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Research

Understanding how governance emerges in social-ecological systems: insights from archetype analysis

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ABSTRACT. This paper is motivated by the question: how does governance emerge within social-ecological systems (SESs)? Addressing this question is critical for fostering sustainable transformations because it directs attention to the context specific and process intensive nature of governance as arising from the internal dynamics (i.e., interplay of feedbacks and interdependencies between the components) of SESs. This contrasts with the commonly held view of governance as an external intervention applied to a system. To systematically examine the recurrent patterns in how the internal dynamics promote/detract from the emergence of different types of governance, we applied archetype analysis to 60 selected cases of irrigation systems from Asia. Drawing inspiration from grid-group typology of cultural theory, we developed four specific archetypes: egalitarian, individualist, hierarchical, and fatalist. To build these archetypes, we applied a robustness framework and several other theories/perspectives to identify the different social-ecological and infrastructural attributes of irrigation SESs, and their interdependencies and feedback structures. We then used these attributes, identified through our theoretical review, to deductively code our selected cases and classify them into the different archetypes. The results show the different configurations of attributes that co-occur in each archetype, and how together these attributes and their inter-relationships lead to specific types of governance. Our archetype analysis also provides several interesting examples of fine-tuning between different SES attributes and how this fine-tuning is being threatened by various social and environmental changes. Through a systematic exploration of recurrent patterns using archetype analysis, our work builds on past efforts to apply ideas from complexity theory—specifically emergence—to unpack the complexities of SESs and offer practical guidance for fostering sustainability.

Key Words: *archetypes; Asia; emergence; governance; irrigation; social-ecological systems*

INTRODUCTION

The critical role of governance in addressing the complex challenges of the Anthropocene is increasingly being recognized in scientific and policy discussions at multiple levels (IWMI 2021, IPCC 2022). Yet our understanding about what is governance and how we can improve governance capacity remains limited. Governance has generally been defined (loosely) in terms of a set of rules/policies, decision processes, and actors that are designed to steer a system toward some desired outcomes. Defined in this way, governance is something (external) that we apply to a system, which can be isolated and plugged into other settings. Based on this definition and the assumption of direct and linear causation between rules/policies and their outcomes, the practice of evidence-based governance reforms has proliferated recently, spearheaded by various international development agencies. Its focus has been to identify, isolate, replicate and test "good governance" or "best practices" in different global settings (Andrews et al. 2013). However, the poor track record of such governance reforms has been noted in a wide range of applications, such as natural resource management (Samad 2002, Shivakoti and Ostrom 2002, Venot and Suhardiman 2014), climate change adaptation (Nightingale 2017, Eriksen et al. 2021), and public administration (Denizer et al. 2011, Van Assche et al. 2012, Andrews et al. 2013). Recent meta-reviews (Mukherji et al. 2010) have shown that this dismal record cannot simply be attributed to inadequate implementation or lack of enabling conditions, as previously thought (Garces-Restrepo et al. 2007). Instead, this record points toward deeper problems with the conceptualization of governance reforms themselves and the underlying theory of change (Scott 1999, Andrews et al. 2013).

There is a growing tradition in political science that recognizes that these policy interventions are not singular actions, and views policies as complex processes that unfold or evolve over time (Sabatier and Jenkins-Smith 1993, Ostrom 2005). Building on this work, Morçöl (2010:53) postulates that "public policies are self-organizing systems" that are "constituted by the actions of self-conscious actors." These actors are not only state actors but may also include varied non-state actors. Orach, Duit, and Schlüter (2020) for instance, show how the behavior of competing interest groups affects sustainable resource management by tracing the policy change process and analyzing its dynamics with an agent-based model. This framing is appealing because it negates the notion that complex social problems can be solved through linear interventions by hierarchically organized bureaucratic organizations. Recent works (e.g. Morçöl 2012, Teisman and Gerrits 2014) discuss how complexity theory and complexity informed methods can lead to a better understanding of the messy day-to-day reality of policy makers.

This review suggests that rather than viewing governance as an external intervention applied to a system, we need to direct attention to the context specific and process intensive nature of governance as arising from the internal dynamics of the system it is embedded within. To understand these internal dynamics, the concept of emergence from complexity theory can be very useful. The game of chess illustrates very well some of the central ideas behind emergence and why it provides a useful way to study governance. As Corning (2002:25-26) explains, in the game of chess,

> *[R]ules, or laws, have no causal efficacy; they do not in fact "generate" anything. They serve merely to describe*

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> *regularities and consistent relationships ... Even in a chess game, you cannot use the rules to predict "history," i.e., the course of any given game ... Why? Because the "system" involves more than the rules of the game. It also includes the players and their unfolding, moment-by-moment decisions among a very large number of available options at each choice point.*

The important insight here is that rules or laws that have been the central focus in governance reform studies, "have no causal efficacy" by themselves. Instead, as the chess example illustrates, to examine what works we also need to pay close attention to the internal dynamics, i.e., the unfolding of the game in terms of the dynamic interactions between the characteristics of the players, the choices they have, and the decisions they take in anticipation of and in reaction to the other players. When we move from games to real life situations, the successful set of strategies/behaviors becomes conventions (Young 1996) that regulate the next rounds of interactions; and continuous learning from these interactions becomes part of governance. Seen in this light, institutions are simply the formal codification of these emergent patterns, and "governance" is the infrastructure that is developed to help stabilize these patterns.

In this paper, we build on the above ideas to conceptualize governance as an emergent phenomenon in social-ecological systems (SESs). We define an emergent phenomenon as one where global (or macro) behaviors/structures result from the context-specific interactions of the components of a system (Holland 1998). The interactions referred to here are not simple, linear cause and effect relations, but complex networks of interdependencies that lead to the generation of novel properties or functionalities that cannot be explained by their constituting elements alone (Miller and Page 2007). Given that SESs are embedded in broader cultural, biophysical, economic, and technological environments, we are interested in examining how the varied configurations of these contextual factors affects what types of governance emerges. We draw on the robustness framework (Anderies et al. 2004) to parse the complexity of SESs and make explicit the internal dynamics, i.e., the working of different types of context specific interactions and feedback structures that stabilize (destabilize) the dynamic relationships between processes in human and natural systems. We argue that externally designed governance reforms, as discussed above, have met with limited success because these have ignored the internal dynamics within these systems.

Although these applications of ideas from complexity science are promising, researchers working in this area have also cautioned about the "dynamics of theory transfer" from the natural sciences (where complexity sciences largely originate) to the social sciences (Teisman and Gerrits 2014:21). Closer examination reveals that a number of applications in social science "use concepts from the complexity sciences as a metaphor. Metaphors can provide genuine insight in the target domain but may lead to disappointment if not applied properly" (Teisman and Gerrits 2014:21-22). There is clearly a need for more work on disentangling and addressing these challenges in theory transfer, as well as on operationalizing these concepts to make them more useful for practical guidance. Given that emergence involves non-linear interactions and complex interdependencies, standard methodological approaches that involve formulating and testing causal hypotheses can be very challenging and not very insightful. Instead, emergence researchers (such as John Holland) recommend advancing our understanding through the search for recurring emergent patterns (regularities) among the numerous possibilities that lead to the likelihood of success (Holland 1998). Archetypes approaches are increasingly being used in sustainability science to classify and understand recurrent patterns in variables and processes, and to support contextually explicit generalizations of results from case studies (Oberlack et al. 2019).

We apply archetype analysis in this paper to systematically examine the diversity of combinatorial possibilities of natural and human-built infrastructures and their inter-relationships that lead to recurrent patterns in the emergence of governance. We focus on irrigation SESs for concreteness, although our analysis can apply to other SES settings also. Given its critical role in food security, the irrigation sector has for centuries provided the basis for human organization, ranging from small-scale communities to large-scale empires (Wittfogel 1957). Drawing inspiration from the grid-group typology of cultural theory (Douglas 1978, 1999) we develop four specific archetypes: egalitarian, individualist, hierarchical, and fatalist. To build these archetypes, we apply a robustness framework and several related theories/perspectives to first identify the different social-ecological and infrastructural attributes of irrigation SESs, and their interdependencies and feedback structures. We then use these attributes, identified through our theoretical review, to deductively code 60 selected case studies on smallholder irrigation systems from Asia and classify them into the different archetypes. Within each of the archetypes, we look for recurrent patterns in the co-occurrence of irrigation SES attributes and their inter-relationships. Looking for these patterns of co-occurrences is important because these often underpin functional complementarities (i.e., synergies) between the constituent parts of a system. As Corning (2002) has emphasized, these synergistic relationships are key to understanding emergence because these often lead the whole to do much more and/or something qualitatively different than the constituent parts.

Overall, our paper integrates the materialities of technological and social-ecological processes with the underlying cultural systems of beliefs and collective identity (see also Crane 2010) to characterize the local (micro) interactions and feedback structures that give rise to the macro governance structures emerging from them. Conducted at an intermediate level of abstraction, our archetype analysis enables us to move beyond panaceas on the one hand and idiosyncrasies of specific cases on the other hand, to provide refreshing insights on the co-occurrence of SES attributes and the fine-tuning between social and ecological attributes that leads to specific types of governance. This fine-tuning underscores the need for considering configurations of SES attributes holistically, and not as separate pieces that can be isolated (often in the form of "best practices") and replicated across different settings. Overall, our work builds on the long tradition of applying ideas from complexity science to SESs and helps make these ideas more concrete and useful for practical guidance through a systematic exploration of recurrent patterns in case studies using archetype analysis.

CONCEPTUAL FOUNDATIONS

Conceptualization of emergent phenomena in SES: a review

The complex adaptive and multilevel nature of SESs that generate emergent and highly uncertain SES behaviors has long been recognized (Levin et al. 2013, Folke et al. 2016). Yet as Schlüter et al. (2019) observe, "the causal processes through which the interplay between local interactions of people and ecosystems with system-level social or ecological structures and processes produce emergent SES phenomena are, however, less known." To fill this gap, Schlüter et al. (2019) have developed a framework that builds on Ostrom's concept of the action situations and networks of adjacent action situations (McGinnis 2011) to capture the links between microlevel interactions and emerging macrolevel structures and processes that codetermine emergent outcomes, such as poverty traps and regime shifts. However, their framework treats the governance of these interactions as exogenously given and does not explain how governance itself emerges.

Ostrom's Institutional Analysis and Development (IAD) and SES frameworks are among the most widely used frameworks to study resource governance. Yet as Morçöl (2014:15-16) argues, even in these frameworks "rule sets and action arenas exist independently of individual actors" and in this sense "Ostrom's framework is static." The central contribution of Ostrom and colleagues' body of work that brings her close to complexity research is to show through careful empirical work that individual actors have self-organizational capabilities, and to codify the conditions, referred to as Design Principles (DPs), that determine whether they will organize themselves. Although she makes some generalizations about the DPs of self-organizing systems, she notes that there are many areas in which no conclusive DPs can be devised. Therefore, a better approach is to develop a configurational understanding of these systems, i.e., to identify specific configurations of the variables for particular conditions, rather than trying to find out the optimal conditions for self-organization (Ostrom 2005). This configurational understanding is critical because as Ostrom stressed repeatedly, DPs should not be taken in isolation and interpreted as panaceas or blueprints to be replicated widely.

Within this configurational understanding of systems, Ostrom's DPs can be understood as functional requirements for collective action. These requirements may be satisfied in varied ways in diverse configurations of SESs. For instance, let us consider the DP related to monitoring the actions of resource users in different common pool resource (CPR) settings. In tightly knit communities in remote mountainous settings, external monitors may not be required as resource users observe each other, as part of their daily activities (Trawick 2001). Thus, monitoring can be seen here as jointly produced or as a spillover from other system wide activities (Baumgärtner et al. 2001). This is clearly not the case in larger more dispersed communities in the plains where additional infrastructure, involving external monitors, is a key requirement for collective action (Wade 1988a). Taken together, these DPs can be thought of as a feedback control for resource use in the sense that they transform information about the state of the system into actions that influence the system (Anderies et al. 2004, 2016). This more dynamic understanding of DPs as feedback control is critical for building our understanding about how governance emerges in any given setting.

Corning (2002) suggests another important feature to look for in understanding emergence. He suggests looking for functional complementarities (i.e., synergies) between the constituent parts of a system, which lead the whole to do much more and/or something qualitatively different than the constituent parts. Corning shows that these functional synergies have played a key role in the evolution of cooperation and complexity at all levels of living systems. As he points out, "synergy shifts our theoretical focus from mechanisms, objects, or discrete bounded entities to the relationships among things, and, more important, to the functional effects that these relationships produce. Synergistic causation is configurational; synergistic effects are always co-determined" (Corning 2002:64). Interestingly, this distinction between individual mechanisms and objects on the one hand, and relationships within a broader context on the other, maps onto what Nisbett and Masuda (2003) refer to as "Western" versus "Eastern" thought patterns, respectively. These different cultural understandings need to be considered along with the more objective factors in our understanding about how governance emerges in different contexts. In the rest of this paper, we apply these ideas as the basis for developing archetypes that can help capture this complexity to advance our understanding of how governance emerges in SESs.

Archetypes to identify recurrent patterns in SES configurations

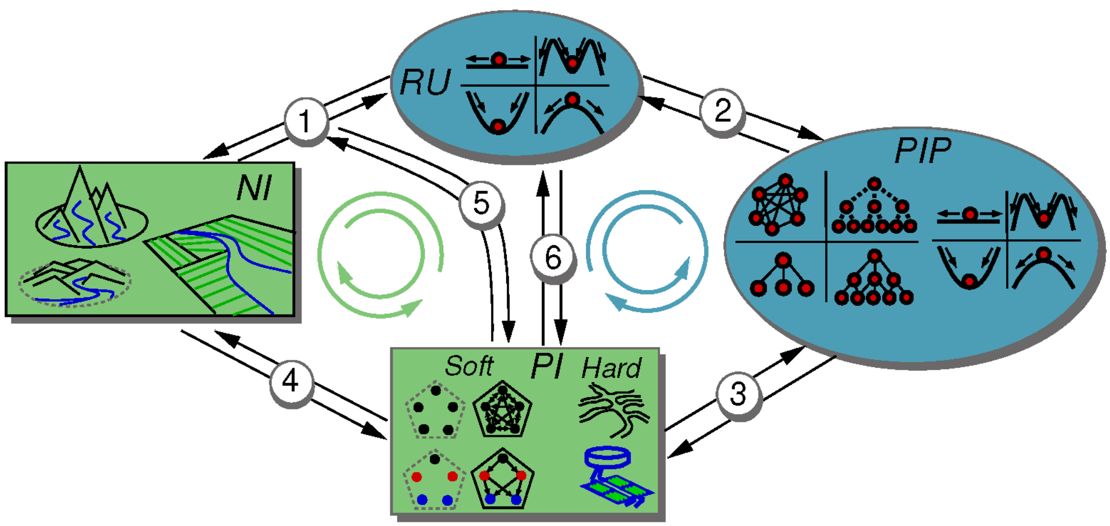
Archetypes represent replicated temporal, spatial, and institutional patterns under specific contextual conditions (Oberlack et al. 2019). In contrast to multivariate methods that search for one general model to explain the relationships between independent variables and outcomes across all observations, archetype analysis is based on the premise that capturing the diversity of contexts, processes, and outcomes of a phenomenon requires developing multiple models and theories to explain the underlying diversity. Such an analysis can also help reveal the deeper (hidden) meanings behind the relationships among these attributes, through contextualizing and bridging, which is the opposite of reductionism. Archetypes analysis is based on three elements (Eisenack et al. 2021): (i) a configuration of attributes; (ii) theories or hypotheses that explain the relation between the attributes; and (iii) a set of cases where it holds.

Robustness framework (RF) as an overarching framework to examine internal dynamics

To examine the internal dynamics of SESs, we draw on the robustness framework (Anderies et al. 2004). RF is particularly helpful for our purposes here because it enables us to explore the interactions and feedbacks between not only the social and ecological sub-systems, but also the design elements of the built environment (canals, diversion, and storage structures) that are critical to irrigation SESs.

RF consists of the following sub-systems: (1) natural infrastructure (NI) sub-system embedded within a specific biophysical context, which is used by (2) resource users (RU) using (3) public infrastructure (PI) consisting of physical, human, and social infrastructures, provided by the (4) public infrastructure providers (PIP). As shown in Figure 1, the actors (RU and PIP, shown in ovals), constantly interact and co-evolve with the various infrastructures (shown as rectangles) in this framework. In the context of irrigation, these infrastructures consist of (a) natural infrastructure (water resources, soils, vegetation, and

Fig. 1. Robustness framework: key attributes for archetype development (adapted from Anderies et al. 2004). The rectangles represent the "biophysical" subsystems: natural infrastructure (NI) and public infrastructure (PI). The ovals represent the "social" subsystems: resource users (RU) and public infrastructure providers (PIP). Within each of these boxes/ovals, visual representations of different possibilities related to the key attributes for the development of archetypes are shown. RU and PIP oval (right side) shows the different types of perceptions/myths related to nature: Ball on top (nature fragile), ball at bottom (nature robust), ball at bottom of rugged landscape with multiple peaks (nature tolerant), ball on flat surface (nature capricious; Thompson 2008). PIP oval (left side) shows the different types of organizational structures of PIPs and their relationship with RU. Dashed lines denote weak links, solid lines denote strong links. Hexagon on left shows non-hierarchical structure and multilateral cooperative relationships; single node at top with multiple nodes at bottom shows monocentric bilateral relationships; single node at top with multiple levels of nodes below shows hierarchical structure with weak links (dashed lines) and strong links (solid lines). NI box shows different altitude levels: Steep, low, and plains. PI box shows different types of hard and soft infrastructure. Soft PI stands for different types of rules and is represented by pentagon with dots and connecting lines. Dots represent rules that create positions (e.g., upstream/ downstream, depicted by different colored dots) and differentiate roles/actions based on those positions versus undifferentiated (all black dots); lines represent information rules: dashed lines represent infrequent and few information channels available versus solid lines that show frequent and multiple information channels. Hard PI shows design of layout of canal and presence/absence of storage structures: hierarchical design with storage upstream, primary canal divided into a few secondary canals, further sub-divided into several tertiary canals; bifurcated design, proportional sharing. Clockwise and anticlockwise circles represent different feedback structures. Green clockwise, collective; green anti-clockwise, private; Blue clockwise, top-down/non-participatory structure; blue anticlockwise, participatory.



topography), and (b) human-built public infrastructure that can be further sub-divided into soft infrastructure (such as formal knowledge and protocols, formal and informal rules and norms), and hard infrastructure (such as canals, diversion, and storage structures). Next, we turn to various theories that enable us to identify attributes of interest within each of these different sub-systems.

Grid-group cultural theory (CT) as foundational basis for developing archetypes

Given our primary interest in understanding the patterns of emergence of governance from the interactions of agents among themselves and with their environment, it is critical to understand the variation in beliefs and world views that underlie the actions of these agents and their relationships. Cultural theories put culture at the center of the explanation of social life (Mamadouh 1999) and thus we start with these as the foundational basis for our archetype development, and then draw upon other theories, as needed, to help identify attributes of the other (non-social) sub-systems.

Among the various variants of cultural theories, we will discuss here the grid-group cultural theory (henceforth CT), which posits that it is possible to distinguish a limited number of cultural types that consist of viable combinations of patterns of social relations and patterns of cultural biases (or cosmologies). Based on ethnographic evidence, Douglas (1978) postulated that people are especially concerned with two dimensions of sociality: grid and group. Group stands for the extent of incorporation into a bounded group: it is strong when an overriding commitment to this group constrains the thoughts and actions of individuals, it is weak when people are self-focused and competitive. Grid is a measure of structure within the group: high grid is associated with strong regulations and/or ranking and stratification that structure social interactions. Assigning two values (high and low) to the two dimensions, Douglas defined four general types (Table 1): (1) enclavists (or egalitarian), (2) positional (or hierarchical), (3) pioneers (or individualists), and (4) isolates (or fatalists). The first three correspond to Max Weber's three types of rationalities: religious charisma, bureaucracy, and market (Weber 1958). Although grid-group cultural theory has been applied to a wide

Table 1. Typology based on grid-group cultural theory.

Grid	Characteristics	Low group	High group
		INDIVIDUALIST	EGALITARIAN
Low grid	Social relations	Competitive relations within and outside group	Reciprocal relations within group; Shared opposition to outsiders
	Goals /pursuits	Pursuit of personal goals	Pursuit of shared goals
	Blame assignment	Blame put on personal failure	Blame put on outsiders
	Views of Nature	Nature robust	Nature ephemeral
	Attitudes to risk	Risk loving	Risk averse
	Type of power	Persuasive power	Moral power
		FATALIST	HIERARCHICAL
High grid	Social relations	Isolated, at margins of organized patterns	Differentiated roles, division of labor
	Goals /pursuits	Not goal driven, attitude of apathy	Pursuit of collective over individual goals
	Blame assignment	Blame put on bad fate	Blame put on deviants of established procedure
	Views of Nature	Nature capricious	Nature perverse/tolerant
	Attitudes to risk	Mixed attitudes	Risk neutral
	Type of power	Coercive power	Coercive power

Source: Based on Douglas (1978, 1999); Thompson (2008).

range of environmental/resource settings, such as, energy futures (de Vries et al. 1999), water management, and water pollution (see Mamadouh 1999 for a survey), it has not been systematically integrated with existing SES frameworks.

Applying CT to identify attributes of RU and PIP

Previous studies have found CT to best apply not to individuals but to the field of relationships; to compare social formations with their cognitive styles and cultural biases (Oldroyd 1986). The different cultural types discussed above are therefore often called (sub)cultures, ways of life or rationalities, social orders, or solidarities. In Appendix 1, Table A1 we have mapped the attributes of RU and PIP that correspond to each type. Interestingly, the grid-group based constructs have close parallels with IAD framework and ecological theory. In the IAD framework, grid can be conceptualized in terms of position and choice rules; and group can be conceptualized in terms of boundary rules. In ecological theory, grid corresponds roughly to the concept of connectedness, whereas group corresponds to idea of boundedness (Thompson 2008). It is important to note that these cultural groups are not rigidly defined sets for which a single label can be placed, rather these types are heuristics that are meant to illuminate cultural patterns at an aggregate level (Castilla-Rho et al. 2017).

Applying CT to identify attributes of NI-RU relationship

An important mechanism that underlies the dynamics of these cultural types is their co-evolution with the natural environment in which they are embedded. Kauffman (1993) uses the metaphor of "fitness landscapes" to describe how species must fit to the landscapes around them and how landscapes themselves change, partly in response to the evolution of the species. These co-evolutionary processes lead over time to cultural types and natural environments settling down in mutually compatible configurations. Among the various attributes of the natural environment, altitude has been found to be an important factor that influences governance structures (Agrawal and Chhatre 2006). This critical role of altitude stems primarily from its close relation to a host of ecological variables like accessibility, temperature, and agricultural possibilities. Thus, for instance, the small and isolated nature of user groups in high altitudes are more likely to lead to the development of shared norms and knowledge, and strong reciprocal relationships based on trust that are characteristic of the egalitarian user group. Other attributes of NI that are likely to be important for irrigation SESs include soil type and climatic conditions.

Following the development of cultural theory, some ecologists have pointed to how different types of beliefs regarding nature may have co-evolved with each of these cultural types (Thompson 2008). These perceptions are represented graphically by a ball in a landscape (Holling 1973), with the different shapes of the landscape revealing the varied perceptions (Fig. 1). For instance, a view that sees nature as tolerant but only within a certain safe zone, reinforces the hierarchical cultural type because of the need for control (through experts/managers). The view of nature as robust is most compatible with individualist type, wherein even with uncoordinated atomistic individual actions, the ball still returns to its best position. At the other end of the spectrum, the view of nature as fragile corresponds with the egalitarian user group, wherein closely coordinated action within the user community is a necessity. Finally, the view of nature as capricious, wherein one does not know which way the ball would move, corresponds to the fatalist type that cares only about the present and finds no purpose in individual or collective action.

Each myth of nature, explained above, captures some aspects of the real world at some time and place, but none of these myths holds true all the time in all places. Change comes about when the real world diverges from the myth that each of the types upholds (Thompson 2008). Surprise (arising from the divergence between actual and expected) disrupts the prevailing order: it displaces people from their specific form of social solidarity into another that better fits with the underlying environment.

Social construction of technology (SCOT) related theories/ perspectives

Studies using a SCOT perspective have conceptualized irrigation systems as "socio-technical ensembles" (Mollinga and Veldwisch 2016). These studies have identified three general tasks (and the associated social dilemmas) in irrigation systems: water allocation, system maintenance, and conflict management (Coward 1980). SCOT perspective delineates how individual irrigation artifacts such as water conveyance, division, and storage structures that are designed to address these tasks, bear the imprint of the culture and the society in which that technology was designed (Coward 1980, Pinch and Bijker 1984, Mollinga and Veldwisch 2016). Thus SCOT related theories/perspectives help us understand the relation between irrigation technology design and social-ecological factors.

Applying SCOT to identify attributes of PI and PIP, and their inter-relationships

At the irrigation system level, an important infrastructure design characteristic is the layout of the canals (Mollinga and Veldwisch 2016). Two main types can be distinguished here: hierarchical and bifurcated (Horst 1998). Under hierarchical design, water is divided into a few large secondary blocks, which are then further sub-divided into several tertiary blocks; resulting in sharp upstream-downstream asymmetries (see under hard PI in Fig. 1). Under the bifurcated design, on the other hand, water is divided in fixed proportions (Horst 1998). The compact layout of the hierarchical system generally results in lower costs per hectare because of shorter lengths of irrigation and drainage canals, but the large number of offtakes along a secondary branch and the large distances between top- and tail-end units often lead to distribution problems (Horst 1998). These trade-offs in design help explain the general pattern: hierarchical design associated with agency-managed irrigation systems (AMIS) and the bifurcated design associated with traditional, farmer managed irrigation systems (Horst 1998, Pradhan et al. 2015). These designs also create different positions in the systems and may lead to differentiated roles/responsibilities associated with these positions (position rules, see under soft PI in Fig. 1).

Another critical design feature is the size and distribution of storage capacity. Increasing storage capacity helps smooth the pulses of water flows (Schlager et al. 1994), but adding stocks to the systems often complicates its control and typically slows down reactions (Moxnes 2004). Learning in such systems is challenging because there is no accurate and immediate feedback about the relation between the conditions of the resource state and the appropriate response, which makes it difficult to attribute outcomes to specific actions (Tversky and Kahneman 2000). The required amount of trust is therefore greater in irrigation systems where storage capacity is higher and not uniformly distributed (Wade 1988a). However, this higher level of trust may not be forthcoming because increasing storage capacity also entails significantly higher capital investments and specialized skills, which may be difficult to self-organize by the user group. Consequently, an external set of actors, i.e., PIP, with specialized skills and private information about changing water stocks may be required. This shows how the design of storage has important implications for the trust needed between RU and PIP.

Irrigation system design as mechanism of power and control (PI, PIP, and RU relationships)

As the above examples illustrate, the design of irrigation technology, in combination with the other sub-systems, structures the nature of the social dilemmas faced by users. The design of technology is, in turn, influenced by the objectives and values of the infrastructure providers. For instance, Mollinga (1998:41) describes how large-scale irrigation systems in India were constructed by the British colonists to "protect" the population from recurrent famines, while simultaneously serving as mechanisms of control over large and dispersed populations. The intention was to avoid crop failure on as large an area as possible, and thus these protective systems were "designed for continuous flow and/or 'automatic' distribution. In this way, the management intensity (number of personnel per acre or unit length of canal) and costs were kept low" (Mollinga 1998:41). Design of such protective irrigation systems is quite widespread across South Asia and differs significantly from those in East Asia (Lam 2006). In a study comparing these systems, Wade (1988a:493) found the density of irrigation staff in South Korean irrigation systems to be five to eight times higher and more evenly distributed along the canal system, resulting in higher performance but also higher staff costs than in the Indian protective systems. Analyzing these trade-offs, and how different societies have navigated these, is critical to our understanding of how governance has emerged under the different archetypes we lay out in the next section.

Applying RF to identify feedback structures

Having described the four entities/sub-systems (RU, NI, PI, and PIP) and the links between them, we turn next to how these links form different feedback structures, and how these feedback structures, in turn, are associated with specific cultural types and reinforce their respective logics.

Robustness framework suggests the possibility of four feedback structures: two green circles (clockwise and anti-clockwise on the left side) and two blue circles (clockwise and anti-clockwise on the right side) in Figure 1.

F1: Collective structure (green clockwise) formed by links 6, 4, 1 and 5 (Fig. 1)

This represents a situation where RUs collectively invest in soft and hard PI (link 6), which influences users' water extraction decisions (link 5) and resource dynamics (link 4). Changes in the resource dynamics as perceived by RU based on their worldviews (link 1) may lead RU to adapt and change the collective rules and their investments in hard PI (link 5) in the next round. This feedback structure is most compatible with the egalitarian cultural type and reinforces its collective logic.

F2: Private structure (green anti-clockwise) formed by links 1, 4, 5, and 6 (Fig. 1)

This denotes a private management situation (including formal/informal market contexts) where RUs make individual decisions regarding investments in private capital (e.g., private wells and pumps) but do not engage in any collective deliberations about the provision of irrigation infrastructure. Thus, PI here is not irrigation specific, but is more diffuse within the community and is not provided by any specific PIP. It takes the form of generic social norms and generalized trust, which are essential even for markets to function (Polanyi 1944, Arrow 1982, Fukuyama 1995), and public perceptions about resource conditions that underlie livelihood patterns, and are negotiated in religious and/or political spheres (Shah 1993, Dubash 2002). In this situation, RUs extract water based on their individual worldviews and preferences (link 1). Changes in water stocks and flows (NI) may lead to changes in public perceptions/attitudes (PI) about water scarcity (link 4), which then lead to changes in individual RU perceptions/attitudes (link 6), and consequently, changes in individual RU harvesting actions (link 5; e.g., through change in prices in a market context). Driven by individualistic logic, this feedback structure is most compatible with the individualist cultural type.

F3: Participatory structure (blue anti-clockwise) formed by links 6, 3, 2

This represents a range of participatory possibilities, where a formal/informal association of farmers, deliberates (with some autonomy) about rules regarding the use and management of their local irrigation system (link 6), but this local system is nested within a larger irrigation system, which is managed and financed by a different higher level agency (PIP, through link 3). This PIP designs and enforces the system level rules and provides resources/expertise but is held accountable (in varying degree) to RU (link 2) for their actions. This feedback structure is most compatible with the hierarchical cultural type and reinforces its logic of strict positionality and group identity.

F4: Top-down/non-participatory structure (blue clockwise) formed by links 3, 6, and 2

This represents the political economy of top-down management, where a specialized external agency (PIP) provides and manages the hard and soft irrigation PI (link 3); and through this PI, it regulates the actions of RU (link 6). RU make payments to PI for their service provision but PI have weak or no accountability to RU (link 2). This feedback structure is most compatible with the fatalist cultural type and reinforces its logic of strict positionality but very limited group identity.

Having identified these different types of feedback structures we will next map them to the different archetypes and show through archetype analysis how "emergence" can be understood as the instantiation of such feedbacks that then stabilize the relationships between the system elements.

METHODS

Case selection

We adopted a specific rather than exhaustive search strategy for case selection (Mollinga and Veldwisch 2016), which was focused on the need to find information-rich examples of illustrative interactions and feedback mechanisms. Thus, our analysis can be viewed as providing a "proof of concept" and was not a systematic comparison covering all possible types of irrigation systems. Our main source for case studies is the SES Library (https://seslibrary.asu.edu/) hosted at the Centre for Behavior, Institutions, and the Environment (CBIE) at Arizona State University, USA. Based on a search conducted in October 2021, using the keyword "irrigation" we obtained 133 records from this Library. Deleting cases that did not provide sufficient details on a specific case or were from outside Asia, we ended up with 50 unique cases. We supplemented this collection with 10 other notable cases from the literature and our own research that provides long-term evidence on irrigation SESs (see Appendix 1, section II for details on selected cases).

Analysis of case studies and code book development

In a recent review, Sietz et al. (2019) point out that there is not yet a universally accepted set of analytical methods for archetype analysis. The methods differ depending on the specific analytical purposes, data requirements, and epistemological and normative foundations. Our data consist of case studies that were conducted by independent researchers and thus are not comparable enough to conduct a systematic variable-centered or process-centered meta-analysis (Sietz et al. 2019). Given our purpose here of identifying recurrent patterns in configurations of variables and their inter-relationships, we used the qualitative classification approach for archetype analysis, in which different observations (i.e., case studies) are grouped according to similarities in their attributes (Eisenack 2012, Bocken et al. 2014).

Archetypes used in sustainability research can be understood as building blocks or typologies of cases (Eisenack et al. 2021). In the former, archetypes are identified such that any single case of the phenomenon of interest can be characterized by a combination of several archetypes. In the latter, each case is characterized by a single archetype. For this study, we use archetypes in the latter sense, and characterize each case by a single archetype defined by the cultural theory typology and then explore the recurrent patterns in co-occurrence of different RF attributes within each of these types. Thus, our first step was to classify cases into the four cultural types based on the attributes of RU and PIP derived from cultural theory (see coding manual in Appendix 1, section I). We were not able to specifically code for beliefs regarding nature in our data, but we were able to code for the basic features of grid and group, from which beliefs regarding nature can be inferred based on previous work (Mamadouh 1999, Thompson 2008). Our second step was to deductively code the cases based on the configuration of the robustness framework (RF) attributes (RU, NI, PI, and PIP) and the four feedback structures outlined in the previous section (see Appendix 1 for details on the codes). Next, we mapped these configurations of RF attributes with the cultural types to identify recurrent patterns in the co-occurrence of attributes within the different irrigation SES archetypes. Using the qualitative analysis software, MAXQDA, we assessed how the different attributes we coded are related to each other and how these are clustered within the different archetypes. Figure 2 presents a visual map of this co-occurrence of attributes, discussed in detail in the results section. Looking for these patterns of co-occurrences is important because these often underpin functional complementarities (i.e., synergies) that are key to understanding emergence (Corning 2002).

RESULTS: IRRIGATION SES ARCHETYPES

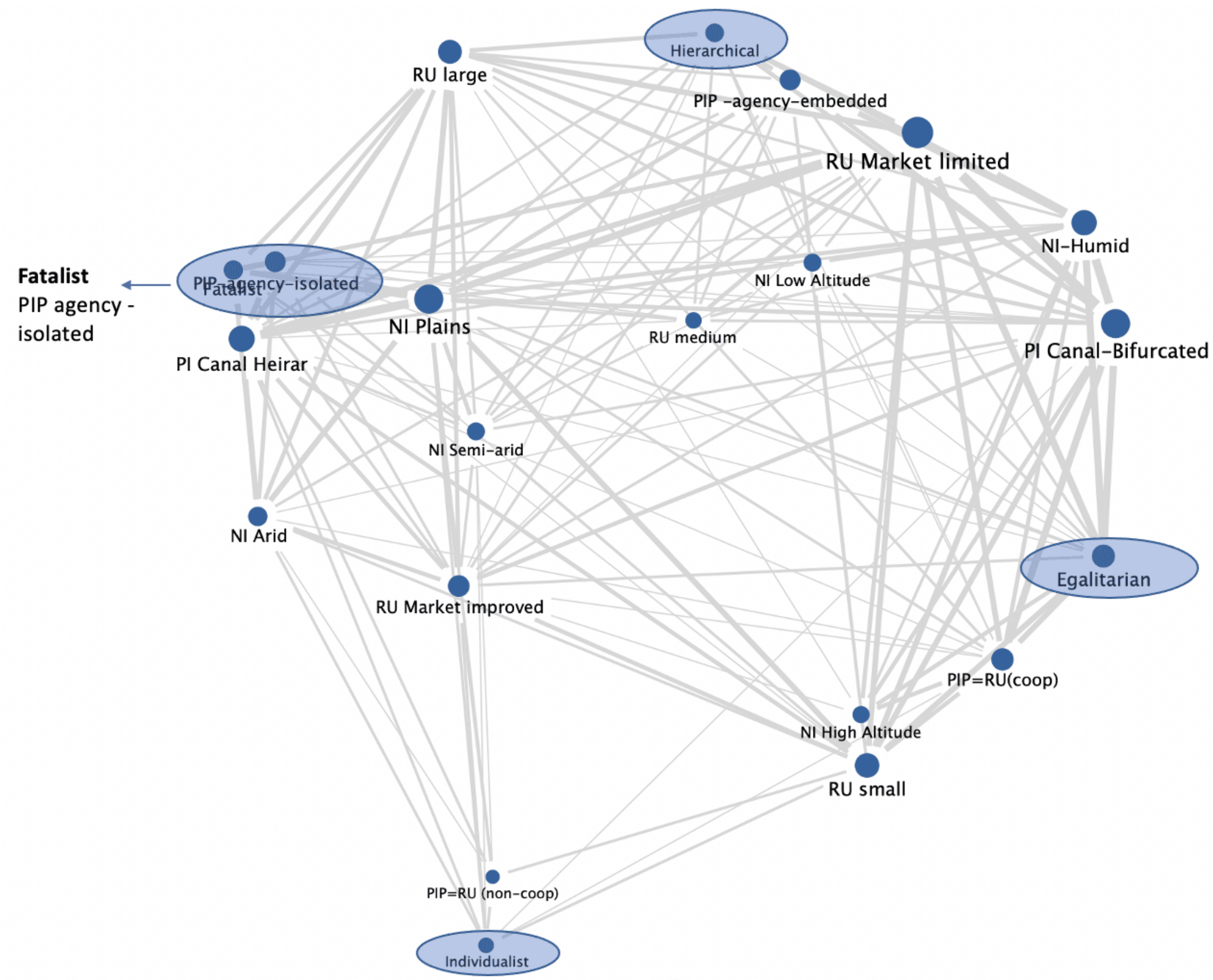
Based on our coding of cases, Figure 2 shows the co-occurrence of the different RF attributes, mapped with the four cultural types. Together these constitute our four irrigation SES archetypes. For each of these irrigation SES archetype clusters, we first discuss the recurrent patterns in co-occurrence of attributes and then mention some notable exceptions to these patterns. Our analysis shows how the fine tuning between social and ecological features within each archetype leads to the emergence of specific types of governance. Because of space limitations, details of this fine tuning and further examples of notable exceptions are discussed in the appendix.

Egalitarian archetype

Recurrent patterns

As shown in Figure 2, this archetype is most closely associated with the following RF attributes: small user group with limited market access (RU); high altitude settings in humid climates (NI);

Fig. 2. Map of co-occurrence of codes. Each circle symbolizes a code (see definitions in Appendix 1, Table A1). The distance between two codes represents how similarly the codes have been applied in the data material. The larger the circle the more code assignments have been made with that code. Connecting lines indicate which codes overlap or co-occur; the connection lines are displayed thicker the more coincidences there are between two codes

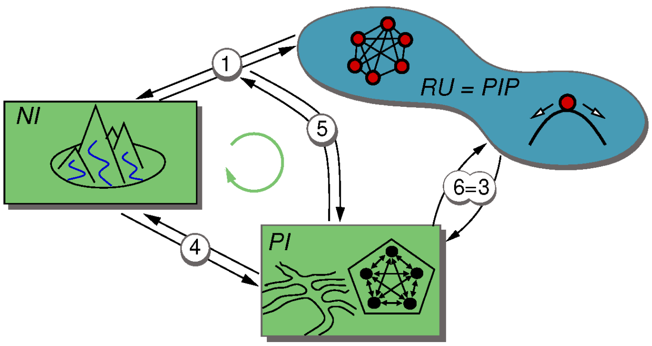


bifurcated canal structures (PI); and RU coinciding almost completely with PI (RU = PIP) with cooperative relations. The 31 cases under this archetype (Table A2) are generally associated with farmer managed irrigation systems (FMIS) in remote (e.g., high altitude) settings with high environmental risks, which are compatible with egalitarian type's beliefs about "fragile nature" (link 1 in Fig. 3). These beliefs/worldviews motivate farmers to self-organize for provision of hard and soft infrastructure (link 6). This infrastructure, in turn, influences users' water extraction decisions (link 5) and the resource dynamics (link 4). These links (1-6/5-4) together constitute the collective self-management feedback structure (clockwise green circle) in Figure 3. Given the small size of the RU group and mountainous settings, the scale of investment in hard infrastructure is small; with no storage capacity and simple technology (e.g., earthen structures, unlined canals, etc.). This simple technology requires regular maintenance, which is ensured through the emergence of fairness-based rules regarding provision of labor from each member household. Another design feature of the irrigation infrastructure here is bifurcated design of canals, which divides the canal water in fixed proportions, further reinforcing the egalitarian logic of equity-based allocations.

Notable exceptions

Although most cases under this archetype operate at relatively small scales (< 200 hectares), there are some notable exceptions. The Kuhl irrigation system in the Himalayan region of India, for instance, has a command area of 30,000 hectares and has withstood major environmental and socio-political shocks (Baker 2005). The uniqueness of this case derives from its unusual topography with multiple ecological niches (broad alluvial plains

Fig. 3. Egalitarian archetype.



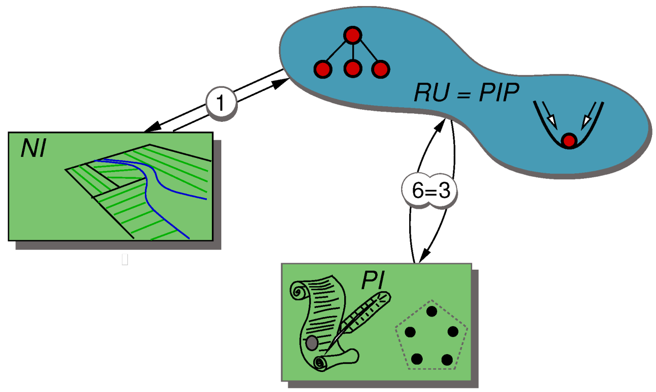
and river terraces), which has led to the emergence of networks of interconnected irrigation user groups (called Kuhls, see details in Appendix 1). These networks play a major role in sharing risks and coordination across large scales. Another notable case is that of the Subaks in the island of Bali in Indonesia (Geertz 1980), whose uniqueness derives from the underlying need to coordinate crop planting and harvesting dates because of the threat of pest outbreaks and water scarcity. This has led to the self-organization of yield-enhancing autonomous networks of water temples (Lansing 1991) that help coordinate the actions of farmers at large scales without any centralized control.

Finally, we also found some cases under this archetype where the feedback structure (F1) that characterizes this archetype is not complete or has weakened over time because of state interference, exposure to markets, and/or new values/beliefs under globalization (de los Reyes 1980, Water and Energy Commission 1987). Climate change was also noted as a major threat. For example, the modeling work of Cifdaloz et al. (2010) on the Pumpa system in Nepal shows how various kinds of fairness-based water allocation rules that had emerged to address past variability in water flows were becoming increasingly threatened by the new kinds of disturbances under climate change. These cases suggest that emergence may happen too slowly relative to the pace of social-ecological changes these communities are witnessing.

Individualist archetype

Recurrent patterns
This archetype is most closely associated with the with following RF attributes (Fig. 2): small user groups with improved market access (RU); located in plains in arid/semi-arid climates (NI); with hierarchical as well as bifurcated canal structures (PI); and RU coinciding almost completely with PI (RU = PIP), but with non-cooperative relations. Based on our case study analysis (5 cases, Table A2), we find that this archetype is best exemplified by the emergence of informal markets in groundwater irrigation, specifically in South Asia. Given that access to groundwater in arid/semi-arid contexts requires large and lumpy investment in wells and pumping equipment, only the relatively rich farmers can invest to access groundwater (link 1 in Fig. 4). Because property rights in ground water are not well defined and groundwater levels are not regularly monitored (link 4 is weak or absent), well owners tend to extract more water than they need and often sell surplus water to their neighboring farmers. Public infrastructure in this case is limited and takes the form of generalized trust and social norms that are needed even in market-based economies to support contract enforcement (link 6). There are no collective deliberations over the rules for groundwater extraction either among the users themselves or through external agencies (links 5 and 2 are missing) leading in most cases to unsustainable extraction of groundwater. In contrast to the egalitarian archetype, this archetype is grounded in underlying economic inequities, and further perpetuates it through its competitive logic and underlying belief in “nature robust.”

Fig. 4. Individualist archetype.



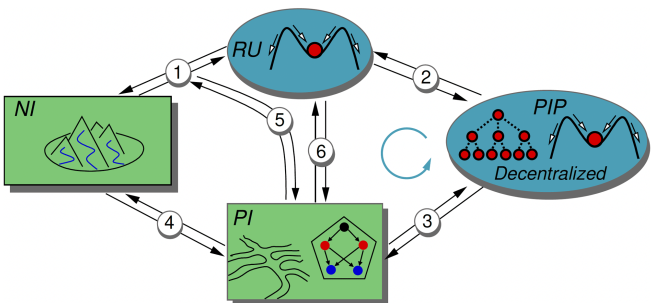
Notable exceptions
Although unregulated groundwater extraction leads to unsustainable use in most cases, there is a narrow range of conditions under which the extraction rates fall below the recharge rates so that the underlying myth of “nature robust” holds true. This type of robustness has been observed in the following cases: (a) floodplains with high groundwater recharge rates; or (b) regions where electricity availability for pumping is severely limited, and the high price of alternative fuels (e.g., diesel) limits groundwater extraction (Shah et al. 2006).

Hierarchical archetype

Recurrent patterns
As shown in Figure 2, this archetype is most closely associated with the following RF attributes: large user groups with limited market access (RU); located in low altitude settings (NI); with a hierarchical canal structure (PI); and PIPs as state agencies with strong links to RU (embedded). Under this archetype we have 13 cases (Table A2) that can be categorized as agency managed irrigation systems (AMIS), wherein a state agency has the responsibility for overall system design and management (Pradhan et al. 2015). The underlying logic of this cultural type that “nature needs to be controlled” defines the overall identity of this agency. This logic is also reflected in the design of PI, which tends to be physical capital intensive and rigid (with permanent headworks and lined canals), and consequently, less reliant on social capital (e.g., rules regarding labor contributions for maintenance) than the FMIS cases we discussed under the egalitarian archetype. In most cases, we found some delegation of responsibilities for water allocation and maintenance to

formal/informal association of farmers (often referred to as Water Users' Associations, WUAs). The type and extent of delegation varied across cases, but in most cases WUAs have some autonomy to deliberate about rules related to water allocation and maintenance of field channels below the tertiary canal that feeds the village (link 6 in Fig. 5). In most cases, a representative from the WUA liaises regularly with the state agency about the timing and flows to be expected in the tertiary canal (link 3), but we found large differences across the cases in the extent to which the WUAs can hold the state agency accountable (link 2). Thus, it is not surprising that evaluations of irrigation systems in Asia have found average performance of AMIS to be lower than FMIS (Ostrom 2015).

Fig. 5. Hierarchical archetype.

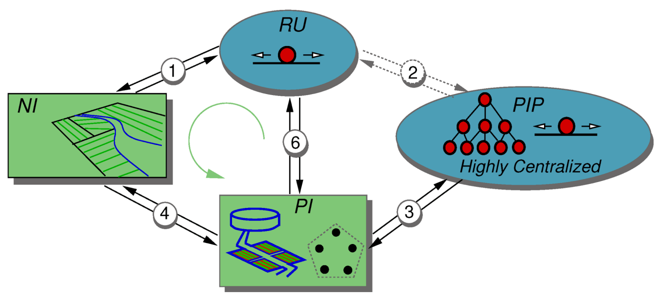


Notable exceptions
Although the average performance of AMIS is lower than FMIS, there are a few notable exceptions. For instance, the IAs in Taiwan have been regarded as among the highest performing irrigation systems in the world (Lam 1996, Lam et al. 2021). Lam (1996) ascribes this higher performance to the emergence of a co-production model of irrigation management in Taiwan. This co-production model stems back in history from the special status of IAs as parastatal agencies that were "legally owned and formed by farmers and supervised by governments at higher levels. Their legal status as juristic entities entitled them to a high degree of de jure autonomy" (Lam 1996:1041). This design feature of co-ownership of IAs and the associated narratives of "farmers being the boss of IAs" was a special feature of the Taiwanese system that enabled a highly decentralized model of irrigation management. Under this co-production model, officials from the IAs worked with Irrigation Groups (self-organized groups of local farmers), to collaboratively draw up plans for water allocation and maintenance, resulting in a more locally responsive and productive system. Whereas in the general case of this archetype we observe only the blue anti-clockwise feedback structure operating (Fig. 5), in the Taiwan case the green clockwise circle on the right (collective self-management) was also found to be operating, and it is the interplay between these two feedbacks that determined system performance and robustness.

Fatalist archetype

Recurrent patterns
This archetype, denoted by F4 cluster in Figure 2, is most closely associated with the following RF attributes: large user group, with extensive market access (RU); located in plains in arid/semi-arid climates (NI); with hierarchical canal structure (PI); and weak PIP-RU link. The 10 cases under this archetype (Table A2) were mostly built by colonial rulers to protect against recurrent famines and to control the vast population with limited administrative staff (link 2 in Fig. 6). The design of PI in these cases reflects the legacy of these colonial motivations, as these protective systems are supply rather than demand driven, and thus not very responsive to farmers' needs. These systems typically have storage structures concentrated upstream (Wade 1995), where most of the administrative staff is also concentrated rather than distributed along the canal as in the Taiwan case (link 3), resulting in poor information flows between agency staff and RUs and low levels of rule enforcement (link 6, blue clockwise circle in Fig. 6). This design of infrastructure leads to sharp upstream-downstream asymmetries, low user autonomy, weak accountability of PIP to RU, and consequently, a strong feeling of apathy among users (consistent with fatalist logic). These characteristics of PI are also not very conducive to trust-building, and consequently, seem to offer little hope for collective action.

Fig. 6. Fatalist archetype.



Notable exceptions
Although, in general, we found very limited evidence of collective action in the cases under this archetype, there are some noteworthy exceptions. One of these is Wade's (1988b) study in the drought-prone plains of South India, where he found remarkably high levels of collective action among some of the downstream villages along a 300 km canal. Wade found that although the downstream villages were relatively disadvantaged in terms of water availability, the quality of soil along tertiary canals of the tail end was quite high because of silt deposition. Wade argues that this variation in soil quality is one of the reasons why we observe greater fragmentation of landholdings in tail-end villages, with farmers of high caste owning small plots of land along different sections of the irrigation channels. This is an interesting example of an emergent institutional response (i.e., land fragmentation) to the underlying biophysical variation and physical infrastructure design (links 1 and 4). This fragmentation helps mitigate spatial concentration of power and explains why high caste farmers in tail-end villages have an incentive to organize collectively to manage scarce water resources. Wade observed four main types of village corporate institutions: village council, fund, common irrigators, and field guards (see details in Appendix 1). Villages at the tail-end were more likely to have all four institutions and used the village funds to bribe irrigation officials to ensure that water reaches the tail-end.

We also found prevalence of bribes reported in other highly centralized bureaucratic irrigation systems in our sample (Lowdermilk et al. 1975, Bottrall and Mundial 1981, Ramamurthy 1995). Mollinga (1998) in his study of another large-scale canal irrigation system in South India also reports on the emergence of political lobbying, as another collective mechanism through which those at the tail-end of the canal exert power on those at the head-end. Both these mechanisms (bribes and lobbying) are a result of the high grid fatalistic nature of the system. Otherwise, one might expect some other sort of collective action mechanism (e.g., water courts or WUAs). This illustrates the idea of fit and fine tuning of institutions to the underlying biophysical and social system.

DISCUSSION AND CONCLUSIONS

In this paper we applied cultural theory and robustness framework as the theoretical basis to guide an archetype analysis of the combinatorial possibilities of natural and human-built infrastructures that lead to recurrent patterns in the emergence of governance. Although the idea of emergence in SESs is not new, our archetype analysis conducted at an intermediate level of abstraction, using evidence from 60 case studies, shows in more concrete and systematic ways how governance can be understood as emerging from the interplay of different kinds of context-dependent relationships and feedback structures. In this section we reflect upon some of the learnings from this conceptualization and our archetype analysis.

Our integration of cultural theory (CT) with the robustness framework (RF) is novel and has proved to be quite effective in terms of teasing out the underlying complexity to show in concrete terms how governance emerges. Given the self-organizing nature of processes that underlie emergence, CT is helpful in outlining the varied ways in which actors in the system (RU and PIP) make sense of the world around them and what types of social organizations are consistent with their belief structures. RF expands this idea of viable combinations of social organizations and cultural types to the domain of SESs, by helping clarify how these socio-cultural relationships are mediated by the underlying ecological relationships. Furthermore, through shedding light on the specific relationships and feedback structures among the various entities in the SES, RF helps us understand the robustness of the varied combinatorial possibilities. Bringing all this together, archetype analysis is helpful to identify recurrent patterns among these combinatorial possibilities in case studies to further clarify, through systematic classification, the idea of emergence.

This conceptualization of governance as emerging from the interactions of the underlying contextual variables helps develop a configural understanding of the role of contextual variables in governance. This is in sharp contrast to the empirical literature on the determinants of collective action, which has largely applied multi-variate regression analysis to examine the role of individual contextual variables, such as size of user group, taken in isolation. Unsurprisingly, this previous work has resulted in contradictory findings about how group size is related to the likelihood of collective action (for a review, see Mukherji et al. 2010). Our analysis reveals the inter-relationships among SES variables, and thus directs attention to the mapping of diverse configurations of SES variables (under specific archetypes) to governance outcomes, rather than single variables taken in isolation.

Going deeper, our archetype analysis has also helped clarify the varied ways in which Ostrom's DPs, taken together, can be thought of as a feedback control for resource use in the sense that they transform information about the state of the system into actions that influence the system (Anderies et al. 2004, 2016). Applying the robustness framework, we identified four different types of feedback structures and mapped them to the different archetypes. We then showed through our archetype analysis how "emergence" can be understood as the instantiation of such feedbacks that then stabilize the relationships and interactions within and between the system elements. For example, under the collective feedback structure (green clockwise circle in Fig. 1) RUs collectively invest in soft and hard PI (link 6), which influences users' water extraction decisions (link 5) and resource dynamics (link 4). Changes in the resource dynamics as perceived by RU based on their worldviews (link 1) may lead RU to adapt and change the collective rules and their investments in hard PI (link 5) in the next round until the ecosystem dynamics, narratives, beliefs, and practices mutually reinforce one another to create a stable regulatory feedback structure. These narratives, beliefs, and practices (governance) may be codified as formal rules (institutions), and "governance" is the infrastructure that is developed to help stabilize these patterns. This is how governance emerges in our conceptualization, and our archetypes provide an interesting approach for systematically classifying and harnessing the diversity of various combinatorial possibilities of SES variables that lead to this emergence.

Our conceptualization provides several insights on where the strength and vulnerabilities in the governance of SESs might lie, and how these might change in response to changes in the underlying social and ecological context. Specifically, within each archetype, we discussed which type of feedback structure is dominant, and then through our case analysis we provided examples of the conditions under which these feedback structures have become weak or incomplete (i.e., with missing links) leading to specific vulnerabilities. For example, under the egalitarian archetype with complete overlap of RU and PIP, we discussed how the ecosystem dynamics, narratives, beliefs, and practices mutually reinforce one another to create what we refer to as the "collective" feedback structure. We showed how this archetype is robust against disturbances experienced in the past but is becoming increasingly vulnerable to the new shocks posed by climate change and globalization. In the individualist archetype there is also complete overlap of RU and PIP but there are no collective deliberations over the rules for groundwater extraction either among the users themselves or through external agencies (links 5 and 2 are missing) leading in most cases to unsustainable extraction. On the other end of the spectrum, in both the fatalist and hierarchical archetypes that generally characterize much larger systems, the PIP subsystem is separate and distinct from the RU system. The critical factor here is the relationship between PIP and RU, specifically the degree of decentralization in decision making. Under the hierarchical archetype, we found wide variability in the degree of decentralization, with the Taiwan case providing an interesting illustration of the interplay of collective management and participatory feedback structures. At the other end of the spectrum, under the fatalist archetype with high degree of centralization, the PIP are not accountable to the RU (link 2 is weak) and there is a strong feeling of apathy among users (consistent with fatalist logic). However, under the special conditions found in the Wade case from South India, we found that village funds are used to bribe irrigation officials to ensure that water reaches the tail-end. This is an innovative, but maladaptive response, which reinforces existing inequities and is highly robust to globalization. Under the other archetypes, specifically the egalitarian archetype, bribes would be inimical to the underlying logic of group solidarity. This illustrates the idea of fine tuning and right fit of contextual variables, which emerge through the feedback structures that support persistent patterns of beliefs and practices that constitute "governance."

In terms of future directions, we think that developing long-term collaborations with practitioners and stakeholders can be helpful in pushing both the theoretical and empirical frontiers of this kind of work. These collaborations can enable a deeper understanding of the context-specific and process-intensive nature of governance and encourage the building of repertoires of case studies that are based on consistent data to test for empirical validity. This will help address a key limitation of this and other archetypes-based work: lack of comparable case studies. These collaborations can also foster sustainability by supporting the right kinds of feedback loops for desirable types of emergent behaviors. As Ostrom (2009:47) observed, "[t]he process of choice ... always involves experimentation" because "[i] t is hard to find the right combination of rules that work in a particular setting"; as such, one has to "try multiple combinations of rules and keep making small adjustments to get the systems working well" (Ostrom 2009:49). Archetype analysis based on evidence from diverse case studies, together with ongoing research in modeling and field experiments, can together provide insights to guide this process of experimentation.

Author Contributions:

Conceptualization, R. M. A. & J. M. A.; Methodology, R. M. A. & J. M. A.; Formal Analysis, R. M. A. & J. M. A.; Resources, R. M. A. & J. M. A. Data Curation, R. M. A.; Writing - Original Draft Preparation, R. M. A.; Writing - Review and Editing, R. M. A. & J. M. A.; Project Administration, J. M. A.; Funding Acquisition, J. M. A & R. M. A.

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Data Availability:

Data used for the study consists of case studies. These data were derived from the following resources available in the public domain at the SES Library (seslibrary.asu.edu) at Arizona State University. The coding manual used for coding the case studies is provided in the Appendix section.

LITERATURE CITED

Agrawal, A., and A. Chhatre. 2006. Explaining success on the commons: community forest governance in the Indian Himalaya. World Development 34(1):149-166. https://doi.org/10.1016/j.worlddev.2005.07.013

Anderies, J. M., M. A. Janssen, and E. Ostrom. 2004. A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecology and Society 9(1):18. https://doi.org/10.5751/ES-00610-090118

Anderies, J., M. Janssen, and E. Schlager. 2016. Institutions and the performance of coupled infrastructure systems. International Journal of the Commons 10(2):495-516. https://doi.org/10.18352/ijc.651

Andrews, M., L. Pritchett, and M. Woolcock. 2013. Escaping capability traps through problem driven iterative adaptation (PDIA). World Development 51:234-244. https://doi.org/10.1016/j.worlddev.2013.05.011

Arrow, K. J. 1982. Gifts and exchanges. Pages 139-158 in M. Cohen, editor. Medicine and moral philosophy. Princeton University Press, Princeton, New Jersey, USA. https://doi.org/10.1515/9781400853564.139

Baker, J. M. 2005. The Kuhls of Kangra: community-managed irrigation in the Western Himalaya. University of Washington Press, Seattle, Washington, USA.

Baumgärtner, S., H. Dyckhoff, M. Faber, J. Proops, and J. Schiller. 2001. The concept of joint production and ecological economics. Ecological Economics 36(3):365-372. https://doi.org/10.1016/S0921-8009(00)00260-3

Bocken, N. M. P., S. W. Short, P. Rana, and S. Evans. 2014. A literature and practice review to develop sustainable business model archetypes. Journal of Cleaner Production 65:42-56. https://doi.org/10.1016/j.jclepro.2013.11.039

Bottrall, A. F., and B. Mundial. 1981. Comparative study of the management and organization of irrigation projects. World Bank, Washington, D.C., USA.

Castilla-Rho, J., R. Rojas, M. S. Andersen, C. Holley, and G. Mariethoz. 2017. Social tipping points in global groundwater management. Nature Human Behavior 1:640-649. https://doi.org/10.1038/s41562-017-0181-7

Cifdaloz, O., A. Regmi, J. M. Anderies, and A. A. Rodriguez. 2010. Robustness, vulnerability, and adaptive capacity in small-scale social-ecological systems: the Pumpa Irrigation system in Nepal. Ecology and Society 15(3):39. https://doi.org/10.5751/ES-03462-150339

Corning, P. A. 2002. The re-emergence of "emergence": a venerable concept in search of a theory. Complexity 7(6):18-30. https://doi.org/10.1002/cplx.10043

Coward Jr., E. W. 1980. Local organization and bureaucracy in a Lao irrigation project. Pages 329-344 in E. W. Coward Jr., editor. Irrigation and agricultural development in Asia: perspectives from the social sciences. Cornell University Press, Ithaca, New York, USA.

Crane, T. A. 2010. Of models and meanings: cultural resilience in social-ecological systems. Ecology and Society 15(4):19. https://doi.org/10.5751/ES-03683-150419

de los Reyes, R. P. 1980. 47 communal gravity systems: organization profiles. Institute of Philippine Culture, Ateneo de Manila University, Quezon City, Philippines.

Denizer, C., D. Kaufmann, and A. Kraay. 2011. Good countries or good projects? Macro and micro correlates of World Bank project performance. Policy Research Working Paper No. 5646. World Bank, Washington, D.C., USA. https://doi.org/10.1596/1813-9450-5646

de Vries, B., M. Janssen, and A. Beusen. 1999. Perspectives on global energy futures: simulations with the TIME model. Energy Policy 27:477-494. https://doi.org/10.1016/S0301-4215(99)00035-X

Douglas, M. 1978. Cultural bias. Royal Anthropological Institute Occasional Paper No. 35, Royal Anthropological Institute, London, UK.

Douglas, M. 1999. The politicization of risk. Implicit meanings: selected essays in anthropology. Second edition. Routledge, London, UK.

Dubash, N. K. 2002. Tubewell capitalism: groundwater development and agrarian change in Gujarat, studies in social ecology and environmental history. Oxford University Press, New Delhi, India.

Eisenack, K. 2012. Archetypes of adaptation to climate change. Pages 107-122 in M. Glaser, G. Krause, B. M. Ratter, and M. Welp, editors. Human-nature interactions in the Anthropocene. Potential of social-ecological systems analysis. Routledge, New York, New York, USA.

Eisenack, K., C. Oberlack, and D. Sietz. 2021. Avenues of archetype analysis: roots, achievements, and next steps in sustainability research. Ecology and Society 26(2):31. https://doi.org/10.5751/ES-12484-260231

Eriksen, S., E. L. F. Schipper, M. Scoville-Simonds, K. Vincent, H. N. Adam, N. Brooks, B. Harding, D. Khatri, L. Lenaerts, D. Liverman, M. Mills-Novoa, M. Mosberg, S. Movik, B. Muok, A. Nightingale, H. Ojha, L. Sygna, M. Taylor, C. Vogel, and J. J. West. 2021. Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? World Development 141:105383. https://doi.org/10.1016/j.worlddev.2020.105383

Folke, C., R. Biggs, A. V. Norström, B. Reyers, and J. Rockström. 2016. Social-ecological resilience and biosphere-based sustainability science. Ecology and Society 21(3):41. https://doi.org/10.5751/ES-08748-210341

Fukuyama, F. 1995. Trust: the social virtues and the creation of prosperity. Free Press Paperbacks, New York, New York, USA.

Garces-Restrepo, C., D. Vermillion, and G. Muoz. 2007. Irrigation management transfer: worldwide efforts and results. FAO Water Reports # 32. International Water Management Institute, Colombo, Sri Lanka and Food and Agricultural Organization of the United Nations, Rome, Italy.

Geertz, C. 1980. Organization of the Balinese Subak. Pages 70-90 in E. W. Coward Jr., editor. Irrigation and agricultural development in Asia: perspectives from the social sciences. Cornell University Press, Ithaca, New York, USA.

Holland, J. H. 1998. Emergence: from chaos to order. Addison-Wesley Helix, Reading, Massachusetts, USA.

Holling, C. S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4:1-23. https://doi.org/10.1146/annurev.es.04.110173.000245

Horst, L. 1998. The dilemmas of water division: considerations and criteria for irrigation system design. International Water Management Institute, Colombo, Sri Lanka.

Intergovernmental Panel on Climate Change (IPCC). 2022. Climate Change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama, editors. Cambridge University Press, Cambridge, UK.

International Water Management Institute (IWMI). 2021. Water's fundamental truths: Part 3 - Is water governance coming of age? South Asia Rainwater Network. IWMI, Colombo, Sri Lanka. https://www.iwmi.cgiar.org/2021/09/waters-fundamental-truths-part-3-is-water-governance-coming-of-age/

Kauffman, S. A. 1993. The origins of order: self-organization and selection in evolution. First edition. Oxford University Press, New York, New York, USA.

Lam, W.-F. 1996. Institutional design of public agencies and coproduction: a study of irrigation associations in Taiwan. World Development 24(6):1039-1054. https://doi.org/10.1016/0305-750X(96)00020-4

Lam, W.-F 2006. Designing institutions for irrigation management: comparing irrigation agencies in Nepal and Taiwan. Property Management 24(2):162-178. https://doi.org/10.1108/02637470610658032

Lam, W.-F., C.-P. Tang, and S.-K. Tang. 2021. Bureaucratising co-production: institutional adaptation of irrigation associations in Taiwan. Water Alternatives 14(2):435-452.

Lansing, J. S. 1991. Priests and programmers: technologies of power in the engineered landscape of Bali. Princeton University Press, Princeton, New Jersey, USA. https://doi.org/10.1515/9781400827633

Levin, S., T. Xepapadeas, A.-S. Crépin, J. Norberg, A. de Zeeuw, C. Folke, T. Hughes, K. Arrow, S. Barrett, G. Daily, P. Ehrlich, N. Kautsky, K.-G. Mäler, S. Polasky, M. Troell, J. R. Vincent, and B. Walker. 2013. Social-ecological systems as complex adaptive systems: modeling and policy implications. Environment and Development Economics 18(2):111-132. https://doi.org/10.1017/S1355770X12000460

Lowdermilk, M. K., W. Clyma, and A. C. Early. 1975. Physical and socio-economic dynamics of a watercourse in Pakistan's Punjab: system constraints and farmers' responses. Water Management Research Project, Engineering Research Center, Colorado State University, Fort Collins, Colorado, USA.

Mamadouh, V. 1999. Grid-group cultural theory: an introduction. GeoJournal 47(3):395-409. https://doi.org/10.1023/A:1007024008646

McGinnis, M. D. 2011. Networks of adjacent action situations in polycentric governance. Policy Studies Journal 39(1):51-78. https://doi.org/10.1111/j.1541-0072.2010.00396.x

Miller, J. H., and S. E. Page. 2007. Complex adaptive systems: an introduction to computational models of social life. Princeton University Press, Princeton, New Jersey, USA. https://doi.org/10.1515/9781400835522

Mollinga, P. P. 1998. On the waterfront. Water distribution, technology, and agrarian change in a South Indian canal irrigation system. Dissertation. Wageningen University, Wageningen, The Netherlands.

Mollinga, P. P., and G. J. Veldwisch. 2016. Ruling by canal: governance and system-level design characteristics of large-scale irrigation infrastructure in India and Uzbekistan. Water Alternatives 9(2):222-249.

Morçöl, G. 2010. Issues in reconceptualizing public policy from the perspective of complexity theory. E:CO Emergence: Complexity and Organization 12(1):52-60.

Morçöl, G. 2012. A complexity theory for public policy. Routledge, New York, New York, USA.

Morçöl, G. 2014. Self-organization in collective action: Elinor Ostrom's contributions and complexity theory. Complexity, Governance & Networks 1(2):9.

Moxnes, E. 2004. Misperception of basic dynamics: the case of renewable resource management. System Dynamics Review 20 (2):139-162. https://doi.org/10.1002/sdr.289

Mukherji, A., B. Fuleki, T. Shah, D. Suhardiman, M. Giordano, and P. Weligamage. 2010. Irrigation reform in Asia: a review of 108 cases of irrigation management transfer. International Water Management Institute (IWMI) Research Reports H042851. IWMI, Colombo, Sri Lanka.

Nightingale, A. J. 2017. Power and politics in climate change adaptation efforts: struggles over authority and recognition in the context of political instability. Geoforum 84:11-20. https://doi.org/10.1016/j.geoforum.2017.05.011

Nisbett, R. E., and T. Masuda. 2003. Culture and point of view. Proceedings of National Academies of Sciences 100 (19):11163-11170. https://doi.org/10.1073/pnas.1934527100

Oberlack, C., D. Sietz, E. Bürgi Bonanomi, A. De Bremond, J. Dell'Angelo, K. Eisenack, E. C. Ellis, G. Epstein, M. Giger, A. Heinimann, C. Kimmich, M. T. J. Kok, D. Manuel-Navarrete, P. Messerli, P. Meyfroidt, T. Václavík, and S. Villamayor-Tomas. 2019. Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making. Ecology and Society 24(2):26. https://doi.org/10.5751/ES-10747-240226

Oldroyd, D. R. 1986. Grid/group analysis for historians of science. History of Science 24(2):145-171. https://doi.org/10.1177/007327538602400203

Orach, K., A. Duit, and M. Schlüter. 2020. Sustainable natural resource governance under interest group competition in policy-making. Nature Human Behaviour 4(9):898-909. https://doi.org/10.1038/s41562-020-0885-y

Ostrom, E. 2005. Understanding institutional diversity. Princeton University Press, Princeton, New Jersey, USA.

Ostrom, E. 2009. Design principles of robust property rights institutions: What have we learned? Pages 25-51 in G. K. Ingram and Y.-H. Hong, editors. Property rights and land policies. Lincoln Institute of Land Policy, Cambridge, Massachusetts, USA.

Ostrom, E. 2015. How farmer managed irrigation systems build social capital to outperform agency managed systems that rely primarily on physical capital. Pages 21-26 in P. Pradhan, U. Gautam, and N. M. Joshi, editors. The trajectory of farmer managed irrigation systems. Farmer Managed Irrigation Systems Trust, Kathmandu, Nepal.

Polanyi, K. 1944. The great transformation. Rinehart, New York, New York, USA. https://doi.org/10.1002/9780470755679.ch4

Pradhan, P., U. Gautam, and N. M. Joshi. 2015. The trajectory of farmer managed irrigation systems. Farmer Managed Irrigation Systems Trust, Kathmandu, Nepal.

Ramamurthy, P. 1995. The political economy of canal irrigation in South India. Dissertation. The Graduate School of Syracuse University, Syracuse, New York, USA.

Sabatier, P. A., and H. Jenkins-Smith. 1993. Policy change and learning: an advocacy coalition approach. Westview, Boulder, Colorado, USA.

Samad, M. 2002. Impact of irrigation management transfer on the performance of irrigation systems: a review of selected Asian experiences. Pages 161-170 in D. Brennan, editor. Water policy reform: lessons from Asia and Australia. Proceedings of an International Workshop held in Bangkok, Thailand, 8-9 June 2001. Australian Centre for International Agricultural Research, Canberra, Australia.

Schlager, E., W. Blomquist, and S. Tang. 1994. Mobile flows, storage, and self-organized institutions for governing common-pool resources. Land Economics 70:294-317. https://doi.org/10.2307/3146531

Schlüter, M., L. J. Haider, S. J. Lade, E. Lindkvist, R. Martin, K. Orach, N. Wijermans, and C. Folke. 2019. Capturing emergent phenomena in social-ecological systems: an analytical framework. Ecology and Society 24(3):11. https://doi.org/10.5751/ES-11012-240311

Scott, J. C. 1999. Seeing like a state: how certain schemes to improve the human condition have failed. Yale University Press, New Haven, Connecticut, USA.

Shah, T. 1993. Groundwater markets and irrigation development: political economy and practical policy. Oxford University Press, Bombay, India.

Shah, T., O. P. Singh, and A. Mukherji. 2006. Some aspects of South Asia's groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh. Hydrogeology Journal 14(3):286-309. https://doi.org/10.1007/s10040-005-0004-1

Shivakoti, G. P., and E. Ostrom. 2002. Improving irrigation governance and management in Nepal. ICS Press, Oakland, California, USA.

Sietz, D., U. Frey, M. Roggero, Y. Gong, N. Magliocca, R. Tan, P. Janssen, and T. Václavík. 2019. Archetype analysis in sustainability research: methodological portfolio and analytical frontiers. Ecology and Society 24(3):34. https://doi.org/10.5751/ES-11103-240334

Teisman, G., and L. Gerrits. 2014. The emergence of complexity in the art and science of governance. Complexity, Governance and Networks 1(1):17.

Thompson, M. 2008. Organising and disorganising. A dynamic and non-linear theory of institutional emergence and its implication. Triarchy Press, Charmouth, UK.

Trawick, P. B. 2001. Successfully governing the commons: principles of social organization in an Andean irrigation system. Human Ecology 29(1):1-25. https://doi.org/10.1023/A:1007199304395

Tversky, A., and D. Kahneman. 2000. Rational choice and the framing of decisions. Pages 209-223 in D. Kahneman and A. Tversky, editors. Choices, values and frames. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9780511803475.013

Van Assche, K., R. Beunen, and M. Duineveld. 2012. Performing success and failure in governance: Dutch planning experiences. Public Administration 90(3):567-581. https://doi.org/10.1111/j.1467-9299.2011.01972.x

Venot, J.-P., and D. Suhardiman. 2014. Governing the ungovernable: practices and circumstances of governance in the irrigation sector. International Journal of Water Governance 2 (2):41-60. https://doi.org/10.7564/14-IJWG57

Wade, R. 1982. Irrigation and agricultural politics in South Korea. Routledge, New York, New York, USA. https://doi.org/10.4324/9780429048746

Wade, R. 1988a. The management of irrigation systems: how to evoke trust and avoid prisoner's dilemma. World Development 16(4):489-500. https://doi.org/10.1016/0305-750X(88)90199-4

Wade, R. 1988b. Village republics: economic conditions for collective action in South India. Cambridge University Press, Cambridge, UK.

Wade, R. 1995. The ecological basis of irrigation institutions: East and South Asia. World Development 23(12):2041-2049. https://doi.org/10.1016/0305-750X(95)00097-V

Water and Energy Commission Secretariat. 1987. Rapid appraisal study of eight selected micro-areas of farmers' irrigation systems, Sindhu Palchok District. Final Report. Water and Energy Commission Secretariat, Kathmandu, Nepal.

Weber, M. 1958. The three types of legitimate rule. Berkeley Publications in Society and Institutions 4(1):1-11. Translated by Hans Gerth.

Wittfogel, K. 1957. Oriental despotism. Yale University Press, New Haven, Connecticut, USA.

Young, H. P. 1996. The economics of convention. Journal of Economic Perspectives 10(2):105-122. https://doi.org/10.1257/jep.10.2.105

APPENDIX

I. Methods: Coding manual

A) *Coding of cases into cultural types*

There is an extensive literature on the application of grid-group Cultural Theory (CT) to various social, political and environmental issues (see Mamadouh, 1999 for a survey). Two methods have generally been used to identify cultural types in these studies: design of special survey measures to directly identify cultural types or reinterpretation of results from previous surveys or cases studies. We relied on the latter approach using case studies in our selected sample and developed the coding manual below based on our review of the literature on CT applications.

i) **Egalitarian:** Low grid-high group. Author(s) provides description of RU as characterized by closely knit and bounded group with low socio-economic differentiation and few formal regulations. The group is maintained through multiplex relations between group members, which are mostly reciprocal and driven by peer pressure and mutualism rather than transactional. Examples of descriptive words used by author(s): group solidarity, reciprocal relations, fairness, moral/religious principles, ritualistic practices and peer pressure.

ii) **Individualist:** Low grid-low group. Author(s) provides description of RU as characterized by individuals with limited group identity and weak regulations or role prescriptions. Here relationships between irrigation users are transactional in nature, as in a market. Examples of descriptive words used by author(s): unregulated environment, entrepreneurialism, voluntary contracts, private transactions.

iii) **Hierarchical:** High grid-high group. Author(s) provides description of RU (farmers' group or water users' association) and PIP (e.g. irrigation association or agency) as distinct entities but with strong links, and differentiated roles based on rank/position within the system with binding prescriptions/rules. These prescriptions are justified by the importance of the collective over the individual. Examples of descriptive words used by author(s): strong regulations, prescriptions, stability and strong structure

iv) **Fatalist:** high grid-low group**.** Author(s) provides description of RU (may or may not be organized as farmers' group or water users' association) and PIP (e.g. irrigation association or agency) as distinct entities with very weak links. This archetype is characterized by weak group identity, and highly differentiated roles based on caste/landholding size/location in the system (upstream/downstream). Given the high level of socio-economic differentiation, the RU do not constitute a cohesive unit and are mostly driven by individual rather than collective logic. Examples of descriptive words used by author(s): apathy, powerlessness, sense of chaos and futility, social exclusion.

We followed a deductive coding procedure, with the description of attributes as identified above serving as the basis of the codes. Then as we delved in the actual process of coding, we had to revise the description of a few codes to narrow the gap between the theoretical concept and the data as it appears in the case studies.

B. Coding of attributes of different sub-systems in Robustness framework

Case study research designs enable in-depth understanding of underlying factors, interactions and causal relationships at a high level of contextual detail. However, this restricts its validity beyond the specific study sites (Poteete et al. 2010) and raises questions regarding which results are generalizable, and how contextual factors modify general insights (Oberlack et al. 2019). In our coding for cases, we coded for the system attributes (related to RU, NI, PI and PIP), as identified in the conceptual framework section and shown in the table below. The coding of these attributes was used for mapping of the co-occurrence of attributes (Figure 2).

Table A1: Coding of Robustness framework attributes

(Descriptions and rationale are provided in Conceptual foundations section)

Attribute	Categories for coding	Additional comments
RESOURCE USERS (RU)		
Group size: # of households	1. Small: < 200 households. 2. Medium: 200 -500 households 3. Large: > 500 households	In case studies where the size of households was not provided by the author(s), it was estimated based on population estimates provided by the author(s)
Market access	1. Limited 2. Improved	Based on author(s) description of walkability to nearest market or access to public transportation
*Nature related beliefs	1.Nature fragile 2. Nature robust 3. Nature tolerant 4. Nature capricious	See description in Conceptual foundations section. 1. Ball on top of single peak (nature fragile) 2. Ball at bottom of single peak (nature robust) 3. Ball at bottom of rugged landscape with multiple peaks (nature tolerant), 4. Ball on flat surface (nature capricious).
Natural infrastructure (NI)		
Agro-climate	1. Arid 2. Semi-arid 3. Humid and sub-humid	Based on CRU (Climate Research Unit) Time Series dataset v. 4.03, as reported Wang and Zhang (2020)
Location-gradient	1. Plains (<300m) 2. Low altitude: (300-1,000m) 3. High altitude > 1,000m	Based on classification used in Agrawal and Chhatre (2006)
Public infrastructure (PI)		
**Size of command area	1. Small: < 200 ha 2. Medium: 200-3,000 ha 3. Large: >3,000 ha	Based on classification generally used in irrigation studies.
Canal layout	1. Bifurcated 2.Hierarchical	See description in Conceptual foundations section.
Public Infrastructure providers (PIP)		
Organizational structure & type of relation with RU	1. PIP same as RU (with cooperative relations) 2. PIP same as RU (with non-cooperative relations) 3. PIP are state agencies, with strong links to RU (embedded) 4. PIP are state agencies, with weak links to RU (isolated)	See description in Conceptual foundations section.

*Attribute not included in co-occurrence of attributes map because sufficient information to code was not available in more than 25% of selected case studies.

** Attribute not included in co-occurrence of attributes map because it was found to be highly correlated with another included attribute (e.g. Size of command area was highly correlated with group size).

II. Results of coding

The first author and another researcher conducted the coding and met to discuss any discrepancies. A couple of discrepancies were noticed in multi-level irrigation cases where two cultural types seemed to co-exist: one at the village/community level and another at the systems level. For example, in Meinzen-Dick's (1984) case, the irrigation system consists of a river that feeds into a system of tanks. At the overall system level (including the river and tanks), the criteria for hierarchical archetype fitted best, but at the level of individual tanks, the criteria for egalitarian type fitted best. Since our focus here is on SES, we chose the representation at the system level.

Our coding of the 60 selected cases according to the attributes of cultural types led to the following distribution (see table below): Egalitarian-31; Individualist-5; Hierarchical -14; and Fatalist -10. Most of the cases in the SES library collection are part of the original Common-Pool Resource (CPR) database at Indiana University, which was developed under the direction of Elinor Ostrom in the 1970s and 1980s. Given Ostrom's interest in self-governance of the commons in traditional small-scale settings, there is an over-representation of cases under the Egalitarian archetype. The individualist archetype, associated with informal water markets, has become more prevalent after the 1980s and so there were no cases falling under this archetype in the SES collection. For this archetype, we selected cases known through our previous research.

Table A2: Cases coded under each archetype

Archetype	Cases from SES library: Author (location)	Other notable cases	Total # of cases
Egalitarian	Bacdayan (Philippines), Beardsley (Japan), Cifdaloz et al. (Nepal), Coward (Phillipines),), Cruz (Philippines**),** de los Reyes (9 cases in Philippines), Fernea (Iraq), Geertz (Indonesia), Gupta (India), Lando (Indonesia), Martin and Yoder (Nepal), Nirola & Pandey (2 cases in Nepal), Potter (Thailand), Pradhan (Nepal), Sarker & Ito (Japan), Sharma et al (Nepal), Spooner (2 cases in Iran), Water and Energy Commission (2 cases in Nepal)	Baker (India), Lansing (Indonesia)	31
Individualist	None	Aggarwal (India), Dubash (India), Janakarajan (India), Meinzen-Dick and Sullins (Pakistan), Shah (India)	5
Hierarchical	Bottrall (Taiwan); Bottrall (Indonesia); Coward (Laos), Coward and Ahmed (Bangladesh), Duncan (Thailand), Gillispie (Thailand), Meinzen Dick(India), Ongkinco (2 cases in Phillipines), Tan Kim Yong (Phillipines), Wang et al. (2 cases in China	Lam (Taiwan), Wade (South Korea)	14
Fatalist	Bottrall(India); Bottrall (Pakistan); Lowdermilk (Pakistan), Merrey and Wolf (Pakistan), Mirza and Merrey (Pakistan), Reidinger (India), Vander Velde (India), Wade (India)	Ramamurthy (India), Mollinga (India)	10
TOTAL			60

III. **Context specific details that are associated with special emergent features observed under each archetype**

A. Egalitarian archetype

Pumpa irrigation system, Nepal (Cifdaloz et al. 2010): emergence of highly adaptive fairness based distribution rules

This is one of the 125 farmer managed irrigation systems in Chitwan district of Nepal (Cifdaloz et al. 2010). Various kinds of water distribution rules—based on fairness norms—have emerged to address the high variability of water flows, without any storage capacity in this case. When water flow is close to average, the optimal strategy is open flow (minimum labor requirements), but when water scarcity increases beyond a certain threshold, the irrigators switch to a sequential water distribution strategy. Under specific conditions of water scarcity, associated with a wash out of the main headgate infrastructure, the optimal strategy for irrigators is to use a 12-hour or 24 hour rotation depending on the time needed to repair the infrastructure. Cifdaloz et al. (2010) show that this system is very robust in the sense that yields can be maintained, in the face of environmental variation and shocks to the infrastructure, though only up to a certain point. Their modeling shows that with climate change, as this threshold is crossed, the system is likely to become highly vulnerable. This is a case where given the harsh bio-physical setting and the primitive technology, the institutions have become highly optimized to manage the tight coupling between the environment (timing of rain, river flows, and the agroecology of rice) and physical infrastructure (constraints on flow rates and distribution of water). This also shows why external attempts at changing institutions—such as through recent efforts towards decentralization—are likely to fail.

Kuhl irrigation system, India (Baker 2005): emergence of networks to share risks

While the majority of cases that fall under the egalitarian archetype operate at relatively small scales (<200 ha.) and are highly vulnerable to large scale drivers (e.g. political economy, globalization, climate change), the case of Kuhls in the western Himalayan state of Himachal Pradesh in India, has managed to survive for centuries despite the recurring destructive environmental disturbances and the shocks imposed by colonialism and globalization (Baker 2005). The uniqueness of this case derives in large part from its unusual, bifurcated topography: broad alluvial plains and river terraces, dissected by numerous perennial snow fed streams. Because of this bifurcated topography, most villages engage with multiple Kuhls: being simultaneously positioned upstream in some Kuhls and downstream in others. Baker describes how at the watershed level, the pattern of multi-kuhl villages and multi village Kuhls creates a network of interconnected regimes, which plays a major role in sharing risks (*ibid*, p.67).

Subaks, Indonesia (Lansing (1991): network of temples to address pest and water scarcity problems

Lansing's research examines the social dilemma here which consists of balancing between two inter-related problems: first, is the need to control pests, which is most effectively done when all rice fields have the same schedule for planting rice; second, is to allocate the limited supply of water, which is best handled by staggering the planting dates for rice. Recent ethnographic and computer work by Lansing and colleagues suggests that the need to coordinate water allocations and pest control led to the self-organization of a yield-enhancing autonomous complex adaptive system of an intricate network of water temples and shrines, which were able to withstand ecological shocks (such as pest outbreaks and droughts) much better than otherwise identical models that lacked temple networks.

Zanjeras, Philippines (Coward 1979; revisited by Yabes and Goldstein 2015): emergence of innovative system of land sub-division for equitable water sharing
In this case, large variability in water flows and high uncertainty (due to frequent typhoons) makes equitable water allocation very challenging. An interesting institutional innovation that emerged within the indigenous communities living here is the subdivision of the main blocks of farming land into smaller units, such that each member had an upstream, midstream, and downstream parcel. As a result, water scarcity was shared by all members and this emergent institution driven by egalitarian logic, served to further reinforce it.

Qanat system, Iran (Spooner 1974): **shows limits of local level collective action**
This is a case that shows limits of local level collective action in management of irrigation. Irrigation here is based on qanats, which are network of underground canals that transport water from aquifers in highlands to surface at lower levels by gravity. The qanats need maintenance that requires highly specialized skills and resources not available in local community. In the past, local tribal patrons (khans) financed the maintenance, but they have out-migrated recently. Although strong community bonds and reciprocal labor exchanges are common for regular canal maintenance, villagers are too poor to pay for qanat specialist. Farmers have turned to private investments in tubewells and tourism, leading to further deterioration of the qanat system.

B. Individualist archetype

Informal groundwater markets, India (Aggarwal, 2006)
Although generally characterized as "informal water markets", several scholars have pointed out that it is more accurate to call these rental markets in well equipment because water rights are not well defined (Saleth 1994). The market structure here is highly fragmented because each well-owner can only sell water to neighbors that are connected via his/her own private investment in pipes and canals. Diverse types of contracts—such as, fixed price and various combinations of output/input sharing—have emerged to address the tradeoffs between sharing risks and reducing transaction costs of monitoring, bargaining, and negotiating (Aggarwal, 2006). Very often these different types of contracts co-exist within the same village and are found to be finely tuned to the specific water requirements of the crops grown, availability of energy for pumping, and the characteristics of the parties involved (Dubash 2002, Shah et al. 2006).

C. Hierarchical archetype

Irrigation Associations (IAs), Taiwan (Lam 1996: 1041)

IAs in Taiwan are legally owned and formed by farmers and supervised by governments at higher levels. Their legal status as juristic entities entitles them to a high degree of de jure autonomy and also certain public authorities to levy water fees. This is a special feature of the Taiwanese system that enabled a highly decentralized model of irrigation management. On the other end of the spectrum are highly centralized irrigation systems in South Asia, largely established by the British for protection against widespread famines, where the central authority has complete control not only at the project level but up to the farm level. Other cases of bureaucratic large scale irrigation systems from Asia fall somewhere in between and highlight different configurations of state, intermediary agencies, and user relationships.

South-Korea (Wade,1982) – parastatals called Farmland Improvement Associations (FLIAs). Objectives of the FLIA are to improve land under paddy cultivation, give advice, cover costs, and collect charges from beneficiaries. No formal mechanisms for co-production with farmers, but FLIA staff are recruited from the same area as beneficiaries and are generally from the same social class. Important instruments for motivating the irrigation staff and holding them accountable include: pay based partly on agricultural indicators (such as agricultural yields) and government orchestrated competitions.

Water Users Association: in most other cases under this archetype we find Water Users' Associations (WUAs) formed by farmers, where farmers have varying degrees of decision making and control relative to the state controlled irrigation agency under different forms of decentralization. Examples from SES library include: Bottrall (1981)for Indonesia; Coward (1979) for Laos, Gillispie (1975) for Thailand, and Ongkinco (1973) for Phillipines.

D -Fatalist archetype

Emergence of village level collective institutions and bribes, India (Wade1988)
Wade reports on the emergence of four main types of village level collective institutions: village council, fund, common irrigators and field guards. Of the 31 villages studied by Wade, 8 had all four of these, 11 had at least some but not all, and 12 had none of them. Villages at the tail-end were more likely to have all four institutions, and used the village funds to raise funds and use their influence to bribe irrigation officials to ensure that water reaches the tail-end. A revisit to Wade's study site by Reddy and Reddy (R&R) (2002) two decades later found the collective institutions to be in order and effective, despite the spread of green revolution technologies, greater penetration of markets, and spread of groundwater irrigation. Interestingly, they found that these emergent (informal) collective institutions continued to operate even after the legislation to formally set up Water User Associations (WUAs) was passed in 1997. R&R compared villages where only the WUAs were operational with villages where informal collective institutions continued to operate and support the newly formed WUAs. They found that the latter set had better water availability, greater equity in distribution, and were better funded. They attributed the greater success of informal institutions to their social embeddedness and their commitment and cohesiveness, as these have "evolved from within the system" (p. 532), and have greater flexibility in adapting to changing conditions, as compared to formal institutions that they found to be "rigid and rule bound" (*op cit.*).

The emergence of bribes in tail-end villages has been reported in other highly centralized bureaucratic irrigation systems across South Asia, where alternative accountability mechanisms between farmers and irrigation officials are lacking. Examples include Ramamurthy (1995) and Mollinga (1996) for South India; and Lowdermilk et al. (1975) and Bottrall (1981) for Pakistan.

Emergence of political lobbying, India (Mollinga 1996)
Mollinga (1996) in his study of a large-scale canal irrigation system, the Tungabhadra Left Bank Canal system in South India, reports on the emergence of another accountability mechanism:

political lobbying. Farmers in this region are closely networked with local Members of the Legislative Assembly (MLAs), and so instead of paying bribes, the farmers find it more cost effective to lobby the local MLA to influence the Irrigation Department officials to implement rotation schedules in their favor. The MLAs have control over the transfer of Irrigation Department officials, and they use this power to influence the official to implement rotation schedules in favor of their constituents. As Mollinga (1996: 168) explains, “there is an accountability feedback loop in political lobby in which the initiative lies on the farmers' side: the threat not to re-elect the MLA.” In contrast to the egalitarian archetype, where rotation schedules are based on norms of fairness, in this case of the fatalist archetype, “the rotation schedules and the way they are implemented can be interpreted as the institutionalisation of the balance of power between head end and tail end farmers, as well as that between water users and the Irrigation Department” (Mollinga 1996: 152).

LITERATURE CITED

Aggarwal, R. M. 2007. Role of risk sharing and transaction costs in contract choice: Theory and evidence from groundwater contracts. Journal of Economic Behavior and Organization 63 (3): 475-496.

Bacdayan A. S. 1980. Mountain Irrigators in the Philippines. In Irrigation and agricultural development in Asia: Perspectives from the social sciences. Ithaca: Cornell University Press.

Baker, J. M. 2005. The Kuhls of Kangra: Community-managed Irrigation in the Western Himalaya. University of Washington Press.

Beardsley R. K, J. W Hall and R. E. Ward 1980. Japanese Irrigation Cooperatives. Irrigation and Agricultural Development in Asia: Perspectives from the Social Sciences. :127-152.

Bottrall, A.F. and B. Mundial 1981. Comparative study of the management and organization of irrigation projects. Washington, DC: World Bank.

Cifdaloz, O., A. Regmi, J. M. Anderies and A. A. Rodriguez. 2010. Robustness, vulnerability, and adaptive capacity in small-scale social-ecological systems: the Pumpa Irrigation system in Nepal. Ecology and Society 15(3): 39. [online] URL:http://www.ecologyandsociety.org/vol15/iss3/art39/

Coward, Jr. E. W. 1979. Principles of Social Organization in an Indigenous Irrigation System. Human Organization. 38:28-36.

Coward, Jr. E. W and B. Ahmed. 1979. Village, Technology, and Bureaucracy: Patterns of Irrigation in Comilla District, Bangladesh. Journal of Developing Areas. 13:431-440.

Coward, Jr. E. W. 1980. Local Organization and Bureaucracy in a Laos Irrigation Project. In Irrigation and Agricultural Development in Asia: Perspectives from the Social Sciences. Ithaca: Cornell University Press.

Cruz, Federico A. 1975. The Pinagbayan Farmers' Association and its Operation. In Water management and operation, edited by the International Rice Research Institute, 243-258. Los Banos, Philippines: International Rice Research Institute.

de los Reyes, R. P. 1980. 47 communal gravity systems: organization profiles, 27-32. Quezon City, Philippines: Institute of Philippine Culture, Ateneo de Manila University. [ILL: Kennedy School of Government; SB 112.04].

Dubash, N. K. 2002. Tubewell capitalism: groundwater development and agrarian change in Gujarat, Studies in social ecology and environmental history. Oxford University Press, New Delhi; New York.

Dunca, S. 1978. Local irrigators' groups: assessment of their operations and maintenance functions. In International Rice Research Institute (IRRI). 1978. Irrigation policy and management in Southeast Asia. Technical Report. International Rice Research Institute. Manila, Philippines.

Fernea, R.A. 1970. Shaykh and effendi: changing patterns of authority among the El Shabana of southern Iraq (Vol. 14). Cambridge, Mass.: Harvard University Press.

Geertz C. 1967. Organization of the Balinese Subak. In Irrigation and agricultural development in Asia: Perspectives from the social sciences. Ithaca: Cornell University Press.

Gillespie V. A. 1975. Farmer Irrigation Associations and Farmer Cooperation. East-West Food Institute No. 3. Honolulu, HI: East-West Center.

Gupta, R. and S. Tiwari. 2002. At the crossroads: continuity and change in the traditional irrigation practices of Ladakh. In Commons in an Age of Globalization," the Ninth Conference of the International Association for the Study of Common Property, Victoria Falls, Zimbabwe.

Hafid A. and Y. Hayami. 1978. Mobilizing Local Resources for Irrigation Development: The Subsidi Desa Case of Indonesia. Irrigation Policy and Management in Southeast Asia. :123-133.

International Irrigation Management Institute (IIMI). 1988. Irrigation Management in Nepal: Research papers from a national seminar. Kathmandu, Nepal:

International Rice Research Institute (IRRI). 1978. Irrigation policy and management in Southeast Asia. Technical Report. International Rice Research Institute. Manila, Philippines.

Janakarajan S. 1992. Inter-linked transactions and markets for water in the agrarian economy of a Tamil Nadu village. In: Subramanian S (eds) Themes in development economics: essays in honour of Malcolm Adiseshiah. Delhi, Oxford University Press, Oxford.

Lam, W. F. 1996. Institutional Design of Public Agencies and Coproduction: A Study of Irrigation Associations in Taiwan. World Development, Vol. 24, No. 6, pp. 1039-1054.

Lam, W. F., C. P. Tang, and S. K. Tang. 2021. Bureaucratising co-production: Institutional adaptation of irrigation associations in Taiwan. Water Alternatives 14(2): 435-452.

Lando R. P. 1979. The Gift of Land: Irrigation and Social Structure in a Toba Batak Village. PhD Dissrtation, University of California, Riverside.

Lansing, J. S. 1991. Priests and Programmers: Technologies of Power in the Engineered Landscape of Bali. Princeton University Press, Princeton.

Lowdermilk M. K, W. Clyma, and A. C. Early. 1975. Physical and Socio-Economic Dynamics of a Watercourse in Pakistan's Punjab: System Constraints and Farmers' Responses. Water Management Technical Report.

Martin, E.G. and R. Yoder. 1983. The Chherlung Thulo Kulo: A case study of a farmer-managed irrigation system. In Water management in Nepal: Proceedings of the Seminar on Water Management Issues, July 31–Aug (Vol. 2, pp. 203-217).

Mollinga, P.P. 1998. On the waterfront. Water distribution, technology, and agrarian change in a South Indian canal irrigation system. PhD thesis, Wageningen University.

Meinzen-Dick R. S. 1984. Local Management of Tank Irrigation in South India: Organization and Operation. Cornell Studies in Irrigation.

Meinzen-Dick, R., Sullins, M., 1994.Water Markets in Pakistan: Participation and Productivity. International Food Policy Research Institute, Washington, DC.

Merrey D. J and J. M. Wolf. 1986. Irrigation Management in Pakistan: Four Papers. International Irrigation Management Institute (IIMI) Research Paper No.4.

Mirza A. H and D. J. Merrey. 1979. Organizational Problems and Their Consequences on Improved Watercourses in Punjab. Water Management Technical Report.

Ongkingco, P. S. 1973. Case Studies of Laoag-Vintar and Nazareno-Gamutan Irrigation Systems. Philippine Agriculturist 59(9-10): 374-380.

Nirola RR, Pandey FP. 1988. A Comparative Case Study of Two Community Managed Irrigation Systems in Chitwan District, Nepal. National Seminar on Irrigation Management in Nepal: Research Results.

Potter, J.M., 1976. Thai peasant social structure. University of Chicago Press.

Pradhan, P., 1988. Pattern of irrigation organizations in Nepal: Comparative study of 21 farmer-managed systems. Manuscript. Kathmandu, Nepal: International Irrigation Management Institute.

Ramamurthy, P. 1995. The political economy of canal irrigation in South India. Ph.D. thesis. The Graduate School of Syracuse University.

Reidinger R. B. 1980. Water Management by Administrative Procedures in an Indian Irrigation System. Irrigation and Agricultural Development in Asia: Perspectives from the Social Sciences. :263-288.

Sarker, A. and T. Itoh. 2001. Design principles in long-enduring institutions of Japanese irrigation common-pool resources. Agricultural Water Management, 48(2), pp.89-102.

Shah, T., 1993. Groundwater Markets and Irrigation Development: Political Economy and Practical Policy. Oxford University Press, Bombay.

Shah, T., O. P. Singh, and A. Mukherji. 2006. Some aspects of South Asia’s groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh. Hydrogeology Journal 14, 286–309.

Sharma, L. N., R. D. Lhapchu, U. Dukpa, C. Dorje, T. Gyeltshen, T. Dorje, S. Chhogyel, and J. Bajracharya. 1989. Report on the Field Visit of Raj Kulo, Argali, Palpa. In Report on training cum observation on rapid appraisal methods and water users’ association activities, edited by the IIMI, Annex 10. Digana Village via Kandy, Sri Lanka: IIMI.

Spooner, B. 1974. Irrigation and Society: The Iranian Plateau. Irrigation's Impact on Society. :43-57.

Tan Kim Yong U. 1983. Resource Mobilization in Traditional Irrigation Systems of Northern Thailand: A Comparison Between the Lowland and Upland Irrigation. PhD dissertation, Cornell University.

Vander Velde, E. 1980. Local Consequences of a Large-Scale Irrigation System in India. Irrigation and Agricultural Development in Asia: Perspectives from the Social Sciences. :299-328.

Wang, X., I. M. Otto and L. Yu. 2013. How physical and social factors affect village-level irrigation: An institutional analysis of water governance in northern China. Agricultural water management, 119, pp.10-18.

Water and Energy Commission Secretariat. 1987. Rapid Appraisal Study of Eight Selected Micro-Areas of Farmers' Irrigation Systems: Sindhu Palchok District, Final Report.

Wang, W. and J. Zhang. 2020. Arid/humid patterns over Asia in response to national-committed emission reductions under the Paris agreement. Progress in Earth and Planetary Science (2020) 7:11. https://doi.org/10.1186/s40645-020-00325-3