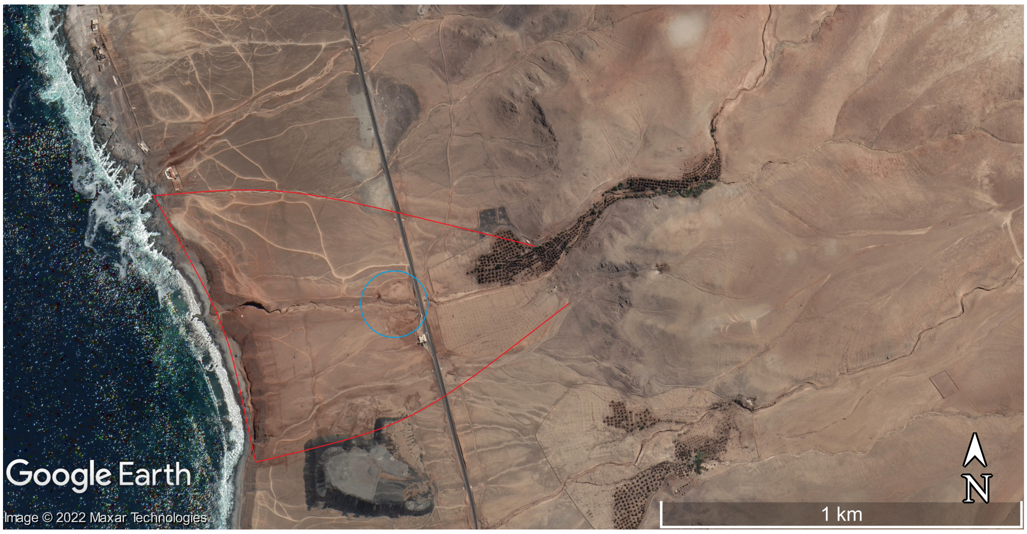


**Figure 7.** Quebrada Miraflores; 2021 satellite image (17°25′49″–17°26′36″S, 71°22′22″–71°21′42″W). The extent of Miraflores Unit according to Satterlee et al. [19] is marked by red line, the location of Chiribaya settlement by blue circle (see text).

In this last area, mobilized sediments spread laterally out of the braided streams and up the ravine walls before descending to the sea across the coastal plain. Large clasts and boulders with a diameter of up to 3 meters were also moved across the coastal plain by the Miraflores Flood [19]. Such a hydrogeomorphic event would be also implicated in the collapse or decline of the Chiribaya culture [103,137]. The imprint on the Peruvian desert surface of this $14^{th}$ century El Niño event is confirmed by zooarchaeological researches. Rubinatto et al. posit "*that the abundance of anuran remains*" they found in Rio Muerto area

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may be related to the Miraflores Flood, since "*this event generated increased rainfall in the desert, creating conditions favorable for frogs and toads*" [123]. However, for a critical examination of such a hypothesis, these authors exhort further paleoenvironmental and zooarchaeological studies. In any case, the potential of Miraflores Unit as horizon marker should be fully exploited in landscape reconstruction.

### *5.9. Discussion Summary*

Landscape processes confidentially ascribed to El Niño events are chronologically summarized in Table 5. They are considered responsible for changes in late pre-Hispanic coastal Peru to varying degrees.

**Table 5.** Chronology of late pre-Hispanic El Niño events argued as possible responsible for landscape modifications

| Date | Landscape process | Basin or Site | Reference |
|---|---|---|---|
| ca. 1450 CE[1] | formation of alluvial terraces | Rio Casma | [14] |
| 1360-1350 CE[1] | debris flow activation, flood sedimentation | Q. Miraflores, Rio Moquegua, Rio Muerto | [19,21,47,76] |
| 1325 CE[1] | formation of alluvial terraces | Rio Casma | [14] |
| ca. 1100 CE[2] | flood sedimentation | Huacas de Moche | [11,12] |
| 1008-995 CE[1] | mud deposition from runoff | Pachacamac | [20] |
| 1000-650 CE[2] | flood sedimentation | Batan Grande | [13] |
| 730-690 CE[1] | debris flow activation, flood sedimentation | Rio Muerto, Rio Moquegua | [21,47] |
| 651-436 CE[1] | mud deposition from runoff | Urpi Kocka | [20] |
| ca. 600 CE[2] | mud deposition from runoff | Pachacamac | [15,82] |
| ca. 600 CE[2] | mud deposition from runoff | Huacas de Moche | [78] |
| 600-550 CE[2] | flood sedimentation | Samaca | [95,96,101] |
| ca. 0 CE[1] | formation of alluvial terraces | Rio Casma | [14] |
| 100 BCE[1] | debris flow activation | Rio Muerto | [47] |
| ca. 1200 BCE[1] | formation of alluvial terraces | Rio Casma | [14,74] |
| ca. 1450-1600 BCE[1] | mud deposition from runoff | Caballo Muerto | [112] |

[1] calibrated $^{14}C$ age; [2] date inferred from archaeological remains.

The above chronology may be tentatively compared with paleo El Niño proxies. By analyzing a high resolution marine sediment record about 60 km west of Lima, Rein et al. [141] argued maximum of El Niño activity during the third and second millennium BP, while El Niño events would have been persistently weak during the Medieval Climate Anomaly (MCA, ca. 900-1300 CE). Yan et al. [143], computing SOI (Section 2) from different precipitation proxy records in Pacific Ocean, found negative index during MCA, which indicates general El Niño-dominated conditions. However, such differences in climatic reconstructions may reflect the geographic complexities of the Pacific coastal regions [41]. As a matter of fact, SOI calculated for the Galapagos Islands (850 km off the coast of Ecuador) shows positive values during MCA in contrast with the ones of western Pacific [143]. Oxygen isotopes ratio ($\delta^{18}O$) of ice core record from Quelccaya ice cap is depleted in $^{18}O$ between 1100 and 1300 CE thus highlighting a warming trend over the Andes [142]. Such a finding is consistent with low El Niño activity during MCA [141,144]. Consequently, the hydrogeomorphic events that can be attributed to El Niño with lowest uncertainties should be those that precede or follow the MCA.

The first evaluable hydrogeomorphic signature is dated at about 3.0 ka BP [112]. To date, the magnitude of landscape response to this event is not yet investigated, while the only identified surface process is mud deposition from runoff over archaeological structures (Section 5.3). It must be emphasized that such an occurrence would have been nearly contemporaneous with the incoming of the modern features of ENSO (Section 2).

Some centuries later (ca. 1200 BCE), Casma Valley was affected by torrential rains, thus related proxies are preserved in both alluvial terrace sequence [74] and archaeological record of Cerro Sechin [70]. The hypothesis that both signatures were produced by the same

El Niño event should be verified by further research (Section 5.4). According to Wells [14], the alluvial terrace system of the Casma Valley contains 13 flood deposits ascribable to late Holocene El Niños. 4 $^{14}$C-dated events occurred in pre-Hispanic time but, unfortunately, no date fits well with events identified in other basins or sites (Table 5). Differently, one or more events transpiring about 600 CE have hit the valleys of Rio Moche (Huacas del Sol), Rio Lurin (Pachacamac), and Rio Ica (Samaca) (Sections 5.2, 5.5, and 5.6). Such evidence has led some authors to speak of a 6$^{th}$ century Mega El Niño (see e.g. [18,20,126]).

Nevertheless, the recognition of one or more events to the transition from the first to the second millennium CE at some sites of northern-central coastal Peru (Table 5), has strengthened the paradigm of the 11$^{th}$ century Mega El Niño (see e.g. [18,52,138]). The seminal reconstruction of the Chimu Flood by Nials et al . [11,12] has greatly influenced the literature but it should be tested by further research, and the related deposits absolute-dated. Also the age of the ethno-historical Naymlap Flood remains unclear [76,125]. It ranges from around 1000 CE (see e.g. [13,20]) to around 1350 CE (see e.g. [14,139,140]). As a matter of fact, Naymlap Flood "*may refer to different floods in different valleys at different times during the Late Intermediate Period*" [25].

If in one hand El Niño events have had catastrophic consequences associated with floodplain stripping, irrigation system damage, and settlement destruction, in the other hand they have also provided cultural opportunities, triggered technological innovation, and played important roles in replenishing and maintaining groundwater resources throughout the coastal desert [47,80]. Nevertheless, extensive human intervention (desert reclamation, *Prosopis* deforestation) have likely determined some variations in landscape response, also increasing exposure to extreme events of settlements and infrastructures (Sections 5.2, 5.6).

Authors have deeply investigated landscape response and destructive effects of the Miraflores Flood, the last hydrogeomorphic event ascribed to a "Mega" El Niño in pre-Hispanic time [19,21,47,76,103,137] (Section 5.8). With the arrival of Spanish conquistadors, the production of historical documents begins, so that the sources of knowledge on El Niño events are enriched with a fundamental element [30,52,73]. However, only with the systematic observations on the warm ocean current running along the central Pacific coast of South America (El Niño in its initial meaning, see Section 2) that all the necessary criteria for proof El Niño events are available.

## 6. Conclusions

Landscape modifications ascribed to El Niño events in late pre-Hispanic coastal Peru were mined and summarized by processing comprehensive databases (Section 3). Then, the review of the selected documents was performed in accordance with dependable guidelines (Section 4). The examination of the reliability of data contained in the reviewed documents made it possible to identify critical knowledge gaps in the treated topic and to suggest possible research goals (Section 5). Discussed El Niño proxies provide incomplete and heterogeneous paleoflood record for the coastal Peru. The current state of geoarchaeological knowledge is not enough to define the temporal and spatial trend of the landscape effects of El Niño events during the late pre-Hispanic time. However, it gives some essential milestones (Table 5).

Several landscape processes ascribable to El Niño events have been recognized by authors (Table 5). The less impressive one, mud deposition from runoff, has however been sometimes identified in archaeological sites (see e.g. [15,112]), thus allowing valuable chronological attributions (Sections 5.3, 5.5). Slack-water deposits found along the valleys of Rio La Leche and Rio Juequetepeque (Section 5.1) as well as other flood sediments recognized along the valleys of Rio Casma and Rio Samaca (Sections 5.4, 5.6), and at the sites Huacas de Moche and Batan Grande (Sections 5.1, 5.2), could have great potential in landscape reconstruction. The activation of debris flows has been recognized throughout Jequetepeque Valley (Section 5.1), Moche Valley (Section 5.3), Moquegua Valley and surrounding areas (Sections 5.8). Within the catchment of Rio Muerto, regolith denudation

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and mobilization have had great size and extent [47]. Miraflores Unit signed one of the major landscape changes for the whole coastal Peru, resulting also involved in the end of the Chiribaya culture. It is apparently the better investigated proxy record related to an El Niño event (Section 5.8, Table 5).

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## Appendix A Full-text analyzed works excluded from the discussion

As explained in Section 4, 20 documents selected from database search were not discussed in Section 5 because they are not appropriate for the review's purpose (Table A1).

**Table A1.** Full-text analyzed works with no data useful for the objective of the review.

| Reference | Main Issue |
|---|---|
| [1] | Geomorphological effects of 1982/83 and 1997/98 El Niños |
| [56] | Morpho-pedological characterization of a Western Andean offshoot |
| [79] | Early-middle Holocene human-nature relationships |
| [87] | Late Quaternary evolution of a stretch of the Ecuador coast |
| [89] | Ancient peoples ability to mitigate El Niño effects |
| [90] | Debris flow burial episode of a Late Pleistocene site |
| [91] | Late pre-Hispanic desert reclamation and El Niño effects mitigation |
| [92] | Development of desert soil under ENSO conditions |
| [46] | Reliability of agricultural practices to face El Niño negative effects |
| [97] | Early-middle Holocene occupation history of a costal site |
| [99] | Introduction on methods and technologies in geoarchaeology |
| [100] | Geomorphological effects of El Niño on Western Andean Slope |
| [102] | Late Quaternary evolution of an Amazon Basin sector |
| [108] | Characterization of late Holocene coastal upwelling in Peru |
| [111,117] | El Niño influences on settlement pattern of a Western Andean offshoot |
| [113] | Paleobotanical analysis aimed to explore ancient desert reclamation |
| [115] | Reconstruction of the paleo-evolution of a coastal lagoon |
| [116] | Biological crusts effects on reg soil evolution |
| [119] | Late Quaternary environmental history of a Western Andean offshoot |

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