Integrating collapse theories to understand socio-ecological systems resilience

Cathy Rubiños and John M Anderies

1 Universidad Del Pacífico, Av. Salaverry 2020, Jesús María, Lima, Peru
2 Center for Behavior, Institutions, and the Environment, Arizona State University, Tempe, AZ, United States of America
3 School of Sustainability, Arizona State University, 800 Cady Mall, Tempe, AZ 85281, United States of America
4 School of Human Evolution and Social Change, Arizona State University, Tempe, AZ 85287, United States of America

E-mail: ca.rubinosv@up.edu.pe and m.anderies@asu.edu

Keywords: socio-ecological systems, societal collapse, robustness, resilience, environmental change, El Niño Southern Oscillation (ENSO)

Abstract

The world is facing new environmental challenges that may trigger the collapse of some social-ecological systems (SES). More extreme weather events may be much more common in the decades to come due to climate change. Although we have an idea of what climatic events to expect in each region, we know less about how SES can cope with these challenges. We study The Peruvian Piura Basin, which has been exposed to harsh environmental events associated with the El Niño Southern Oscillation (ENSO) for centuries. The Piura basin was home to the ancient Moche civilization, which collapsed due to a combination of factors, but strong El Niño events likely played a significant role. To analyze the resilience of The Piura Basin to flood events, we used as guidance the Robustness Framework and different propositions from prominent collapse theories to carry out a longitudinal study based on both primary and collected secondary data. We found that the Piura basin is very fragile based on almost all of the predictions of collapse theories (especially with respect to selfish elites, centralized governance, systems interconnection, anticipation capacity and sensitive dependence on resources), but the biggest strength is its growing stock of social capital. In small steps, user associations have been collectively working towards solutions for water conservation and public-infrastructure maintenance. There is a long way to go, but with the right policies to encourage the strengthening of these associations, the Piura basin could become more resilient to future El Niño events. This study also provides methodological and theoretical insights that can contribute to theory building for the resilience of SES.

1. Introduction

Historically, we find that civilizations are built around water sources and land resources that make agriculture possible. Mesopotamia, Egypt, China, the Indus Valley, Andean South America, and central Mexico are some examples (Lucero 2002). This is not surprising, since it was agriculture that made place-based societies possible (Ehrlich and Ehrlich 2013). But agriculture was not a panacea (Ponting 1993). We can imagine our ancestors after discovering agriculture asking themselves how to increase water availability and stability to feed the growing population that was a product of the now stable food source, and so on in a vicious cycle (Tainter 1988, Harari 2016). From this example we can easily perceive the resilience-fragility tradeoffs inherent in securing the most basic needs of societies: food and water.

History reflects how, in different cultures, human curiosity, intelligence, and imagination have been enough to overcome these challenges and build different irrigation infrastructures and the rules to govern them, not only to manage the valuable resource, but also to respond to environmental threats (Diamond 2005, Costanza et al 2007, Ehrlich and Ehrlich 2013). However, we have also observed that many civilizations were unable to overcome challenges, and collapsed (Diamond 2005).

The world is facing new environmental challenges that may trigger a collapse, or, more precisely, ‘loss of socio-political-economic complexity usually accompanied by a dramatic decline in population...
of social capital. In small steps, user associations have found that the Piura basin is apparently very fragile, and their propositions for resilience-fragility trade-offs in the Piura Basin; (iv) finally, we conclude. We use as a case study the Peruvian Piura Basin, an agricultural based society, is highly exposed to environmental perturbations (Angulo 2006). The basin has been exposed to harsh environmental events associated with the El Niño Southern Oscillation (ENSO) for centuries and is now threatened with more frequent and intense flood episodes due to climate change (Bustamante 2010). The Piura basin was also home of an ancient civilization named Moche, which collapsed due to a combination of factors, but strong El Niño events likely played a significant role (Fagan 2009). Given that many societies have experienced droughts, floods, or other environmental perturbation without showing major social disruption (Tainter 1988, Diamond 2005), authors suggest that the resilience of socio-ecological systems (SES) to those disturbances may depend on combinations of specific factors such as political, economic, or ecological characteristics (Motesharrei et al 2014). We perform a systematic literature review to identify prominent collapse theories and extract propositions as key factors observed in SES collapses. We then leverage those propositions to analyze the resilience of SES to environmental disturbances, using as a case study the Peruvian Piura Basin.

A resilient system does not necessarily perform at its maximum potential (Csete and Doyle 2002), but it does remain functional despite internal (e.g. population growth) or external (e.g. droughts) perturbations. To study resilience of a SES, we need to be explicit about specific perturbations, given that systems face tradeoffs between resilience to particular expected disturbances and uncertain fragilities to others (Janssen and Anderies 2013). We analyze the resilience of the Piura Basin to flood events, and by performing a longitudinal analysis of the basin we illustrate how this outcome has been affected by efforts to increase water availability and stability to feed a growing population, among others.

This article is arranged in the following sections: (i) we describe our case study, the environmental perturbation to be analyzed, the framework and methods used; (ii) we highlight prominent collapse theories and their propositions for resilience-fragility tradeoff analysis; (iii) we assess fragility-resilience tradeoffs in the Piura Basin; (iv) finally, we conclude. We found that the Piura basin is apparently very fragile based on almost all of the predictions of collapse theories, but an important strength is its growing stock of social capital. In small steps, user associations have been collectively working towards solutions for water conservation and public-infrastructure maintenance.

There is a long way to go yet, but with the right policies to encourage the strengthening of these associations, the Piura basin could become more resilient to future El Niño events.

2. Method

2.1. Case study

The Piura River is 280 kilometers long, and the basin surface is 12 216 km$^2$ (see figure 1). The basin is divided into two irrigation systems, 'Alto Piura' on its right margin in the highlands, and 'Medio y Bajo Piura' on its left margin on the coast. This study is focused on the Medio y Bajo Piura sub-basin, because this area is more exposed to El Niño flood events than the Alto Piura sub-basin. Water from the Piura River is almost completely used before reaching Medio y Bajo Piura, but the sub-basin receives water from the Poechos Dam (on the Chira River) through the ‘Daniel Escobar’ canal that was built in the 1970s (GRP et al 2009).

The Piura River’s flow is normally low, but in El Niño events the river grows to a point that it becomes dangerous. For example, in the station of the river that is called 'Sanchez Cerro,' river flow in a normal year is no more than 140 m$^3$ s$^{-1}$ at its highest, but in 1983 it increased to 3200 m$^3$ s$^{-1}$, and in 1998 to almost 4500 m$^3$ s$^{-1}$, damaging irrigation and road infrastructure (GRP et al 2009).

Agriculture is an important activity in the basin, involving about one-third of the population (INEI 2016). 48 534 ha are used for agriculture, of which 84% is irrigated. There are 75 176 farmers with small parcels averaging 0.65 ha. By 2016, the main crops in the Medio y Bajo sub-basin were rice (67%), corn (23%), and cotton (7%), all of which have a safe market, with their growers having access to credit and technical assistance.

2.2. ENSO effects on the Piura Basin

El Niño is a climatic phenomenon related to the warming of the east equatorial Pacific Ocean, which happens cyclically but erratically. The cycle takes between three and eight years, but with the impacts of climate change, it is expected to be more frequent (Bustamante 2010). El Niño is the warm phase of the three phases of the ENSO. In its most intense manifestation, causes catastrophic floods in the equatorial zone, and especially affects the southern coast of Ecuador and northern coast of Peru. El Niño is rated from ‘moderate’ to ‘very strong,’ depending on the sea-temperature change and its intensity. When El Niño is moderate, it can bring more benefits than damage as, for example, the regeneration of dry forests, and even the creation of new water sources (Woodman 1998, Brack and Mendiola 2000). In the 20th century, the two El Niño events...
rated as very strong were those of 1982–1983 and 1997–1998, the latter being the strongest episode ever recorded. During the El Niño of 1997–1998, the precipitation in Piura was 260 times the average of normal years. The excess precipitation flooded the city and affected 120,637 people in Piura, destroyed 10,255 houses, took around 200 lives, and was responsible for 40 million USD of crop loss (INDECI 1998). In 2017, Piura experienced a Coastal El Niño, different from other Niño events because it was confined to the Peruvian and Equatorial coasts, and not a basin-wide phenomenon (Takahashi 2017). The damage caused by El Niño Costero was significant and similar to that of 1982–1983 and 1997–1998, and Piura was the most affected region in Peru (PAHO 2017).

There is evidence that the Peruvian north coast has been affected by El Niño for centuries, and that the Moche ancient civilization, located in the north coast of Peru, including the Piura basin, collapsed after a very strong El Niño event (Fagan 2009). The effects of El Niño in the basin have been recorded and analyzed as discrete incidents in windows of time and specific sectors. They have not been analyzed longitudinally or using a systems-thinking approach as performed here. The Piura Basin is threatened with more frequent and more intense episodes of El Niño than the episodes that Piura has experienced so far, which makes an urgent case for studying its fragility and resilience in order to direct current policies and to avoid potential catastrophic events.

2.3. Framework

For internal validity, and to facilitate logical reasoning (Miles and Huberman 1994, Yin 1994) we use the Robustness Framework proposed by Anderies et al (2004) as a guide for data collection and analysis. The Robustness Framework was created to systematically develop a theory of SES robustness; a concept related to resilience that also addresses the question of conscious institutional designs (Anderies et al 2004, Janssen and Anderies 2013).

Unlike other frameworks for resilience (e.g. Leach et al 2010, Garmestani and Harm 2013), or SES (Ostrom 2005, 2007) research, the Robustness Framework enables the analysis of system relationships (links 1–6 shown in figure 2) among key SES components (A–D) to foresee potential perturbations (links 7 and 8) and the system outcomes they might produce (Anderies 2016). Hence, we use the Robustness Framework to analyze how in a specific context (Piura Basin), the characteristics of the resource system (A; watershed), their main users (B; farmers), public infrastructure (D; reservoir, canals, rules, laws), public infrastructure providers (C; regional and national government, water association), and the relationship among them, contribute to the resilience of the basin to flood events. The framework was also used to organize identified propositions from collapse theories reviewed. Components (A–D) and Links (1–8) were used to code selected research works and to identify and classify proposition as explained in the next subsection.

Figure 1. Map of the Piura Basin.
2.4. Literature review

For building validity, we follow the analysis of propositions (Miles and Huberman 1994, Yin 2003) from theories or hypotheses proposed in previous research of collapse of societies. We reviewed articles and books (referred in 4) that, by applying case study comparisons, proposed explanations for the collapse of societies beyond exogenous environmental or other perturbations. Even though the complexity of SES makes it impossible to find key recipes of collapse or resilience (Weiss and Bradley 2001, Costanza et al 2007, Butzer 2012, Middelton 2017), we consider each of these propositions as elements that can shed light on the design of resilient systems. Following the systematic literature review method suggested by Gough et al (2012), we developed a search protocol with inclusion criteria for the selection of studies to be reviewed. A flowchart of studies selection and selection criteria are detailed in figure 3.

To locate references, we used Google Scholar search engine by entering as key words: ‘society’, ‘civilization’ and ‘collapse’. A total of 48 500 references matched with the search criteria, which after filtering by relevance and title screening 250 studies were preselected. 38 references where chosen after abstract screening, and after a full text review 36 references were selected for its inclusions in the analysis. Figure 4 shows how the propositions extracted for the literature review were organized with the guidance of the Robustness Framework, along with the references of authors that supports each of them.

2.5. Data collection and analysis

We used secondary (journal articles, situation reports, newspaper columns, internet articles) and
Figure 4. Robustness framework and propositions for the analysis.

| N | Framework | Proposition (causes of collapse) | Reference |
|---|-----------|----------------------------------|-----------|
| [1] | A | Environmental perturbations highly unpredictable | Ponting (1993); Ehrlich and Ehrlich (2013). |
| [2] | B | Attachments to values that are detrimental to the environment / Moral decay | Diamond (2005); Timmerman (1981); Ehrlich and Ehrlich (2013); Butzer (2012) |
| [3] | C | Selfish elites | Diamond (2005); Butzer (2012) |
| [4] | D | Poor anticipation capacity | Diamond (2005); Johnson (2016) |
| | | The system is too complex and rigid | Tainter (1988); Brunk (2002) |
| [6] | Link 1 | Overshoot (large number of users with respect to the resource system) | Culbert (1973, 1988); Redman (2004, 2005); Holling (2001); Ponting (1993); Ehrlich and Ehrlich (2013); Motesharreiet al. (2014); Abel (1980); Catton (1982); Kammern (1994); Lauder (1987); Postan (1966); Redman (1999); Redman et al. (2004); Wood (1998); Wright (2004) |
| [7] | | High definition of "subsistence" | Pezzey and Anderies (2003); Motesharreiet al. (2014) |
| [8] | Link 2 | Centralized governance | Yoifer and Cowgill (1991); Lucero (2002); Butzer (2012) |
| [9] | Link 3 and Link 6 | Sunk Costs | Janssen et al. (2003) |
| [10] | Link 4 | Physical constraints to adapt to new circumstances | Diamond (2005); Butzer (2012) |
| [11] | Link 5 | Economic stratification of society into elites and masses | Timmerman (1981); Ponting (1993); Motesharreiet al. (2014); Brenner (1976); Parsons, (1991); Turchin, (2005); Turchin, (2006); Turchin and Nefedov (2009); Diamond (2005); Goldstone (1991); Ibn Khaldun (1958) |
| [12] | Link 7 and Link 8 | The fragility is transmitted by the interconnection of systems | Brunk (2002) |
primary data, as recommended by Patton (1990) and Yin (2003), to supplement and compensate for the limitations of each other. We collected primary data from fieldwork in Lima (for national governance information) and Piura during the month of July, 2016. We performed semi-structured interviews. No longer than 90 min in-person interviews were performed in Spanish, at the location of the interviewee’s preference, either their office or farm (see translated interview protocol in supplementary material (stacks.iop.org/ERL/15/075008/mmedia)). Most of the time, actors supported many of their answers with secondary information and own written statistics.

Since the aim of this research is not to propose any generalization, but to realize an in-depth exploration of phenomena we applied a purposeful sampling (Patton 1990) and selected information-rich actors that contributed on secondary source validation and in new data generation. Hence, different types of actors were interviewed: five farmers, three members of the Local Water Authority (ALA), two members of the National Water Authority (ANA), the Vice-minister of Environmental Disasters Prevention (Ministry of Agriculture), three members of academia, four major infrastructure managers, two minor infrastructure managers, and one archeological expert on the Moche civilization. Even though due to time and resources constraints sample size for primary data is small (19), we were able to collect all the information needed about the Piura Basin according to the guidance of the Robustness Framework. Secondary data provided the guidelines for primary data gathering and for cross-validation in an iterative fashion. Collected data (primary and secondary) was then organized and input in a table following the framework components and links and subcategories shown in table 1 of supplementary material. Few contradictory information was identified among interviewees’ answers, but when identified, information was validated with secondary sources.

We performed a fragility-resilience assessment of the basin (section 4 and summarized in table 1) by contrasting the propositions extracted from our collapse theories review and information gathered and organized according to components and links of the framework. When a proposed cause of society collapse (e.g. high levels of inequality) was identified in the basin, then we assessed the system as ‘fragile’ in that proposition. Similarly, when we found that the basin outperforms a proposition of collapse (e.g. low levels of inequality), we assessed the system as ‘resilient’ in that proposition.

3. Collapse theories propositions

Societal collapse is a fascinating topic that has been of interest to many scholars (Butzer 2012). As a result, it is possible to find diverse propositions as determinants of socio-ecological systems (SES) collapse (see figure 4), that recognize the combination of environmental or other external perturbation as stressors, and weak institutional arrangement as determinants of collapse (Butzer 2012). Tainter (1988), for example, suggests that as societies mature, institutions and hard infrastructure become so complex and rigid that they become extremely vulnerable to shocks. When a civilization reaches that point, it becomes unable to withstand a disturbance of any type (environmental, wars, social, etc), and the population either disappears or migrates out of the system. Brunk (2002) agrees with Tainter’s theory, and argues that in societies that are more interconnected, cascade effects of collapses may occur.

A larger group of scholars (Postan 1966, Cubí 1973, 1988, Abel 1980, Caton 1982, Ladurie 1987, Ponting 1993, Kammen et al 1994, Wood 1998, Holling 2001, Redman 2004, 2005, Wright 2004, Ehrlich and Ehrlich 2013, Motesharrei et al 2014) argues that a major cause of collapse, is the ‘overshoot effect,’ in which case a large population demands more than the available resources in a system. As a result, people either migrate to another system, or perish. The overshoot effect is also considered in the ‘release’ phase of adaptive-cycle explanations (Holling 2001) from resilience theory. Combined with the overshoot effect, Pezzey and Anderies (2003) propose that culturally defined subsistence needs affect the process of collapse due to the high levels of what Motesharrai et al (2014) referred to as ‘depletion per capita.’ They argue that it is not only the population-resources ratio, but also, and most importantly, population consumption needs perception (and thus their consumption) that determines the ‘release’ or ‘overshoot’ point.

Another prominent hypothesis suggests that economic stratification of society into elites and masses, has a key role in societal collapses (Khalid 1958, Brenner 1976, Timmerman 1981, Goldstone 1991, Parsons 1991, Ponting 1993, Diamond 2005, Turchin 2005, 2006, Turchin and Nefedov 2009, Motesharrei et al 2014). Authors stress the relevance of societies’ perceptions of equity, arguing that class conflicts can create internal disturbances that weaken the system as a whole. Others suggest that the centralization of power in few decision-making actors has an effect in the speed and quality of reaction to perturbations, making it suboptimal for adaptation (Yoffee and Cowgill 1991, Lucero 2002, Butzer 2012).

Jansen et al (2003) proposed that a sunk-cost effect should be also considered as a factor that may contribute to SES collapses. They claim that some societies that collapse may have been attached to the efforts of achieving high returns after completing large investments, even when experiencing the
Table 1. Resilience assessment of the Piura system based on collapse theories.

| N  | Proposition (causes of collapse)                                                                 | Assessment                          |
|----|-------------------------------------------------------------------------------------------------|------------------------------------|
| 1  | Environmental perturbations highly unpredictable (e.g. the impacts of El Niño 2015–2016 were much less than expected, and 2017 Coastal El Niño was not timely forecasted, occurring even under a severe drought; it is considered a climate surprise) | Fragile                            |
| 2  | Attachments to values that are detrimental to the environment                                   | Fragile                            |
| 3  | Agricultural expansion is one of the causes of deforestation and land degradation upstream of the Piura River, where the runoff during flood events increases. | Resilient                           |
| 4  | Selfish elites                                                                                | Fragile                            |
| 5  | Local governments tend to give priority projects investments that increase their likelihood of reelection, which are regularly unrelated to disaster prevention. |                                    |
| 6  | Disasters risk management is unstable, with changing policies and staff. It is also unclear with respect to responsibilities and hierarchy. Main decisions are made at a national level with few local input and low flexibility to adapt to local conditions. The challenges of identifying high-risk areas, combined with the socio-economical characteristics of the population living in these areas make governmental efforts of population resettlement very problematic. | Fragile                            |
| 7  | Coastal El Niño of 2017 developed rapidly with no warning and had catastrophic effects. There were conflicting forecast between international and national monitors. For the Coastal El Niño of 2017, once the danger was identified, the communication channels for evacuation failed, and the majority of residents was unaware of which were the safe areas, or preferred to stay in their residence for fear of losing their belonging to strangers. | Fragile                            |
| 8  | The system is too complex and rigid                                                            | Fragile                            |
| 9  | Overshoot (large number of users with respect to the resource system)                          | Fragile                            |
| 10 | Definition of ‘subsistence’                                                                    | Fragile                            |
| 11 | Centralized governance                                                                        | Resilient                           |
| 12 | The current society settled in the Piura Basin has a more decentralized and less hierarchical governance structure for water management |                                    |
| 13 | Sunk Costs                                                                                   | Fragile                            |
| 14 | The Poecho project (canals, reservoir, and drainage system) has a high cost of maintenance due to its size, and its water-retention performance in flood events is low. There are many squats settlements in the path of the river. Resettlement is very costly. |                                    |
| 15 | Physical constraints to adapt to new circumstances                                            | Fragile                            |
| 16 | The Bajo y Medio Sub-basin is located in an area of flat slope, while the upper sub-basin presents steep slopes making the river runoff in flood times very dangerous. —Ecosystem prone to salinization, desertification and mudslides. Social: The Poechos Reservoir helps to capture water from floods. It has, however, lost its 50% of capacity. Lack of proper rainwater drainage systems in urban and agricultural areas. Immigrants that formerly lived in different ecological areas possess different construction technologies and adaptation strategies that are not consistent with the ecological risks of the basin. | Fragile                            |

(Continued)
opposite. As a result, they may have been unsuccessful to overcome a perturbation by failing to switch strategies. Diamond (2005) after studying 15 systems that collapsed and some others that did not, found some commonalities in the cases that collapsed, and brought to the conversation additional potential causes of collapse, that are also supported by other scholars: (i) selfish elites, (ii) moral decay (iii) physical constraints to adapt, and (iv) limited anticipation capacity.

Selfish elites refer to rulers that were benefiting most from the system opposed change at the expense of society and who do not favor ecological conservation either (Butzer 2012). The moral decay proposition refers to society’s attachment to values and activities that were detrimental to the ecological environment (Timmerman 1981, Butzer 2012, Ehrlich and Ehrlich 2013). Soil degradation, deforestation, or groundwater depletion, are examples of, consequences of productive activities that undermine the importance of the ecological conditions. This proposition argues that a stressed or degraded environment potentiates the effects of perturbations (e.g. slope failures, lower productivity that pressures the environment), unleashing catastrophic consequences.

Butzer (2012) supports the physical constraints on people adaptation to new circumstances proposition and highlights how arid lands in the Near East have been more vulnerable than societies in southern Europe. Arid lands tend to turn over to desert after a temporary abandonment making reconstitution very difficult, contrary to non-arid regions. Hence, less social effort and investment is needed for reestablishment. Finally, failure to anticipate or perceive the problem (Johnson 2016) refers to the human capacity to cope with uncertainty whereas another proposed factor, also related to uncertainty, refers to the ecological characteristic ‘highly unpredictable’ (Ponting 1993, Ehrlich and Ehrlich 2013), as in the case of El Niño events.

4. Resilience to flood events in the Piura Basin

The Piura Basin has attracted multiple settlements and supported societies dating from 9000 B.C. (Huertas 1996). The Moche society is one of the most well-known civilizations that settled in the Piura Basin for approximately 700 years, (100–300 AD to 500–800 AD), The Moche were agriculturally based, with a well-developed and large network of irrigation canals and reservoirs (around 816 km) to divert and store river water to supply their crops in desert areas. Archeologists (Larco et al 1945, Butters and Castillo 2008) suggest that the Moche society was much wealthier than other societies of the same period because of their irrigation capacity. Their main agricultural products were corn, peanuts, cotton, fruits, and, in the highland areas, different types of potatoes (Velásquez 2015), which they traded with other societies (Butters and Castillo 2008), especially in the highlands to the east.

The society collapsed after being affected by El Niño, but that climatic disaster was not the sole cause. The Moche would have experienced hundreds of El Niño events over their history. Thus, other factors must have been involved that led to the end of Moche civilization (Diamond 2005, Butters and Castillo 2008). One main hypothesis about the factors that could have contributed to the collapse of the Moche, relates to the centralized and very hierarchical political system, with a caste of religious and military leaders dominating farmers (Bawden 1995). Lucero (2002) analyzed the role of water control of the Maya civilization, a well-studied example that is similar to the Moche in this sense. She proposed that societies that have a centralized governance structure over a main resource for the community, as is the case for many irrigation systems, tend to become trapped in a downward spiral of social crisis when rulers lose control of the main resource as a consequence of climatic changes. Lucero (2002) explains that the crisis starts with the collapse of power of rulers as they lose credibility and their capacity to collect tribute, which at the same time potentiates the disruption of the hard (e.g. the reservoir) and soft (e.g. rule enforcement) public infrastructures, which ends up decreasing the population’s wealth. The decrease in wealth causes internal conflicts, population migration, or population loss due to decreasing health.

As opposed to the Moche, the current society settled in the Piura Basin has a more decentralized
and less hierarchical governance structure for water management, since farmers are entitled to participate in local water governance. To be eligible for irrigation, farmers must be members of the non-governmental and non-profit National Irrigation Association, Junta Nacional de Usuarios de los Distritos de Riego del Perú (JUNDPR), which is subdivided by valleys, and to be registered in the Local Water Authority of the Region (ALA). For the Bajo y Medio Piura, there are three irrigation associations: Bajo y Medio Piura, Sechura, and Huancabamba. Farmers elect association leaders, and although the participation in elections is low (less than 50% of attendance), farmers feel that they are well represented. This may be a result of a well-articulated network of sub-associations.

The three main associations are divided into users’ commissions, which are subdivided into canal committees, which at the same time have 10 delegates that are elected by and represent 200 farmers. The main role of the association is to operate and maintain the minor public irrigation infrastructure (secondary canals and drainage systems), distribute water, collect and manage fees for water use, determine water tariffs, cut water services to non-compliant farmers, represent water users in meetings with other associations and governmental authorities (e.g. National Water National Authority, Regional Government of Piura, Agriculture and Environmental Ministries, and major infrastructure operators called ‘Proyecto Especial Chira Piura’), and to generate activities for the economic, social, and institutional development of agriculture in the area (Gallo and Oft 2011).

This multi-level organization that involves 75 176 members, is time efficient, enables fluent coordination, effective monitoring, and increases efficiency in communicating concerns or claims and even in solving conflicts in different instances. Farmers seem to understand the importance of improving water management and the role of the water fee in its success. The water associations still have to reduce the default rate of water-fee payments, and to agree on a higher price that reflects the real cost (public and social) of water. However, they have made an improvement from 2014 to 2015: fees collected increased from S/4 million (around USD 1.2 million) to S/6 million (around USD 1.8 millions). Different actors that have responsibilities as managers (e.g. National Local Water Authority, Mayor Operation Managers), revealed their satisfaction with the progress that the Bajo y Medio Piura Water Users Association has achieved. They have improved by themselves the minor canals that they are in charge of maintaining and have collected their own funds for emergency events. This growing social capital, enhance the resilience of the system (table 1, P2), especially because infrastructure for irrigation (reservoirs, canals and drainage) is crucial for water collection during flood events.

However, farmers’ technical knowledge in the basin is limited, and farmers’ agricultural practices and water management capabilities are still developing (CEPLAR 2016) which makes their individual economic development slow. Poor farming practices (e.g. excessive watering, pesticide and fertilizer use, no crop rotation) degrade the soil and, at the same time, lock farmers into low economic returns on land and labor. It is more difficult for farmers with low profits to finance the necessary irrigation infrastructure maintenance and to be better prepared for disastrous events (table 1, P7).

Bajo y Medio Piura shares the irrigation infrastructure of the Poecho Project, including the reservoir (see figure 1), with the Chira Basin. This independence makes the transaction cost of coordinating to collect enough resources for infrastructure maintenance even higher, especially because the Chira Basin has less-developed collective action than Bajo y Medio Piura (table 1, P12). The Bajo y Medio sub basin’s river flow, infiltration, groundwater recharge, sedimentation, and contamination also depend on farmers and other actors in the upper basin (Ostovar 2019). The 1997–98 El Niño, and the 2017 Coastal Niño evidenced how the high deforestation levels (around 80% of the forest in the basin with a majority in the upper basin) reduced the natural rain catchment capacity and facilitated extensive rains to run strong downhill and washed loose sediment downstream into the irrigation infrastructure (Ostovar 2019, Cultivalu 2019).

Because of sediment accumulation, the Poecho Reservoir currently has only 50% of its initial capacity (885 mmc). Other irrigation infrastructure, as the major canals are under maintained (water distribution loss is around 15%), and the drainage-system maintenance is almost completely ignored, leaving a significant part of the Valley with salinization problems (CEPLAR, Centro Regional de Planeamiento Estratégico 2016). The physical condition described (natural and engineered) reduces the resilience of the sub basin to flood events (table 1, P10). The government has unofficially announced that it will progressively reduce its financial assistance for major infrastructure maintenance. User associations will therefore need to grow even stronger to ensure public provisioning, in this case through water tariffs. Moreover, self-financed systems are becoming more and more necessary because of the reduction in support from international aid sources. Since Peru has improved its human development in literacy and GDP per capita, it is now a country that is less prioritized for international aid (GRP 2016).

Similar to the Moche’s centralized governance system, the current Piura society’s disaster prevention
The Piura capital, also called Piura, is located in the lower basin of the Piura River. Policies are highly centralized and decisions are taken in the national capital, with few local input and low flexibility to adapt to local conditions (French and Mechler 2017). The national government allocates a special budget for disaster prevention to the regional government, however interviewees mentioned that the regional and local governments are more concerned about re-election and public visibility than in the effects of El Niño (table 1, P3). During the 2017 Coastal Niño, the regional government was severely critiqued for spending just 3% of the 2016 budget for prevention programs (French and Mechler 2017). Centralized disasters prevention policies, weak regional governance, and simultaneous floods in different regions of the country combined, limits emergency response (table 1, P8 and P12).

The 2017 Coastal El Niño caused economic losses of around USD 3.1 billion (Leon and Kraul 2017), and affected 1.5 million people (French and Mechler 2017) of which the majority was from Piura (32%), followed by Lambayeque (16%), La Libertad (5%), and Lima (5%), where the capital is located (PAHO 2017). Even though the damage is comparable to the 1982–83 and 1997–98 events (French and Mechler 2017), the rain and flood were not as strong (SENAMH 2019), revealing a system’s resilience decline. Ramirez and Briones (2017) argues that the 2017 Coastal El Niño had disastrous effects partially because it developed rapidly (table 1, P1), there were contradictory forecasts between the national (Peru) and international (US) monitoring agencies that delayed governmental response, and because of an underestimation of impacts, given that some regions (including Piura) were experiencing drought at the time, and because the effects of the previous ENSO (2015–16) were far less than expected (table 1, P4). However, once the danger was identified, the communication channels for evacuation failed, and the majority was unaware of which were the safe areas, or preferred to stay in their residence for fear of losing their belonging to strangers (French and Mechler 2017). The 2017 Coastal Niño also uncovered the lack of proper rainwater drainage systems in urban and agricultural areas (French and Mechler 2017). The effects revealed a fragile social resilience that in a context of growing population (10% average from 2007 to 2017, INEI 2017), can be catastrophic.

Piura is the second most-populated region of the country (INEI 2017 and has a population density of 52.1 habitants km² (INEI 2017)). The population dynamic in Piura dates back to the 1970s, when to increase the region’s capacity to cope with drought seasons, the government built the biggest reservoir in Latin America (Poecho Reservoir). The Peruvian government implemented The Agrarian Reform, that aimed to return the agricultural land owned by hacendados to the people who had worked it for decades and who, during the reform, were organized in cooperatives. To strengthen the reform process, the first water law was formulated, initiating a series of water policies that, in one way or another, place agricultural activity at the center of the articulation of water law. It was in this context that the Poecho Reservoir and its related infrastructure were built. With the execution of the project, water from the Chira River was diverted to the reservoir, and then released into the Piura River, favoring farmers of the Bajo y Medio Piura.

Thanks to this project, water availability became stable, and agricultural activity started to grow. In only 10 years, agricultural land area grew by 10% (from 84 000 ha in 1976 to 93 000 ha in 1986), and population grew as well (3% per year in the same period). Population density in Piura is problematic for two reasons (table 1, P6): (i) Piura hosts 6% of total population, and the total amount of water available in this region is less than 1% of the total available in the country (CEPLAR 2016), and (ii) Population that migrates from different regions and low-income families settle down in flood high-risk areas due to limited territory available (table 1, 11). Never have so many people lived in the Piura river flood zones exposed to raging torrents during El Niño events.

The Piura Basin presents attractive features for agriculture and trade: good weather conditions with different ecological zones that allow for a diversity of crops, forest on the highlands of the basin, sea life on the ocean, significant rivers running from the Andes to the Pacific Ocean, and a central geographic location that is excellent for trade in the region. However, at the same time, the basin presents a fragile ecosystem with major challenges for human settlement. The Moche society was well known for its engineered irrigation system, but was still unable to cope with the severe droughts and floods from El Niño events. In the end, the remaining population decided to migrate to the high areas of the basin. After many decades in the 1970s, policymakers unaware of the dangers of El Niño, attracted and incentivized population growth in a region highly exposed to strong floods, by building hard public infrastructure (e.g. reservoir, canals, roads, bridges) and soft public infrastructure (e.g. water law, agrarian reform). According to Tainter’s (1988) theory of collapse, this complexity puts at risk the resilience of the system, and it is now more difficult to mobilize a big population to relocate to another region less exposed to environmental perturbations (table 1, P5 and P9). Moreover, as suggested by Holling and Gunderson (2002), even though the built infrastructure aimed to stabilize

6 The Piura capital, also called Piura, is located in the lower basin of the Piura River.

7 Decreto Ley Nº 17752 of July 24th of 1969 (a month later of the promulgation of the agrarian reform law).
food production by reducing water flow variability, it also changed the stability of the landscape, thereby creating more rigid and myopic management, and thus more sensitive to disturbances.

It seems that everyone in Piura is well aware of the fragility of the basin given the impacts of past Niño events. However, many recommendations made after previous El Niño disasters are yet to be implemented. Most of the time the policy focus is on engineered infrastructure and less on improvement of governance infrastructure and social cohesion. Information about engineered infrastructure is available and well understood, but the source of funding for hard infrastructure maintenance is barely considered. From the analysis summarized in table 1, we can see that the most resilient aspect of the system is the way both individual and, networks of farmers’ associations are developed. It is, however, still far from being ideal, and the analysis shows that it can make a significant difference if the associations get support to build their capacity and to become more knowledgeable about how authorities can support them, how to get out of poverty traps, how to better manage their resources, and how to prepare better for future threatening events. Since poverty and developing agricultural practices are aspects that are identified as root causes that show fragilities in the system, by underpinning this strength there might be a positive effect on other aspects of the system.

5. Conclusions

With the guidance of the Robustness Framework and by leveraging propositions from past research on collapse, it was possible to assess the resilience of the Medio y Bajo Piura Sub-basin to flood events. It seems that, in general, the SES of the Bajo y Medio Piura sub-basin is quite fragile to future drought and flooding events. The Peruvian State or International Aid agencies modestly invest in El Niño years in emergency programs (e.g. canals and rivers reinforcement before the event, sensitivity programs for water use, housing, and main infrastructure restoration after the event). Our analysis suggests that without this support, we would likely see the regional Piura system eventually collapse again, repeating the Moche experience. However, the analysis has demonstrated a significant strength in the system: considerable capacity for collective action. This capacity is built on social capital that provides a foundation for generalized capacity that may be mobilized to prevent damage from future Niños and to develop sustainably.

As shown in this study, public infrastructure is an essential feature of functioning societies within SES, and for SES resilience. However, too much attention has been paid to physical infrastructure, with the result that opportunities to strengthen SES have been overlooked. If we pay more attention to soft public infrastructure, we may find some more effective potential solutions for increasing the resilience of the system to floods. In addition to strengthening water-users association as discussed earlier, policies that pay more attention to identifying and reducing the socio-economic drivers of fragility that affect the population and infrastructure should be implemented.

This is the story of the Piura basin SES. There are many other similar cases in Peru, and around the world, that will be exposed to future climate change events. Because this was only one case study, it is not possible to draw any general theoretical conclusions. However, this research provides methodological and theoretical insights that can contribute to theory building for SES resilience, which is an urgent endeavor. By reviewing collapse theories with the assistance of an interdisciplinary framework, we were able to complement and integrate propositions from isolated disciplines or perspectives. Contrary to proposing deterministic causes of collapse (e.g. environmental, war, epidemics), we exemplify how the inclusion of a combination of diverse factors (biophysical, institutional and socio-economical) into the analysis provides a more comprehensive explanation of phenomena. Future research can use the same methodological approach to analyze more cases and refine the theory.

Acknowledgments

We thank the two anonymous reviewers whose comments and suggestions helped improve and clarify this manuscript. We are grateful to Marco A Janssen, Joshua Abbott, and Jordane Boudevsel for feedback and inspiration. We also acknowledge financial support from the National Science Foundation (Grant GEO-1115054).

The data that support the findings of this study are available from the corresponding author (CR) upon reasonable request.

ORCID iD

Cathy Rubiños @ https://orcid.org/0000-0002-6004-4684

References

Abel W 1980 Agricultural Fluctuations in Europe: From the Thirteenth to Twentieth Centuries (Abingdon: Routledge)
ANA, Autoridad Nacional del Agua 2016 Identificación de zonas vulnerables ante inundaciones en ríos y quebradas 2016 Ministerio de Agricultura y Riego (http://sigrid.cenepred.gob.pe/docs/PARA%20PUBLICAR/ANA/Piura_NOV2016.pdf)
Anderies J M 2016 Understanding the dynamics of sustainable social-ecological systems: human behavior, institutions, and regulatory feedback networks Bull. Math. Biol. 77 259–80
Anderey J M, Janssen M A and Ostrom E 2004 A framework to analyze the robustness of social-ecological systems from an institutional perspective Ecol. Soc. 9 18
Angulo L 2006 Cambio climático, patrones de riesgos de desastres y escenarios futuros Retos para el desarrollo regional y local en la cuenca del río Piura Tecnología y Sociedad Revista Latinoamericana 7 69–131 (http://brevap.indect.gob.pe/ download/1357.pdf)
Bawden G 1995 The structural paradox: Moche culture as political ideology Latin Am. Antiq. 6 255–73
Brack A and Mendoza C 2000 Ecología del Perú Editorial Bruto Lima–Perú 495
Brenner R 1976 Agrarian class structure and economic development in pre-industrial Europe Past Present 30 70–35
Brunk G G 2002 Why do societies collapse? A theory based on self-organized criticality J. Theor. Polit. 14 195–230
Bustamante M J 2010 Cambio Climático en el Perú. Costa Norte (Lima: Fundación M J Bustamante De La Fuente)
Butters L J C and Castillo S U 2008 The Moche of Northern Perú Handbook of South American Archaeology ed H Silverman and W Isbrell (New York: Springer Science & Business Media) pp 707–30
Butzer K W 2012 Collapse, environment, and society Proc. Natl. Acad. Sci. 109 201114845
Catton W R 1982 Overshoot: The Ecological Basis of Revolutionary Change (Champaign, IL: University of Illinois Press)
CEPLAR, Centro Regional de Planeamiento Estratégico 2016 Gobierno Regional de Piura: Análisis Prospecutivo Regional (2016–2030). Aprobado con Ordenanza Regional N° 367-2016/GRP-CR Piura, octubre de 2016 (https://www.regionpiura.gob.pe/documentos/ceplar/prospectiva2015-2030.pdf)
Costanza R, Graumlich L, Steffen W, Crumley C, Dearing J, and W Isbell (New York: Springer Science & Business Media) pp 707–30
Csete M E and Doyle J C 2002 Reverse engineering of biological complexity Science 295 1664–9
Calbert T P 1973 Maya downfall at Tikal The Classic Maya Collapse ed P Calbert (Albuquerque: University of New Mexico Press) pp 63–92
Calbert T P 1988 Political history and the decipherment of Maya glyphs Antiquity 62 135–52
Cultivalu 2019 El 80% de la cuenca del río Piura está deforestada, advierte consorcio Inundaciones Piura (https://www.latocultivador.org/el-80-de-la-cuenca-del-rio-piura-esta-deforestada-advierten-inundaciones-piura/)
Diamond J 2005 Collapse: How Societies Choose to Fail or Succeed (New York: Penguin)
Ehrlich P R and Ehrlich A H 2013 Can a collapse of global civilization be avoided? Proc. R. Soc. B 280 20122845
Fagan B M 2009 Floods, Famines, and Emperors: El Niño and the Fate of Civilizations (New York: Basic Books)
Field C B et al 2014 IPCC, 2014: climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva: IPCC)
French A and Mechler R 2017 Managing El Niño Risks Under Uncertainty in Peru: Learning from the Past for a More Disaster-Resilient Future (Luxemburg: International Institute for Applied Systems Analysis)
Gallo M and Off P 2011 Pautas para la Gestión del Riesgo y Seguro frente al Fenómeno el Niño
Garmestani A S and Benson M H 2013 A framework for resilience-based governance of social-ecological systems Ecol. Soc. 18 9
Gobierno Regional de Piura 2016 Análisis prospectivo regional gobierno regional de Piura CEPLAR (https://www.regionpiura.gob.pe/documentos/ceplar/prospectiva2015-2030.pdf)
Gobierno Regional de Piura—ANA—GTZ/PDERS 2009 Proceso de elaboración del plan de gestión de la cuenca del río Piura—Aspectos Metodológicos Folleto 2 Lima 32p (https://core.ac.uk/download/pdf/48024098.pdf)
Goldstone J A 1991 Revolution and Rebellion in the Early Modern World (Berkeley, CA: University of California Press)
Gough D, Oliver S and Thomas J 2012 Introducing Systematic reviews. An Introduction to Systematic Reviews ed D Gough et al (Los Angeles, London, New Delhi,Singapore, Washington DC: SAGE Publications, Inc)
Harari Y N 2016 Homo Deus: A Brief History of Tomorrow. Random House (London: Harvill Secker)
Holling C S 2001 Understanding the complexity of economic, ecological, and social systems Ecosystems 4 390–405
Holling C S and Gunderson L H (ed) 2002 Resilience and adaptive cycles Panarchy: Understanding Transformations in Human and Natural Systems (Washington DC: Island Press) pp 25–62
Huertas L 1996 Patrones de asentamiento poblacional en Piura (1532–1850) Bull. Inst. Fr. Etudes Andines. 25 91–124
INDECI, Instituto Nacional de Defensa Civil 1998 Estadística de emergencias producidas en el Perú durante 1997 Instituto Nacional de Defensa Civil (https://www.indeci.gob.pe/listalo.php?item=NDY&item=MzQ3)
INEI, Instituto Nacional de Estadísticas e Informática 2016 Perú Producto bruto interno por departamentos 2007–2016 (https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib4139/libro.pdf)
INEI, Instituto Nacional de Estadísticas e Informática 2017 Resultados Definitivos de Los Censos Nacionales 2017: Piura. Censos Nacionales 2017: XII de Población, VII de Vivienda y III de Comunidades Indígenas (https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1553)
Janssen M A and Anderies J M 2013 A multi-method approach to study robustness of social–ecological systems: the case of small-scale irrigation systems J. Inst. Econ. 9 427–47
Janssen M A, Kohler T A and Scheffer M 2003 Sunk-cost effects and vulnerability to collapse in ancient societies Current Anthropology 44 722–8
Johnson S A 2016 Why Did Ancient Civilizations Fail? (New York: Routledge)
Kammen D M, Smith K R, Rambo A T and Khalil M A K 1994 Preindustrial human environmental impacts: are there lessons for global change science and policy? Chemosphere 29 827–32
Khalidun I 1958 The Muqaddimah: An Introduction to History, tr F Rosenthal (Princeton, NJ: Princeton) Ladurie E L 1987 The French Peasantry, 1450–1660 (Berkeley, CA: University of California Press)
Larco R, Uhle M and Kroeber A L 1945 Los Mochicas (Pre-chimu, de Uhle y Early Chimu, de Kroeber) (Buenos Aires: Sociedad Geográfica Americana)
Leach M, Scoones I and Stirling A 2010 Governing epidemics in an age of complexity: narratives, politics and pathways to sustainability Glob. Environ. Change 20 369–77
Leon A and Kraul C 2017 Peru’s brutal seasonal of floods leaves 94 dead, 700,000 homeless The Los Angeles Times 28 March 2017 (http://www.latimes.com/world/mexico-americas/la-fg-peru-floods-20170328-story.html) (accessed July 2019)
Lucero I 2002 The collapse of the Classic Maya: a case for the role of water control Am. Anthropol. 104 368–84
Middleton G D 2017 Understanding Collapse: Ancient History and Modern Myths (Cambridge: Cambridge University Press) (https://doi.org/10.1017/978110716584941)
Miles M B and Huberman A M 1994 Qualitative Data Analysis: An Expanded Sourcebook (New York: Sage)
Motesharrei S, Rivas J and Kalnay E 2014 Human and nature dynamics (HANDY): modeling inequality and use of
resources in the collapse or sustainability of societies Ecol. Econ. 101 90–102
Ostovar A L 2019 Investing upstream: watershed protection in Piura, Peru Environ. Sci. Policy 96 9–17
Ostrom E 2005 Understanding Institutional Diversity (Princeton, NJ: Princeton University Press)
Ostrom E 2007 A diagnostic approach for going beyond panaceas Proc. Natl. Acad. Sci. 104 15181
PAHO, Pan American Health Organization 2017 Rains and floods in Peru Situation report (Lluvia e inundaciones en Peru. Reporte de situacion) No. 13, 23 April 2017 (https://reliefweb.int/sites/reliefweb.int/files/resources/Informe_Situacion_13-2017_Peru_Inundaciones_23_abril%5B1%5D.pdf) (accessed July 2019)
Parsons J 1991 Population control and politics Popul. Environ. 12 355–77
Patton M Q 1990 Designing qualitative studies Qualitative Evaluation and Research Methods ed M Patton (Beverly Hills, CA: Sage) pp 169–86
Pezzey J C and Anderies J M 2003 The effect of subsistence on collapse and institutional adaptation in population–resource societies J. Dev. Econ. 72 299–320
Ponting C 1993 A Green History of the World: The Environment and the Collapse of Great Civilizations (New York: Penguin Books)
Postan M M 1966 Medieval agrarian society in its prime: England The Cambridge Economic History of Europe vol 1 (Cambridge: Cambridge University Press) pp 549–632
Ramirez I J and Briones F 2017 Understanding the El Niño costero of 2017: the definition problem and challenges of climate forecasting and disaster responses Int. J. Disaster Risk Sci. 8 489–92
Redman C L (ed) 2004 The Archaeology of Global Change: The Impact of Humans on Their Environment (Washington DC: Smithsonian Books)
Redman C L 2005 Resilience theory in archaeology Am. Anthropol. 107 70–77
SENAMHI 2019 Precipitation historical data (https://www.senamhi.gob.pe/?&p=escenarios-lluvia) (accessed July 2019)
Tainter J 1988 The Collapse of Complex Societies (Cambridge: Cambridge University Press)
Takahashi K 2017 The El Niño phenomenon: global vs coastal (Fenómeno El Niño: global vs “Costero”) Generacion de informacion y monitoreo del Fenómeno El Niño—Boletin Tecnico vol 4(4) (Perú: Instituto Geofisico del Perú, Ministerio del Ambiente) pp 4–7 (in Spanish)
Timmerman P 1981 Vulnerability Resilience and Collapse of Society: A Review of Models and Possible Climatic Applications (Toronto: Institute for Environmental Studies, University of Toronto)
Turchin P 2005 Dynamical feedbacks between population growth and sociopolitical instability in agrarian states Struct. Dyn. I 1
Turchin P 2006 War and Peace and War: The Life Cycles of Imperial Nations (New York: Pi Press)
Turchin P and Nefedov S A 2009 Secular Cycles (Princeton, NJ: Princeton University Press)
Velásquez J G 2015 Archaeological Heritage in a Modern Urban Landscape: The Ancient Moche in Trujillo, Peru (New York: Springer) 10.1007/978-3-319-15470-1
Weiss H and Bradley R S 2001 What drives societal collapse? Science 291 609–10
Wood J W 1998 A theory of preindustrial population dynamics demography, economy, and well-being in Malthusian systems Curr. Anthropol. 39 99–135
Woodman R 1998 El fenómeno El Niño y el clima en el Perú Documento publicado por el Congreso de la República en “El Perú en los Albores del Siglo XXI/2” pp 1997–8
Wright R 2004 A Short History of Progress (Toronto: House of Anansi)
Yin R 1994 Case Study Research: Design and Methods (Beverly Hills, CA: Sage)
Yin R K 2003 Case Study Research: Design and Methods 3rd edn (Thousand Oaks, CA: Sage)
Yoffee N and Cowgill G L (eds) 1991 The Collapse of Ancient States and Civilizations (Tucson: University of Arizona Press)
Young O R, Berkhout F, Gallopin G C, Jansen M A, Ostrom E and van der Leeuw S 2006 The globalization of socio-ecological systems: an agenda for scientific research Glob. Environ. Change 16 304–16