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The institutional analysis and development framework: A mathematical representation in water arena

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ABSTRACT

Institutions are human-designed systems facilitating structured interactions to achieve specific objectives. The Institutional Analysis and Development Framework (IAD), introduced by Elinor Ostrom, is a valuable tool for analyzing these systems. This study formulates a mathematical representation of the IAD within an operational context related to water demand and supply services. It demonstrates that structuring institutional (sub)systems entails a cost driven by external factors and interactions. Such a cost functions as an outcome within the scope of the IAD. This outcome can be mathematically expressed based on the components of the action arena and exogenous variables within a given context and over a distinct timeframe. This concept provides a theoretical basis for computationally evaluating and comparing different system states across varying (sub)system structures.

1. Introduction

Elinor Ostrom, Nobel laureate in Economic Sciences (2009), empirically challenged Hardin's (1968) "tragedy of the commons" by showing the effectiveness of community-based resource management among small local groups. She contributed to building new models of human behavior in the study of social dilemmas and collective action (Ostrom, 1998). Her scholarly work has been widely utilized by researchers across diverse fields, including water, energy, and environmental management and governance (Folke et al., 2002; Karl and Trenberth, 2003; Barrett, 2003; Berkes, 2004; Carpenter et al., 2009; Cox et al., 2010; An, 2012; Binder et al., 2013; Abson et al., 2017; Ungar, 2018; Jordan et al., 2018; Swilling, 2020; Komendantova et al., 2021).

The Institutional Analysis and Development Framework (IAD), introduced by her, serves as a valuable analytical tool for examining the institutional configurations designed to address intricate collective action dilemmas, where individuals or groups must work together to achieve shared goals. These situations frequently entail competing interests and constrained resources, which can give rise to challenges such as the overexploitation of common-pool resources (CPRs) (Ostrom, 2008; McGinnis, 2019; Lubell et al., 2023), coordination difficulties in the provision of public goods (Ostrom, 2019; Heikkila and Andersson, 2021), complexities in multi-level governance (Ostrom, 2017; Vitale et al., 2023), and equity concerns in decentralized resource governance (Pappas et al., 2021; Newaz and Rahman, 2022). Institutions consist of structured and logical relationships that can gradually adapt in response to contextual demands (McGinnis, 2011a). The strength of the IAD lies in its systematic theoretical focus on the impact of rules and norms on individual incentives in complex systems (Cole et al., 2019a).

The IAD, referred to by its developer as a "map", aids in understanding and explaining human behavior patterns for specific purposes. This framework allows for a methodical analysis of the structures of situations faced by acting entities. It helps analysts explore how these situations evolve over time, shaped by community interplay, the nature of the events involved, and the governing rules. It is emphasized that the variables influencing situational dynamics are diverse and context-specific, with values that vary based on the unique circumstances of individual cases (Ostrom, 2005).

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Since 1973, the framework has progressed from focusing on local self-governance to examining institutional diversity and heterogeneity (Oakerson, 1999; Dietz et al., 2003; Karkkainen, 2004; Ostrom, 2005). Recent studies emphasize the challenges of heterogeneity and pluralism in institutional design (Aligica and Tarko, 2012), with the IAD addressing this complexity to assess institutional impacts and explore institutional evolution and change (Cole et al., 2019a).

In the realm of water governance, this pioneering framework for Institutional Analysis has gained widespread acclaim from researchers for its profound contributions to understanding and navigating governance challenges (Rogers and Hall, 2003; Cash et al., 2006; Huitema et al., 2009; Pahl-Wostl et al., 2010; Pahl-Wostl et al., 2012; Groenfeldt and Schmidt, 2013; Daniell et al., 2014; Adams and Zulu, 2015; Özerol et al., 2018; Patterson and Huitema, 2019).

For instance, the IAD has proven instrumental in informing adaptive governance across multiple scales, particularly in water management, where ecological, social, and institutional contexts uniquely shape local and regional interactions (May, 2022; Blanco and Donoso, 2024). This multi-scalar adaptability bridges local water governance with broader environmental policies, enhancing sustainability in the face of climate impacts (Ostrom, 2017; Brisbois et al., 2019; Srigiri and Dombrowsky, 2022). Its flexibility across varied contexts is evident in applications ranging from integrated river basin management and groundwater governance to community-based strategies for climate resilience (Ak and Benson, 2022; Nsoh, 2022; Pipan et al., 2023), co-management of water resources (Whaley and Weatherhead, 2015), and coastal adaptation programs (Rahman and Islam, 2024).

A key strength of the IAD is its ability to analyze the interplay between institutional arrangements, stakeholder participation, and governance outcomes (Ostrom, 2019). This is particularly valuable for understanding barriers to collaborative governance and fostering collective action. For example, studies of multi-objective water management governance, and polycentric flood management governance emphasize how the framework helps identify mechanisms for improving governance outcomes (Molenveld and van Buuren, 2019; Dennis and Brondizio, 2020). In self-organized systems, Wang et al. (2019) applied institutional design principles to water user associations, revealing how local political contexts influence governance effectiveness. Similarly, Kamal et al. (2021) examined top-down regulatory policies in river basin management, demonstrating how such approaches disrupt local collective action, and highlighting the importance of decentralized, participatory governance.

The IAD also contributes to fostering social-ecological resilience, particularly in cross-boundary ecosystem governance. It facilitates navigation through interconnected subsystems and governance scales, enhancing environmental stewardship (e.g., Lubell et al., 2014; Cox et al., 2021). For instance, Laeni et al. (2021) underscore its role in fostering inclusive flood resilience, while Riazi et al. (2023) extended its application to the circular water economy, emphasizing the management of competing demands and promoting regulatory alignment.

Furthermore, systematic reviews, such as those by Raja Ariffin et al. (2024), reaffirm the critical role of institutional frameworks in effective water governance. Their studies identify key variables, including stakeholder engagement, policy implementation, and resource management, as pivotal in addressing challenges like urban–rural disparities and weak governance structures. Likewise, Jiménez et al. (2019) state in their review article that their proposed model—the enabling environment for meaningful participation—draws directly on the IAD. Their approach distinguishes between contextual factors and procedural elements that shape the participatory space in the delivery of water and sanitation services.

Incorporating a broad range of analytical viewpoints, the IAD facilitates in-depth assessments of multifaceted challenges in natural resource management (Andersson and Ostrom, 2008; McGinnis, 2017; Ortiz-Riomalo et al., 2023). The framework's scalability in analyzing hierarchical and interconnected subsystems at both micro and macro levels was emphasized, offering valuable insights into governance complexities and sustainability pathways (Ostrom, 2005). Additionally, complementary findings from other scholars reinforce the IAD's utility. For example, Hammond and Butler (2003) argue that rules alone are insufficient to fully guide the behavior of a system or determine its outcomes. And Marwell and Oliver (1993) emphasize the critical role of system interactions in shaping these behaviors and outcomes.

Even though the IAD is widely applied, based on the available literature, there is no universally accepted, comprehensive mathematical model of the entire framework. Nonetheless, the measures already undertaken hold particular significance in clarifying key aspects of the IAD and its associated extensions, thereby contributing to mathematical computations that reflect the framework's concepts and resonate with multiple scholarly purposes and approaches (Anderies et al., 2004; Ostrom, 2011; Anderies and Janssen, 2013; Schlüter et al., 2014; Yu et al., 2015; Garcia et al., 2016; Anderies et al., 2016; Cenek and Franklin, 2017; Homayounfar et al., 2018; Muneepeerakul and Anderies, 2020; Villamayor-Tomas et al., 2020; Garcia et al., 2022; Nagel and Partelow, 2022; Osman et al., 2022; Wiechman et al., 2024). For instance, Janssen (2010) used laboratory experiments to study how participants develop institutional arrangements under varying ecological dynamics, thereby operationalizing aspects of the IAD in an experimental setting. However, these approaches rely on agent-based simulations, using conceptual models structured from qualitative data, rather than providing strict mathematical formalizations (Ghorbani et al., 2015). Crawford and Ostrom (1995) introduced the Institutional Grammar (IG), offering a structured syntax (ADICO) for describing and categorizing institutional statements. Subsequent work has further developed and applied the IG for empirical analysis, institutional design, and computational text analysis, but it remains a conceptual and operational tool rather than a full mathematical model (Frantz and Siddiki, 2021; Siddiki et al., 2022; Pieper et al., 2023). Thus, while the IG supports thorough institutional analysis, it does not provide a comprehensive mathematical formalization.

More recently, Montes et al. (2022) introduced an Action Situation Language (ASL) that encodes the IAD's building blocks, particularly rules and interaction contexts, into a machine-readable logical syntax, enabling the automatic generation of formal game-theoretic models. Such computational approaches, along with recent integrations and case applications of IAD methods (Cole et al., 2019b; Sarr et al., 2021), and broader developments in Computational Institutional Science (Oesterling et al., 2024), have advanced the formal and analytic precision of institutional analysis. Nevertheless, these computational and simulation-based models—while operational and systematic—do not yet constitute a comprehensive mathematical system that fully captures all dimensions of the IAD (Montes et al., 2022).

The primary developers of the IAD have emphasized that "action situations" can be formally modeled as games, using game-theoretic logic to represent actor interactions, rule configurations, and payoffs (McGinnis, 2011b, 2011c, 2019). However, such models typically capture only individual action situations or networks thereof, rather than providing a full formalization of the entire IAD as a whole (Ostrom, 2011, 2020; McGinnis, 2019).

Also, existing efforts using tools such as set theory (Fiss, 2007; Schneider and Wagemann, 2012), category theory (Abderrahim and Maamri, 2018; Durand and Thornton, 2018; Frey et al., 2023), or computational modeling (Rengs and Wäckerle, 2014; Montes et al., 2022) address only selective components or layers, without capturing the framework's full multi-level complexity and feedback dynamics.

To date, the IAD lacks a complete formalization in algebraic or classical mathematical terms. Extending the previous scholarly trajectory, the present work seeks to introduce an alternative philosophical standpoint that interprets the framework through its perceived operative (kinetic) and structural (potential) attributes, thereby offering a distinctive lens for its mathematical articulation. Correspondingly, this study strives to contribute to filling the disciplinary gap by advancing the formal representation of the IAD in the literature.

As an early step toward a comprehensive mathematical formalization of the IAD, this perspective article aims to conceptualize its core components and associated variables through an accessible and intuitive approach. To guide future research with tangible steps, the study assumes a structured environment governed by a set of hypothetical rules. Within this context, key concepts of the IAD are mathematically represented, particularly in the domain of institutional water (demand-supply) analysis. To this end, select propositions from "*Understanding Institutional Diversity*" (Ostrom, 2005), are scrutinized to extract relevant elements that inform the study's content and customize suitable mathematical variables and equations. To the best of the authors' knowledge, to date, no scholarly investigation appears to have advanced a mathematical framework for the variable descriptions within the IAD pertaining to the water sector. Given the significance of this theoretical framework, particularly in light of its main founder's call for scholarly discourse on the foundational components shaping structured environments, this perspective endeavors to unveil a specific conceptual formulation concerning this matter.

2. Concept elucidation

2.1. Subject matter

In the book *Understanding Institutional Diversity*, institutions are defined as "prescriptions that humans use to organize repetitive, structured interactions". It is emphasized that the presence or absence of governing rules critically influences interaction dynamics and outcomes. These rules emerge from interactions within the deeper-layer situations of constitutional choice, collective choice, and operational choice settings. The central question is whether universal "building blocks" exist across all structured situations, to which the author tentatively responds "yes", while encouraging open discourse on this hypothesis. Another insightful point raised in this work is that, in the absence of a universal or simplified model capable of adequately addressing complex situations, theorists should consciously incorporate multiple assumptions to assess these scenarios effectively.

2.2. Core components of the framework

Holons are underscored as primary units of analysis, echoing the insights of Koestler (1970), who conceptualized them as nested subassemblies within complex adaptive systems, exhibiting both rule-governed behavior and structural constancy, thereby encompassing any stable sub-whole within organismic or social hierarchies (Ostrom, 2005). Correspondingly, an action arena is introduced as a holon comprising two sub-holons of participants and action situation, influenced at least at the time of analysis, by exogenous variables (Fig. 1a and b).

The action situation is further clarified as "*the social space where participants with diverse preferences interact, exchange goods and services, solve problems, dominate one another, or fight*". Besides, it can be characterized by seven clusters of variables which are: "*(1) participants (who may be either single individuals or corporate actors), (2) positions, (3) potential outcomes, (4) action-outcome linkages, (5) the control that participants exercise, (6) types of information generated, and (7) the costs and benefits assigned to actions and outcomes*".

In the context of water demand-supply management, the concept of holons is particularly relevant for analyzing water governance systems. For instance, this concept applies to the interactions between participants with distinct roles—local water users (e.g., farmers, households) and regional water governance bodies (e.g., water districts, state authorities)—where each influences and is influenced by the other's actions in the course of their interactions. More specifically, the action situations are classified as operational situations when they relate to the engagement of entities in the provision, production, distribution, and consumption of goods and services (Ostrom, 2005). To this end, in an administrative water demand-supply service action situation or operational situation, these interacting entities can include corporate actors (e.g., water utilities, regional authorities) that address the water needs of their respective jurisdictions, adhering to regulatory frameworks while also responding to local demands and environmental constraints (e.g. Stavenhagen et al., 2018; Pahl-Wostl, 2019; Arjomandi A. et al., 2022a; Arjomandi A. et al., 2022b). This dynamic illustrates the nested structure of water governance systems, where decision-makers at various levels—local, regional, and national—engage in action situations that influence how water resources are allocated and managed across scales (Moss and Newig, 2010; Julio et al., 2021; Arjomandi A. et al., 2024).

The interactions yield outcomes that, in turn, influence both the participants and the action situation (Fig. 1b). However, as suggested by the framework's pioneer the structure of the situation may be considered stable in the short term, a concept that extends to the status of exogenous variables during analysis. Despite the overall stability in the institutional structure and rule-governed interactions, external factors such as long-term climate shifts or changing legal frameworks may influence the equilibrium of this system over time (Li et al., 2022). In the short term, however, the system remains relatively stable, with

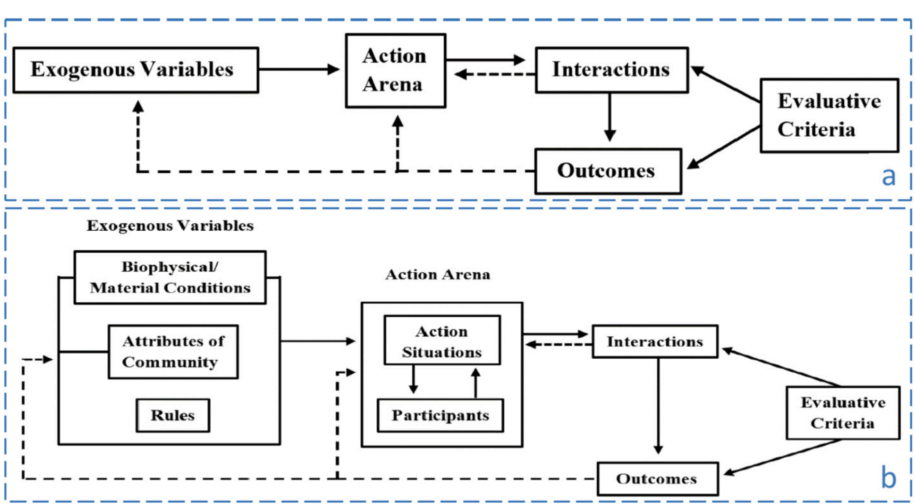

Fig. 1. The models presented in *Understanding Institutional Diversity* (Ostrom, 2005) draw on: a) the concept of the action arena; and b) the institutional analysis framework.

established practices and institutional norms guiding management decisions (Cosens, 2018; Hindriks, 2022). This aligns with the notion that the structure of the situation can be considered stable, yet remains subject to change due to the influence of exogenous variables and outcomes (Ostrom, 2005, 2008).

Based on the IAD concepts, subsequent to recognizing the initial structure of an action arena, analysts may undertake two additional steps: one entails examining exogenous factors and their influence on the action arena's structure, while the other involves addressing interconnections among action arenas either simultaneously or sequentially. Through the first course, any specific action arena is perceivable as a set of dependent variables, the framework's proponent indicates. In this domain, the factors influencing the structure of an action arena are summarized in three clusters of variables: (1) the rules that are used to shap the relationships among participants, (2) the biophysical element that participants act upon that in such arenas, and (3) the context of the community within which an identified arena is placed. Relevant to water governance, this advocates that analysts can examine how exogenous factors—such as variability in water resources, legal reforms, individual goals, or political-economic objectives—affect the structure of the arena (e.g., Pahl-Wostl, 2019; Arjomandi A. et al., 2024). Furthermore, within the realm of IAD, rules are introduced as a set of instructions incorporated into a particular environment to create an action situation or effect changes there. These findings reinforce the idea that while the internal structure of action arenas may appear stable in the short term, the forces of rules can challenge and reshape these systems, leading to adaptive changes in response to new environmental, economic, or socio-political contexts (Cleaver and Whaley, 2018). Also, in alignment with the IAD, recent studies suggest that institutional stability in water governance is shaped not only by biophysical and community attributes but also by the outcomes (Young et al., 2018).

Once these factors are identified, the second step involves considering how interconnected action arenas operate, either simultaneously or sequentially. For example, water governance systems typically encompass multiple action arenas operating at various scales, ranging from local water-user groups to regional and national authorities. These arenas involve diverse sectors, including drinking water, industrial usage, and agriculture (Partelow et al., 2023). This initiative particularly encounters an assemblage of action situations involving diverse positions and complex power dynamics (Oberhauser et al., 2023). Interactions across these scales (e.g., between local users and state water agencies) within one action arena (e.g., agricultural water management) can influence initiatives in other action arenas (e.g., drinking water management) within a specific spatiotemporal context (Dennis and Brondizio, 2020; Kellner, 2023).

2.3. Actions, outcomes, and valuation

In *Understanding Institutional Diversity*, two primary categories of variables are identified: state variables and control variables. The state variable is represented by valuations assigned to physical results and the associated costs or benefits of joint actions, prompted by governing rules. Conversely, the control variable is defined as an instrument that can proportionately influence an outcome. Anticipatedly, the state variable may be modified by various control variables associated with it. Accordingly, the author defines an action as selecting a setting or value on a control variable, thereby affecting an outcome variable, similar to the selection of a value within the water allocation policy (exogenous variables), which affects the achievement of the expected amount of water in a region.

Theoretical models assume that actions are costly, and outcomes can be beneficial (Ostrom, 2005, 2019). However, it is foreseen that these benefits may not fully satisfy the participants, depending on their intrinsic values and priorities. Extrinsic (external) values, assigned to costs and benefits, represent returns based on system operations and are interlinked with actions and outcomes. These values, the author stresses, are subject to positive or negative evaluations based on the participants' intrinsic insights. For instance, although a regional policy has been successful in meeting the overall water requirements of a region (extrinsic value), some local areas have not been able to satisfy a sufficient proportion of their water demands, leaving them dissatisfied based on their localized objectives or specific needs (intrinsic value). Additionally, the connection between action and outcome, determined by stochastic transformation functions, can be subject to uncertainties. However, despite uncertainties where the outcomes of probabilistic actions may be unknowable, the set of actions, outcomes, and their linkages are assumed to be knowable (Ostrom, 2005).

3. A mathematical interpretation

Assume an operational situation where a community of N participants, indexed by i ($i = 1{:}\, N$), engage in interactions concerning a shared resource. For example, in an organizational context, corporate actors occupy roles as users and suppliers, engaging in activities related to water. Thus, a value (B_{ij}) attributed to a quantity of water may reflect the nature of interaction related to the demand and supply. We envision a set of behavioral trait values (s_i) within a given situational context, connected with the participants' roles. These trait values mirror the opinions or responses (behaviors) that the participants might exhibit in the operational environment. For instance, if a participant is satisfied, the value of $+1$ is assigned, otherwise the value of -1 is ascribed. This approach to actor behavior—based on a binary framework—is intended to enhance theoretical clarity and simplify the understanding of the mathematical formulation. It serves as a starting point, open to future refinement through more nuanced or probabilistic frameworks (McKelvey and Niemi, 1978; DellaPosta et al., 2017; Diebecker and Sommer, 2017; Dragu and Simpson, 2017; Desmarais-Tremblay and Stojanović, 2022).

Such behavior can be categorized into two distinct types: i) genuine and ii) affected. In the genuine state, it is assumed that no external factors influence the opinions of the user and supplier. Their actions are driven solely by their satisfaction with the quantity of water requested and provided, with their trait values (s_i, s_j) assigned accordingly. Thus, within this context, participants may engage in a mutual interaction to adopt the trait value that minimizes a cost function. Such a cost can be defined as the cost (R_{ij}) for participant i to either be satisfied or dissatisfied with the response of participant j, and conversely, the satisfaction of participant j with the request of participant i. Hence, the cost can be formulated as:

$$R_{ij}(s_i, s_j) = -B_{ij} s_i s_j. \quad (1)$$

We assume that based on the logic, if the supply could reasonably meet the demand, B_{ij} has placed a positive value on mutual opinions and both participants are satisfied. Therefore, the product $s_i s_j$ is equal to $+1$. Otherwise, B_{ij} is entangled over a negative value due to the dissatisfaction of one of the participants, and therefore the product $s_i s_j$ becomes -1 (since one of them possesses a trait value that directly contradicts the other's opinion). If both participants are dissatisfied, their interaction is consequently disregarded.

The situation becomes complex when a participant, such as a supplier, engages with multiple other participants, such as various users. Subsequently, the costs associated with each interaction (R_{ij}) accumulate to determine the overall cost (R_i), (Fig. 2a):

$$R_i(s_i) = \sum_{i,j} R(s_i, s_j) = -\sum_{i,j} B_{ij} s_i s_j. \quad (2)$$

Interactions within a system are influenced by forces (f_i) resulting from the interference of exogenous factors, as previously indicated. These factors exert influences on participants, directing their behavior toward achieving consensus (Fig. 2b). For instance, despite a user's dissatisfaction with the proposed amount by the supplier, they may

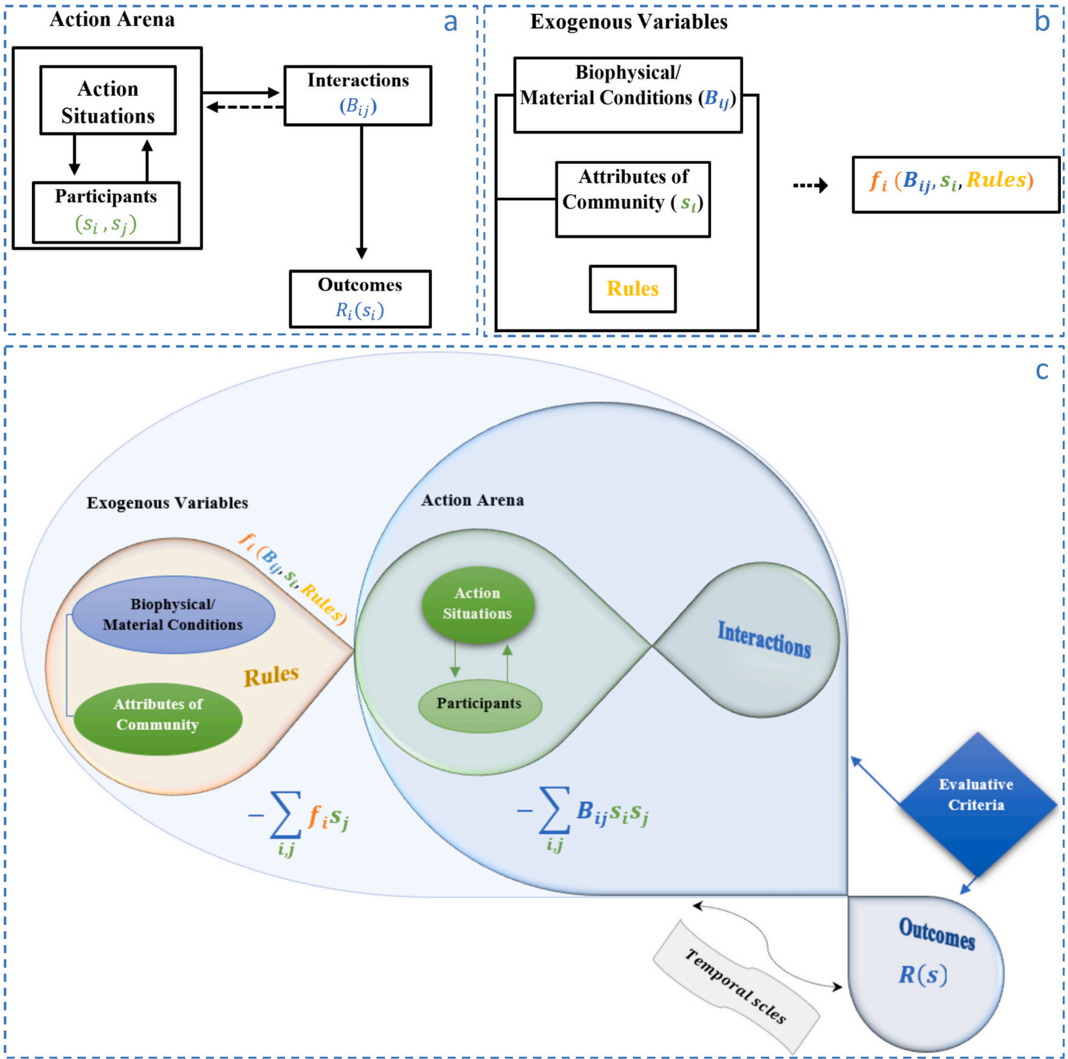

Fig. 2. a) A snapshot of action arena, interactions and outcomes at the time of analysis; b) The function of the resultant force of exogenous variables; c) A pictorial mathematical representation of the framework.

acquiesce to it under the compulsion of external factors. In this instance, the status may undergo a transformation from genuine to a kind of affected one. Hence, the Eq. 2 can be modified as:

$$R_i(s_i) = -\sum_{i,j} B_{ij} s_i s_j - f_i s_i. \tag{3}$$

Such forces are inclined to react negatively ($f_i < 0$) to negative traits and opinions ($s_i = -1$) and positively to positive ones. The magnitude of f_i embodies the impact exerted by various factors, consciously or unconsciously considered by participants during interactions. For example, it may encapsulate the effects of developmental initiatives, regulatory frameworks, water resource availability, and similar factors. Overall, this quantity is influenced by both natural (i.e. water) and anthropogenic elements.

Eventually, the total community cost function can be attained by summing the individual cost functions of all participants (Fig. 2c):

$$R(s) = \sum_i R_i(s_i) = -\sum_{i,j} B_{ij} s_i s_j - \sum_i f_i s_i. \tag{4}$$

This cost function provides a theoretical computational basis for identifying and monitoring inefficiencies, or losses, within the system. The measure of this cost represents a collective result connected to the participants' interaction structure, upon which a community can gauge its corresponding benefit. This outcome is observable as a state variable, arising from a series of actions undertaken by participants in relation to their trait values. Here, trait values (s_i) emerge from the conditional circumstances facilitated by B_{ij} and f_i. Thus, B_{ij} and f_i can be considered as control variables, with the potential to influence participant behavior through the mechanisms of their combined product. Indeed, participants may lack awareness or conscious measurement of these costs. In systems featuring interacting participants, the minimization of costs corresponds to the improvement of the system state (Arjomandi et al., 2022a; Arjomandi A. et al., 2024). Therefore, the formulation of variable $R(s)$ should prioritize minima aligned with participants' trait values, facilitated by strategic provisions in operational situations.

Before the outcomes could be experienced by participants and their community, a series of exogenous variables were influencing the interactions. These variables, relative to the timing of the outcomes, function as antecedents that prompt the subsequent effects. The force they generated, shaped by pre-existing community behavior traits, can be measured within a specific timeframe. Given that the structure of an action situation can be considered fixed in the short run (Ostrom, 2005), at the time of analysis, such force can be explored through a function of an averaged effect prior to the time of analysis. The average effect ($B_{ij}m_i$), linked to an average behavioral trait value (m_i) inferred from individual trait values (s_i), characterizes a community in line with the overall behavior which has been possessed in a period of time. To formulate this feature, a function of an average trait value was derived, incorporating the effects of rules on interactions. As illustrated in Fig. 1b, within the compartment of exogenous variables, the rules format the system space, and the biophysical condition ($\mathbf{B}_{N\times N}$) and attributes of the community ($\mathbf{m}_{N\times 1}$) are connected to each other ($\mathbf{m}$ denotes the compact vector notation of $m(s) = \frac{1}{N}\sum_i s_i$). The resultant arrangement through rules ultimately attempts to handle the acts upon the biophysical element (i.e., water) by influencing the behavior of the participants. In this context, the force mechanism can be (compactly) formulated by inverting the Eq.4 along with the incorporation of $\mathbf{m}$ (Fedele et al., 2013; Seyedi, 2015), as

$$\mathbf{f} = tanh^{-1}(\mathbf{m}) - \mathbf{B}(\mathbf{m}) \tag{5}$$

After estimation, the force can be integrated into the model to determine the subsequent system cost.

4. Discussion

This study was initiated in response to the call for discourse on the foundational constitutive components underlying structured situations, as outlined in *Understanding Institutional Diversity*. Leveraging insights from the IAD, we conducted an evaluation of a mathematical interpretation aligned with its principles to investigate human behavioral patterns, focusing on water demand-supply administration as a hypothetical operational situation. The devised formulation helps elucidate the interactions within the system and effectively illustrates resultant outcomes. To this end, the concept considers the associated impact of community ($\mathbf{m}$), rules ($\mathbf{f}$), and natural element ($\mathbf{B}$) on action arenas and interactions. The system cost $R(s)$ is identified as an extrinsic outcome. It emerges from aggregating all costs incurred by participants within a specific structure or configuration, thereby aligning the evaluative criteria of the framework with the basis of judgment. Nevertheless, the costs perceived by participants ($R_i(s_i)$) may instigate an intrinsic valuation that can elicit unfavorable perceptions.

Participants' opinions (s_i), primarily, could also be touched with a probability in respect to the amount of (demanded/supplied) water, denoted as B_{ij}. In this domain, A multitude of factors, including expectations, requirements, resources, capabilities, and various political, socioeconomic, or psychological parameters, interfere with their cognition and decision-making processes (Yazdanpanah et al., 2014; Arunrat et al., 2017; Arjomandi A. et al., 2023; Arjomandi A., 2023; Arjomandi A. et al., 2025a; Arjomandi A. et al., 2025b). However, this circumstance may allude to a critical threshold (B_{cr}) capable of fostering a favorable perception, in conjunction with the influence exerted by exogenous factors on a participant's (decision-making) behavior. This pivotal threshold can instigate a predisposed trait value. Thus, given the function of forces ($\mathbf{f}$), it is imperative to investigate the B_{cr} based on the context of a specific action situation.

To sustain the system, the force of exogenous variables endeavors to steer such opinions toward consensus, ultimately reducing the system cost. More specifically, although the effects of previous outcomes ($R(s)$, $R_i(s_i)$), and water amount (B_{ij}) may lead to changes in the subsequent behavior of participants (s_i) and seed population-wide trait variation ($m(s)$), the force (f_i) strives to handle the (water demand-supply) interactions to eventually ensure system sustainability and dynamism in line with the system's objectives. For instance, in a community where water resources are expected to be shared equitably among all stakeholders, some participants who have not received their expected share (B_{ij}) may become dissatisfied based on their intrinsic evaluation of the outcomes they have experienced ($R(s), R_i(s_i)$). However, since the water is managed under a common system with certain regulations, and they still require a specific proportion to fulfill their needs, they may begin to adapt to the circumstances. This adaptation is driven by a force arising from both the interplay of need for water and water availability, as well as the prevailing conditions within the shared management system. Thus, the force exerted by exogenous variables mediates the antecedent average behavioral trait of a community over a specific time frame, amidst the influence of the (dis)satisfactions and outcomes experienced by participants in preceding stages or times. This concept articulates an orientation toward determinacy at the system level through the (controlling) role of f, despite the uncertainty in participants' actions.

5. Demonstrative application

To merely illustrate the application of this perspective, empirical water demand-supply data (MOE, 2014) for a given year (considered as the time of analysis) were drawn from a shared water basin characterized by two distinct institutional settings governing water demand and supply services within the basin. These settings encompass a number of water utilities interacting with their respective regulatory authorities (corporate actors) to manage water demand and supply within the basin. For analytical simplicity, participants were categorized into two groups, A and B. Group A consists of 14 solicitor participants responsible for water demand within their administrative jurisdictions and one supplier striving to meet these demands. Similarly, Group B comprises 11 solicitors and one supplier. According to the established rules of interaction, water-demanding participants (i.e., water utilities) are not permitted to coordinate or negotiate water requirements among themselves. Instead, they may only engage with their corresponding hierarchically superior authority (the supplier) to express and fulfill their needs.

To clarify the study's objective, three scenarios regarding water demand-supply agreement (B_{ij}) were considered, whereby participants may either concur or dissent on the expected volume of supplied water:

1. In the first scenario, a water-demanding participant is deemed to agree with its supplier if the supplied amount reaches or exceeds 95 % of the demand.
2. The second scenario lowers this agreement threshold to 90 %.
3. The third scenario further reduces it to 65 %.

According to these hypotheses, a solicitor's trait value (s_i) is assigned to be identical to that of the supplier if the ratio of supplied to demanded water meets the scenario-specific threshold; otherwise, it is regarded as contrary. This reflects the dynamics of an operational (action) situation, wherein participants interact with one another based on established rules of interaction and in consideration of their expected or required amounts of water within this context.

As evidenced by the data, under the first scenario ($\geq$ 95 %), Group A consists of 10 agreeing and 4 disagreeing participants, resulting in a community-level trait value ($m(s)$) of 0.375. Group B comprises 9 agreeing and 2 disagreeing participants, with a community-level trait value of 0.692. In the second scenario ($\geq$ 90 %), Group B experiences one fewer disagreeing participant, increasing its community-level trait value to 0.846, while Group A's values remain unchanged. In the third scenario ($\geq$ 65 %), all participants are satisfied due to the lower expectation level, yielding a community-level trait value of 1 for both groups.

Based on this composition, costs (outcomes)—denoted as $R_i(s_i)$ for the individual level and $R(s)$ for the community level—are computed (see Figs. 3.a and b), alongside the influence of exogenous variables ($\mathbf{f}$) depicted in Fig. 3.c.

As observed, both individual- and community-level costs tend to decrease as the expected level of water supply declines and the number of agreeing participants increases. Notably, at the 65 % agreement threshold, the associated outcome costs are significantly reduced. This aligns with Ostrom's (2005) concept that the set of actions, outcomes, and their linkages can be discerned despite the probabilistic nature of actions within a specific spatiotemporal scale.

Furthermore, the effect of marginal changes in individual costs becomes evident when analyzing Group B. Specifically, when the threshold decreases from 95 % to 90 %, the addition of just one more agreeing participant results in lower individual costs at the 90 % threshold

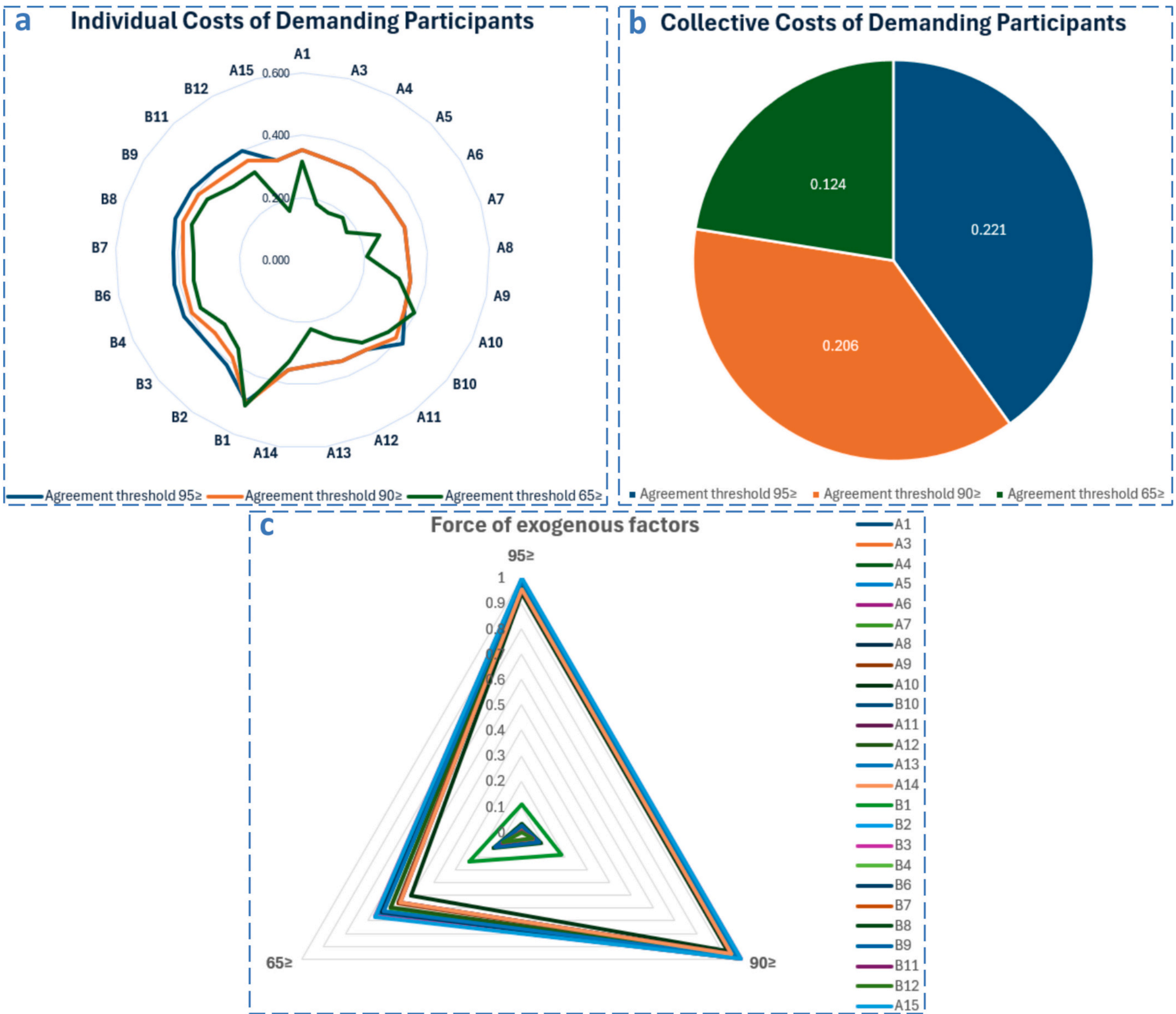

Fig. 3. Global rescaled rates illustrating (a) individual-level outcomes ($R_i(s_i)$), (b) community-level outcomes ($R(s)$), and (c) the effect of exogenous variables (**f**).

compared to the 95 % level within this group. This clearly illustrates how variations in actors' behavior linked to the expected supply level can directly influence individual costs within an institutional (sub)system, and how these individual-level outcomes, in turn, shape the collective outcome for all participants within the broader system.

Additionally, the observed pattern concerning the influence of exogenous factors further supports these findings. The extent of such external forces diminishes as the expected water supply level decreases and participants agree to smaller water supply amounts. In particular, the force rates at the 65 % agreement threshold demonstrate the lowest overall influence of external forces on participants' interactions within the water demand-supply system.

While this introductory example aims to facilitate the presentation of the perspective's application, it is limited to a single-year snapshot representing the time of analysis in this example. To capture the evolving states of the system over future temporal scales, while accounting for the effects of previous stage outcomes and other relevant determinants, it is essential to have access to and incorporate the appropriate data.

6. Concluding remarks, limitations, and future prospects

To contribute to the relatively limited body of literature on the mathematical interpretation of the widely applied IAD, this study is grounded in Ostrom's foundational work, *Understanding Institutional Diversity* (2005), for the identification and detailed description of key variables. Adhering to Ostrom's response to the major question of common building blocks that underlie structured situations, the formula (Fig. 2) disseminates a concept. This concept is underpinned by two pillars, grounded in a set of kinetic and potential attributes that define the environment of such situations. In this context, the mathematical representation conveys these attributes in the form of forces resulting from the influence of both exogenous variables and the interactions. This feature provides it with a degree of versatility and utility in studying various action situations. In this stream, it proposes the variables of biophysical and man-made mechanisms, namely B, s, and f, as suitable candidates that can be useful for determining the building blocks of action situations concerning (at least) the commons. Correspondingly, the output of the proposed formulation communicates how a system's function can be affected by these variables and, in turn, how the outcome can affect them. In fact, such outcomes can be affected simultaneously by variations in subsystem configurations within the system. Accordingly, this perspective offers an interpretive and analytical approach to examining institutional structures, aligning with the principles of the IAD and the unique needs of the case study at hand.

Although this brief perspective aims to project a mathematical interpretation of the IAD within an administrative water demand-supply action arena, it has limitations in accommodating contexts where players have full freedom of action. The conceptualization in this study is grounded in specific hypothesized attributes of water demand-supply services within formal organizational water authorities. While it provides a structured approach, its application to informal situations may face limitations, requiring careful adaptation to incorporate context-specific dynamics and psychological factors. Such an issue is highlighted by Cleaver (2017), who emphasizes that the IAD prioritizes formal institutions over informal governance, often overlooking the intricate role of community-driven or culturally embedded practices. Future advancements could broaden the analytical focus of this perspective to encompass a wider range of behavior-determining factors, such as emotional, cultural, economic and political dimensions, particularly in informal contexts, which are critical to governance outcomes (Hinkel et al., 2015). Moreover, in its current form, this formulation serves as the primary framework addressing institutional structures at the time of analysis. To capture the system's evolution over future temporal scales, incorporating influences from prior stage outcomes and other relevant factors, future research may develop this static framework into a dynamic state modeling approach. Additionally, subsequent investigations could systematically integrate theoretical constructs and analytical techniques derived from alternative formal methodologies, thereby augmenting and generalizing the binary paradigm adopted herein, with the aim of advancing its mathematical development and scope of applicability. Given these limitations, this perspective emphasizes scholars' observations that the development of a widely accepted and comprehensive mathematical model remains a significant challenge. It highlights the need for targeted and advanced future research efforts to push the boundaries toward establishing a generally recognized and integrative framework.

CRediT authorship contribution statement

Peyman Arjomandi A. and Seyedalireza Seyedi contributed equally to this work as the first authors. Also, Nadejda Komendantova, Masoud Yazdanpanah and Matteo Mannocchi contributed equally to this work as the second authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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