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Understanding Disturbances and Responses in Social-Ecological Systems

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Current research in coupled social-ecological systems (SESs) often draws on theories of complex adaptive systems, resilience, and robustness. Many studies analyze the resilience, robustness, or vulnerability of these systems to disturbances and stressors, but do not connect their particular case with a general notion of what counts as a disturbance. This makes theoretical generalization of how outcomes are coproduced by disturbances and SESs difficult. These outcomes, in turn, serve as an entry point to represent SESs as dynamic systems that evolve and change over time. This study proceeds by first building a typology of disturbances to facilitate a better understanding of disturbance-response dyads in an SES. It then introduces a simple framework for analyzing SESs over time. Finally, the article applies this framework to case studies drawing on previous fieldwork.

Keywords acequia, conservation, disturbance, irrigation, resilience, robustness, social-ecological systems

Disturbances, perturbations, stressors, and pressures are essential parts of theories of social-ecological resilience and institutional robustness (Abel et al. 2006; Anderies et al. 2007; Folke et al. 2005; Janssen et al. 2007). The concern of researchers who deal with such theories generally lies in the characteristics of a system and its capacity to absorb, withstand, resist, or weather a disturbance or set of disturbances. However, few authors clearly articulate exactly what is meant by such disturbances beyond their specific case, or consider in a generalizable manner how outcomes are co-produced by the interactions between disturbances and social-ecological systems (SESs). This article intends to help fill these gaps in the literature in three ways: first, by adding a typology of disturbances to an existing framework in order to understand disturbance–response dyads of an SES; second, by using this combination to

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introduce a simple framework to understand the interactive effects of disturbances on SESs; and third, by applying this to a case study.

If resilience research is to continue its progression from metaphor to measurement, researchers need a means to categorize their observations of interactions between SESs and disturbances (Carpenter et al. 2001). This article addresses this need in two ways. First, we want to clarify what may be meant by a disturbance to an SES. In spite of the pervasiveness of the term in the resilience literature, few studies clearly articulate a general conceptual definition of disturbance. Instead, "most published accounts of regime shifts involve a single dominant shift defined by one, often slowly changing, variable in an ecosystem" (Anderies et al. 2006, 2). Disturbances come to be identified as whatever happens to change or impact a system for a particular study. Examples include excessive nutrient loading in the form of phosphorus (Carpenter 2005), and market or population pressures on traditional social systems (Agrawal and Yadama 1997). Multiple dimensions along which a system is robust or vulnerable are infrequently considered, as is a more general framework in which they might be compared. This makes cross-case comparisons difficult. Thus, we need to formulate a working conceptualization of disturbances in such settings to facilitate such comparisons.

Following this, we want to clarify the multiple ways that a system can change and evolve over time in response to disturbances. Early research on SESs often took a static snapshot of a system and overlooked or discounted the dynamic nature of the system. Recent work (Armitage 2005; Janssen et al. 2007) takes a more dynamic approach, and several researchers have begun to develop frameworks for such analyses that this article draws upon for our approach (Redman et al. 2004; Waltner-Toews et al. 2008).

In addressing these two points, our article starts with the view that to advance our understanding of resilience and robustness, cross-case comparison is required. To gain insight across cases, a typology for disturbance and a framework for describing system change are necessary. In addition, the typology and framework can be used heuristically to guide a particular analysis of a particular site. In this manner, researchers can examine the types of disturbances that seem to be affecting the system, the interactions between disturbances, and how they cause the system to respond and change over time.

This article proceeds by laying out the theoretical background of resilience and robustness, SESs, and the relationship between disturbances and SESs. Next, a typology for disturbances and their interactions with SESs is described, and a simple framework for dynamic analysis is introduced. Although there is not an explicit temporal component in the framework itself, its application naturally lends itself to a dynamic analysis, because disturbances and responses interact and iterate over time. The fourth section uses this typology and framework to analyze a particular system and the main categories of disturbances. The fifth section addresses some final points and conclusions.

Theoretical Background

SESs, Resilience, and Robustness

It is fair to say that the terms *resilience* and *robustness* are not used consistently and with great clarity in much of the literature. Our purpose in this article is not to address this problem. However, given that one of our primary goals is to improve the analytical rigor associated with the usage of these terms, a brief discussion is warranted.

The analytical use of resilience began in ecology, mainly within ecological stability theory, and was popularized in Holling's (1973, 14) definition of resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables." Within ecology there has been a high level of conceptual confusion regarding resilience and related terms (Grimm and Wissel 1997). Schoon (2005) references several other common definitions of resilience in SESs, including the ability of a system to reorganize following disturbance-driven change. One statement we can safely make is that resilience has been associated with the maintenance of a set of relationships in a system, and these sets have been referred to as alternative steady states, attractors, basins of attraction, domains of attraction, equilibria, regimes, states, steady states, and stability domains.

Robustness is sometimes used interchangeably with resilience (Levin et al. 1992; Levin and Lubchenco 2008; Newman 2003) but has a distinct scientific lineage, mostly from the discipline of engineering, and has been defined as "the maintenance of some system characteristics despite fluctuations in the behavior of its component parts or its environment" (Carlson and Doyle 2002, 2539). The desire of predictability, the notion of a performance objective in system design, and the design characteristics that are integral to robustness theory all reflect the engineering background of the concept and the pertinence of the theory toward the designed aspects of a system. This is in contrast to the evolved aspects inherent in the ecologically based resilience. In this article we use the concept of robustness to emphasize the issue of performance in the designed aspects of SESs.

The Relationship Between Disturbances and Social–Ecological Systems

Conceiving of SESs and events and disturbances that affect them as distinct objects, we recognize that outcomes are co-produced by the interactions between them. Thus, as a general principle, a system is not robust. Rather, it is robust with respect to a particular disturbance or set of disturbances. A central tenet of theories dealing with robustness, resilience, and other concepts such as highly optimized tolerance is that complex systems become increasingly vulnerable to one set of disturbances when they adapt to another set (Carlson and Doyle 2002; Janssen et al. 2007). "Complex systems must trade off the capacity to cope with some types of variability in order to become robust to others" (Janssen et al. 2007, 309). Levin (1999) and Levin and Lubchenco (2008) offer similar arguments.

Another way of stating this situation is that vulnerability does not disappear. It can be shifted spatially, as in irrigation systems transferring vulnerability from upstream to downstream regions, temporally (into the future), to a different system (shipping hazardous waste to a less developed country), or to a different type of perturbation (reducing risk of drought at the expense of flooding). In linear control systems, Bode's law demonstrates mathematically that a system that becomes more robust to disturbances of high amplitude and low frequency also becomes less robust to ones of low amplitude and high frequency, and vice versa. This tenet of control systems serves as a metaphor for system robustness in response to some disturbances at the expense of system performance or other disturbances. Because of this specificity, in order to understand outcomes in these settings we need a typology of disturbances to facilitate the explicit formulation of such trade-offs.

A Framework for Studying Disturbances to Social-Ecological Systems

Disturbance Typology

Several frameworks and organizing ideas have been proposed for studying SESs, including Gunderson and Holling's (2002) panarchy concept, coupled human–natural systems (Liu et al. 2007), McLeod and Leslie's (2009) conceptual framework for ecosystem-based management, Ostrom's (2007) hierarchical framework, the Anderies et al. (2004) conceptual SES, the Janssen et al. network approach (2006), and the robust control framework presented by Anderies et al. (2007). Defining various types of disturbances that affect SESs is a natural step to take once we have recognized that systems trade off robustness and vulnerabilities between various types of disturbances. Furthermore, combining aspects of these frameworks to conceive of an SES as a system made up of interacting components (a network) that receives inputs from an external environment, which is a system itself with its own components and state variables, lends itself to a particular typology of disturbances. These are presented in Table 1.

The four main types of disturbances we consider are: (1) fluctuation of a flow into or out of an SES; (2) fluctuation in a parameter that affects an SES; (3) a change in the network structure of the system; and (4) a change in the social or ecological connectivity between the SES and the external environment. We refer to these as (1) a *flow disturbance*, (2) a *parameter disturbance*, (3) a *network disturbance*, and (4) a *connectivity disturbance*, respectively.

For our purposes a flow is a transfer of a social or biophysical quantity across the boundary of an SES, while a parameter is a variable internal to the SES. Each fluctuates naturally over time, and may fluctuate enough to disturb the system. We do not consider every fluctuation above or below a mean value to be a disturbance, which would result in interpreting the system being disturbed all of the time. There are several properties of a fluctuation that can be used to evaluate whether it is a disturbance or not. These are its intensity, its duration, and its severity, adopted from Dingman's (2002, 516–517) discussion of drought analysis. The intensity of a drought is its average deviation from a norm for a period of time. The norm is what Dingman refers to as a "truncation level," which need not be the historical average, but could be one standard deviation from the average, for example. The duration is the length of time the variable remains above or below this truncation level, and severity is the cumulative difference, or simply the intensity times the duration.

Although these properties help us explore the dimensions of quantitative disturbances, they do not provide us with an unambiguous criterion for distinguishing "normal" fluctuations from "real" disturbances. This issue is similar to that of determining statistical significance in an analysis. In spite of trends toward confidence intervals, the threshold of a .05 p value is still widely used in order to divide statistically significant from nonsignificant results. However, this value is arbitrary and can be misleading; ultimately when a continuum is condensed into a binary variable, information is lost. We still use it because it simplifies our interpretation of a set of results. In our opinion, however, reporting a p value provides more information

Table 1. Four disturbance types

Disturbance type	Properties of disturbance type
D1—*flow disturbance*: Disturbance as a fluctuation in a flow into or out of the system.	Intensity: Average degree of deviation from a norm
	Duration: length of time that the rate deviates from the norm
	Severity: Intensity × duration
	Frequency: $1/X$, where X is the average number of time periods in which one such deviation occurs.
	Uncertainty: How predictable the deviation is to user groups
D2—*parameter disturbance*: Disturbance as a fluctuation in a parameter that affects the system	Intensity: Average degree of deviation from a norm
	Duration: length of time that the rate deviates from the norm
	Severity: Intensity × duration
	Frequency: $1/X$, where X is the average number of time periods in which one such deviation occurs.
	Uncertainty: How predictable the deviation is to the user groups
D3—*network disturbance*: Disturbance as a change in network structure of the system (additional or removal of a node or link)	Node addition
	Node removal
	Link addition
	Link removal
D4—*connectivity disturbance*: Disturbance as a change in the connectivity between the SES and external social or ecological nodes or actors	Increased connectivity
	Decreased connectivity

than a condition of significance and is not excessively onerous to a reader. Likewise, when discussing quantitative (flow and parameter) disturbances, we should probably worry more about reporting the actual severity of the deviation as defined above as a measure of how to identify a disturbance.

A network is a collection of actors or nodes and the links or relationships between them. Any SES would have multiple social and biophysical networks within it, just as it receives inputs from a variety of flows. A common example of an ecological network is a food web, where nodes are species and links are predatory relationships. Other types of connections are possible, such as networks of pollination. A network disturbance is an alteration in the biophysical or social network structure of a, SES. Scholars focusing on network resilience previously have focused primarily on their resilience to the removal of node or, less frequently, a link (Albert et al., 2000; Ash and Newth 2007; Barabasi 2000; Dunne et al. 2002, 2004). The addition of a node can be disturbance as well. An ecological example of a new node in a food web would be an invasive species, as opposed to a species extinction (node loss). A social example would be a new user group or official who affects how a resource is governed.

Finally, it is important to consider changes in the overall connectivity between the SES itself and external actors, because this may expose the SES to new forms of variation, "such as national governmental policies, technological change, or international economic developments" (Janssen et al. 2007, 312). These may affect, among other things, the users' dependence on the resource and their incentives for collective action. Thus, we include what we call connectivity disturbances. Socially, this type of disturbance maintains the network perspective adopted in the previous one. Socially connectivity is a function of particular relationships between actors in a system and external actors. Similar to network disturbances, connectivity disturbances may occur by the addition or removal of connections between an SES and its external environment.

Connectivity disturbances blur the lines slightly between what may be an external and an internal change or disturbance. The scale of the event is what separates a social or biophysical change within the system from a disturbance. What is a system change for one analysis may be a disturbance at a smaller spatial or temporal scale. An interesting question to ask is, are the patterns of incidence of and response to various types of disturbances consistent across scales? Researchers frequently comment on the importance of scale in the analysis of SESs (Gunderson and Holling 2002; Silver 2008), and one way that the typology introduces cross-scale effects is through connectivity disturbances.

We are not arguing that our typology is exhaustive or that different system perspectives would view a disturbance in the same manner. Rather, we argue that the four disturbance types encompass the four principal interaction points between an SES and a disturbance. Furthermore, we maintain that introducing such a typology provides a foundation to begin to study disturbance-response interactions in an SES. In this manner, we have a tool to begin to systematically and empirically examine the evolution of SESs. Table 2 provides several examples of each of the four types of disturbances. This provides guidance on how to use the typology and apply it to cases. Scale of analysis plays a major role in categorizing these disturbances, with connectivity disturbances at one scale appearing as network disturbances in another. Likewise, parameter disturbances at one scale may be flow disturbances at another.

A Framework for Studying Disturbances in a Social–Ecological System

We proceed by using the framework of SES developed by Ostrom (2007), along with this typology of disturbances, in order to present an adapted framework that enables

Table 2. Examples of the four disturbance types

Disturbance	Type	Social/Biophysical	Example
Drought	D1—Flow	Biophysical	Declining flows due to loss of snowmelt in mountain systems, Aral Sea desiccation
Flooding	D1—Flow	Biophysical	Hurricane Katrina
Change in nutrient flows	D1—Flow	Biophysical	Excess nitrogen and phosphorus inputs downstream of agricultural regions
Pollution	D1—Flow	Biophysical	Heavy metals; acid rain
Change in radiative fluxes	D1—Flow	Biophysical	Global warming
Loss of external assistance	D1—Flow	Social	Removal of foreign aid programs
Change in salinity	D2—Parameter	Biophysical	Groundwater salinization following irrigation
Loss of topsoil	D2—Parameter	Biophysical	Desertification due to overgrazing
Acidification	D2—Parameter	Biophysical	Ocean acidification due to rising atmospheric CO_2 levels
Change in average temperature	D2—Parameter	Biophysical	Climate change
Change in chemical nutrient concentration	D2—Parameter	Biophysical	Eutrophication in the Gulf of Mexico and Chesapeake Bay
Loss of social capital	D2—Parameter	Social	Loss of interpersonal trust due to a violent event
Market price fluctuation	D2—Parameter	Social	Changes in international coffee, crude oil prices

(*Continued*)

Table 2. Continued

Disturbance	Type	Social/Biophysical	Example
Invasive species	D3—Network	Biophysical	Asian long-horned beetle; kudzu; Norwegian rat
Loss of keystone species	D3—Network	Biophysical	Loss of sea otters; honeybees
New user groups	D3—Network	Social	New landowners in the Taos Valley acequias
Social node removed	D3—Network	Social	Assassination or death of leadership
Change in trade agreements	D3—Network	Social	Disintegration of economic trade agreements
Public infrastructure programs	D4—Connectivity	Biophysical	Construction of aqueducts
Market demand	D4—Connectivity	Social	Water markets in New Mexico; international demand for forest timber
Public policies	D4—Connectivity	Social	Application of governmental regime on local groups

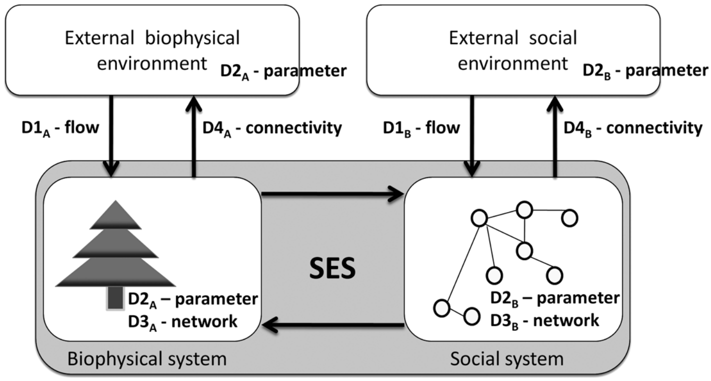

Figure 1. A framework for studying disturbances in a social-ecological system.

us to analyze disturbance-response relationships in complex SESs. Figure 1 displays our adapted framework. The labels D1, D2, D3, and D4 correspond to the location in an SES we can expect to observe the four types of disturbances just described. D1 is a flow disturbance, D2 is a parameter disturbance, D3 is a network disturbance, and D4 is a connectivity disturbance. The subscript A refers to predominantly biophysical disturbances and the subscript B denotes predominantly social disturbances.

Thus far we have established the possible incidence of multiple types of disturbances upon different components of an SES. However, robustness is an inherently temporal concept, and this framework can be better understood by thinking about how disturbances and SES responses coproduce outcomes, which, as we show, can include the incidence of additional disturbances.

Moving From Theory to Application

The next obvious step in this process is to explore the utility of both the typology of disturbances as well as the framework shown in Figure 1 for over-time analysis of SESs by applying them to case studies. The case study that follows is drawn from the authors' field work and analysis. It illustrates the incidence of the various disturbances outlined in the typology, and examines how the SES changes over time through its interactions with various disturbances.

Case: The Taos Valley Acequias Study

This section describes an example of each of the four disturbance types (see Table 1) on a collection of community-based irrigation systems in northern New Mexico known as acequias. The descendants of the area's original Spanish colonists, who migrated up the Rio Grande River from Mexico beginning in the early 1600s, continue to run the acequias in New Mexico and in parts of southern Colorado. As the original colonists settled the area, they established networks of canals to irrigate private fields and common grazing lands in order to maintain themselves in a high desert environment.

An acequia is a community of irrigating farmers. Each has a well-defined governance structure, led by a mayordomo and a commission commonly made up of three commissioners. The mayordomo, as an executive officer, is in charge of deciding how the water is distributed within his or her acequia and is the primary monitor and enforcer of infractions. The commissioners act as a legislative and judicial body and are in charge of the formal bylaws of the acequia. They frequently are called on to arbitrate disputes and support the mayordomo in enforcing ditch rules. Water is distributed within each acequia in accordance with a commonly accepted set of rules, and compliance with community obligations is required in order for an individual to maintain his/her water rights. Such communal obligations are an important feature of the common property arrangements that are common among community-based systems.

The information presented here comes from a research project on 51 acequias in Taos Valley, New Mexico. The average number of members of the 51 acequias as recorded by hydrographic surveys around 1970 was 40, and the median was 18.[1] These numbers of have since increased somewhat, although there is no current data to confirm this. A series of 44 in-depth, in-person interviews was conducted with acequia officials in the valley in order to understand how they have adapted to persist in a high desert environment and what new challenges they are currently facing. Several spatial and time series statistical analyses were conducted to complement this qualitative information.

Taos valley is 2,070 m above sea level and encompasses roughly 400 km^2. The acequia-irrigated area in the valley is around 40 km^2. The main use of water in the valley is irrigation, with a large, recent growth in municipal and domestic usage. The valley is bordered to the east and southeast by the Sangre de Cristo Mountain range, which supplies most of the available water through snowmelt. To the west the valley slopes down to the Rio Grande River gorge.

Historically, the acequias have had to deal with two *flow disturbances* ($D1_A$): droughts and, secondarily, floods. Using a truncation level of one standard deviation below the historical average, as discussed earlier, we can look at the hydrographs from the valley's main rivers and state that the acequias have experienced eight drought years since 1965.[2]

The acequias have several social and biophysical properties that have enabled them to respond robustly to these disturbances. Their basic challenge is to mitigate upstream–downstream conflict that characterizes all irrigation systems and that is exacerbated when water is scarce, where an upstream user's appropriation subtracts from what is available downstream. If these conflicts cannot be resolved, the system will likely deteriorate over time.

Socially, the acequias have adopted a relatively decentralized, multitiered governance system, with one level being the institutional arrangements that govern water distribution within acequias, and the second level being the institutions that govern water distribution between them. Instead of having to form and maintain one set of agreements between thousands of farmers at once, this breaks the system down into more manageable social groups, each of which is able to come to a consensus regarding its own rules. This is the first governance level. Then, key actors (mayordomos and commissioners) from each acequia often take part in decisions made between acequias about how they should distribute water during times of shortage. This social structure serves to minimize the transaction costs involved in maintaining a common understanding of how water is to be divided throughout the entire system by breaking up the system into subgroups. These subgroups are then able to independently come to internal agreements, which enable them to act as coherent actors (acequias) and then form agreements that govern the larger system.

Biophysically, two features are important in mitigating upstream-downstream conflicts. The first is the *desague*, or drainage ditch, which returns unused flows to the river from which the water is appropriated. This also helps avoid flooding problems. Second, the acequias' irrigation ditches are unlined, which allows water to flow from their ditches into a shallow groundwater aquifer system in the valley. This water frequently seeps up downstream from where it percolated originally, providing downstream users with additional sources of water. Within the valley there is a strong connection between groundwater and surface water (Drakos et al. 2004).

More recently, the acequias have been experiencing a suite of novel disturbances resulting from economic growth surrounding the town of Taos, which has become a major tourist center. This has had several important effects. First, the acequia members now are fully integrated into local labor markets fueled by the demand for tourism-related goods and services and no longer depend on farming for a living. This is a *connectivity disturbance* ($D4_B$). It drastically lowers their dependence on water, and in turn lowers their incentives to maintain their traditional irrigation practices. This would not be so significant a problem if there were not competing demands for this water from other sources, such as the municipality of Taos. An additional feature of this growth is a *network disturbance* ($D3_B$), in the form of new members in the acequias. The problem with new members is that they are frequently unaware of or do not agree to conform to the historical rules that the acequias have developed to govern their systems. Through a spatial statistical analysis, Cox and Ross (2009) have established that acequias with substantial land rights subdivisions resulting from the addition of new members have tended to be less agriculturally productive over time. This productivity is estimated using a vegetation index known as the normalized difference vegetation index. Finally, the transfer of water out of the acequias, or to new members within acequias, is facilitated by the historical legalization of water rights transfers independent of the land historically associated with the source of water. The State of New Mexico has a functioning, although hardly transparent, water market system. The imposition of this system on the acequias can be seen as an additional *connectivity disturbance* ($D4_B$). In this case, the new connections are market transactions. Clearly, the effects of the various novel disturbances discussed here are synergistic.

As a result of these new social disturbances, important functions of the acequias have deteriorated. Several farmers reported simply not irrigating when there was no water during a drought, because there was no longer a necessity to do so. Interviewees also reported low levels of attendance at important events, such as annual meetings and canal cleanings. Additionally, the common grazing system that is an essential component of the acequias' historic persistence and self-reliance has almost entirely disappeared, and the livestock counts of primary grazing animals have plummeted in the last 30 years. Previous research has proposed that community-based systems such as acequias are frequently vulnerable to social disturbances that involve increases in market demand (Agrawal 1994; Rose 2002).

Interestingly, one interviewee commented that a lack of response by the acequias to these disturbances results from their relative decentralization, which has impeded a coordinated inter-acequia effort to respond. While the central actors in the acequias' traditional network, the mayordomos and commissioners, might have been expected to facilitate this kind of effort, interviewees have also noted that because of the lower dependence on the resource, it has become more and more difficult to find members to fill and carry out those positions.

Additional vulnerabilities that have been introduced as a result of this connectivity are the vulnerability to changes in wage rates (a *parameter disturbance*: $D2_B$), and the loss of the *social connectivity* itself ($D4_B$). The acequias exhibit a property of many complex systems, this being an asymmetry when moving between old and new system configurations.[3] The acequias cannot now easily move back to their previous, self-sufficient regimes. Because of knowledge and technical expertise that has been lost between generations, such a reversal would now prove quite costly, and they should now be considered to be vulnerable to the removal of this connectivity.

An additional dimension of these disturbances that is important to consider is their periodicity and cumulative nature, which are related. The historical droughts and floods experienced by the acequias are periodic and are not generally cumulative. Janssen and Anderies (2007, 51) note that such periodicity, or the lack thereof, affects the ability of a system to maintain its robustness to a disturbance: "A challenge regarding decisions to invest in enhancing robustness is the lack of feedback from previous investments made." If disturbances are not periodic, then it is more difficult to obtain this feedback and maintain robustness.

The increase in connectivity that the acequias have contended with is not periodic, but rather steadily increasing in its severity. This is unlike the disturbances they have faced in the past, and does not allow for trial-and-error experimentation that could facilitate a robust response. Unfortunately, some of the greatest challenges that such systems face seem to be of this nature, whether it is increasing economic and political connectivity or the threat of global climate change. This latter example is not considered here, as it has not affected the acequias in any appreciable way yet. However, it may well semipermanently affect the flow regime of the rivers on which the acequias depend if, with warming temperatures, much of the precipitation in the mountains falls as rain rather than snow. In terms of severity as defined in Table 1, such a *flow disturbance* ($D1_A$) would be many times more severe than a single drought, given the extremely long duration that is likely involved in such a regime change.

Finally, this climate change example reinforces an observation found in the acequias: that one disturbance can introduce others. With the acequias, increasing connectivity also involved a change in the internal network structure of the acequias. With climate change, changing environmental parameters and flows may be accompanied by network disturbances via invasive species, when such species' geographic distributions are altered by environmental changes.

Although the primary objective of the typology is to facilitate cross-case analysis and theory-building, there are several ways in which the typology contributes to the case study itself. In conducting the study, an inchoate version of this framework helped as a heuristic guide to search for structural components of the acequia SES and the types of disturbances it was facing. The typology also helps to organize our understanding of the system and reinforces our conceptualization of the acequias SES as a set of networks that interact with internal parameters, external connections, and flows to and from an external environment. This typology is co-dependent on a particular conceptualization of an SES, and each is required in order to understand dynamics and outcomes in SESs. Finally, the typology improves the analytical content of the study by making important terms scientifically meaningful, and helps to move the presenting of it beyond interesting storytelling.

Discussion and Conclusion

The goal of this article is to increase our understanding of disturbances and their ramifications on SESs (i.e., how systems respond to the disturbance). Without some type of standardized framework, generalizable findings about the interaction between disturbances and SES responses are extremely difficult to identify. By using a framework, however, new studies can be conducted and guided by hypotheses based on previous observations in existing studies that explore the interactions between specific SES properties and specific types of disturbances. For example, the acequias study indicates that community-based systems will likely be vulnerable to connectivity disturbances. At the same time, such a framework needs to allow for the dynamic nature of SESs and their development over time. This framework may also facilitate cross-case comparisons (or single-case comparisons across time) into how one type of disturbances affects SESs differently from other types of disturbances when examined aggregately. For this reason, we saw a need to create a new framework for understanding disturbance-response interactions—to better understand system dynamics, to clarify the relationship between specific types of disturbances and how they affect system robustness, and to help identify patterns of disturbance and system responses across a range of cases.

Through development of this framework, the article demonstrates its application through a detailed case study. We think that such a framework provides generalizable insights into disturbance effects on SESs and how the interactions between an SES and various types of disturbances reshape the SES over time. These interactions form the crux of robustness studies. For this reason, we see the use of a common framework that accounts for interactions between an SES and disturbances as a necessary means to gain understanding of the dynamic nature of resilience and robustness.

Notes

1. These hydrographic surveys recorded the geographic location and extent of water rights of the acequias in the valley. They were conducted by the New Mexico Office of the State Engineer as a part of its mandate to quantify and govern all water rights within the state.
2. A hydrological drought occurs when "stream discharge, lake, wetland, and reservoir levels, and water-table elevations decline to unusually low levels" (Dingman 2002, 509). USGS stream gage data for New Mexico are available at: http://waterdata.usgs.gov/nm/nwis/rt. The drought years (with number of standard deviations below the mean in parentheses) were 1972 (1.26), 1974 (1.03), 1977 (1.23), 1984 (1.23), 1996 (1.1), 2000 (1.36), 2002 (1.64), and 2006 (1.2).
3. This is also sometimes referred to as hysteresis or path dependence.

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