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Explaining and Measuring Social-Ecological Pathways: The Case of Global Changes and Water Security

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Abstract

The Social-Ecological Systems (SES) framework serves as a valuable framework to explore and understand social and ecological interactions, and pathways in water governance. Yet, it lacks a robust understanding of change. We argue an analytical and methodological approach to engaging global changes in SES is critical to strengthening the scope and relevance of the SES framework. Relying on SES and resilience thinking, we propose an institutional and cognitive model of change that institutions and natural resources systems co-evolve to provide a dynamic understanding of SES that stands on three causal mechanisms: institutional complexity trap, rigidity trap, and learning processes. We illustrate how Data Cube technology could overcome current limitations and offer reliable avenues to test hypothesis about the dynamics of social-ecological systems and water security by offering to combine spatial and time data with no major technical requirements for users.

Keywords: Social-Ecological System, Water security, Governance, Institution, Learning, Data-Cube

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1 Introduction

Pressures on natural resources are increasing and a number of challenges need to be overcome to meet the needs of a growing population in a period of environmental variability. The key to sustainable development is achieving a balance between the exploitation of natural resources for socio-economic development, and conserving ecosystem services that are critical to everyone's well-being and livelihoods (Costanza et al., 2017).

Water is a crucial natural resource supporting life on Earth and underpinning equitable, stable, and productive societies and ecosystems (Gain et al., 2016). The cumulative effects of overexploitation, pollution, and challenges posed by climate change ask to carefully monitor and assess trends and evolution of water resources (Lawford et al., 2013). This is an essential pre-condition to ensure a sustainable use and access to water that can serve as a basis for water security. This important role has been recognized as one of the seventeen Sustainable Development Goals (SDGs) defined by the United Nations. From a territorial management perspective, to support monitoring and reporting commitments and obligations, managers need information that are synoptic, consistent, spatially explicit and sufficiently detailed to capture anthropogenic effects (Scott and Rajabifard, 2017).

The Social-Ecological Systems framework combines in one setting these different components to organize consistently the analysis of human and nature co-evolution (Ostrom, 2009). It is designed as a diagnostic tool to help identify relevant variables that can help explain sustainability in social-ecological systems and allow for analysis of relationships among levels and scales. As such, it helps to provide a common framework to facilitate multidisciplinary research efforts, better understand and study the complexity of these systems (Ostrom, 2009), and allow for cross-institutional comparisons and evaluations (McGinnis and Ostrom, 2014). Yet, SES lacks a robust understanding of change. We argue an analytical and methodological approach to engaging global changes in SES is critical to strengthening the scope and relevance of the SES framework. Identifying the methodological needs for carrying-out large-N dynamic analyses of SESs is needed for knowledge accumulation.

In this paper, we put forward a way to explain change and dynamics in SES that could be testable across a large number of cases. Current literature offers mainly in-depth investigations highlighting mechanisms and triggers of changes. Yet, there is a need to scale-up the knowledge toward more generalizable results. Relying on SES and resilience thinking, we propose an institutional and cognitive model of change that institutions and natural resources systems co-evolve to provide a dynamic understanding of SES. It stands on three causal mechanisms: institutional complexity trap, rigidity trap, and learning processes. We offer a simple framework that draws an institutional and cognitive model of change enabling systematic and explanatory tests, and combine them.

Methodologically, we highlight current methodological limitations and needs for carrying out these studies about SES dynamics. Then, we provide insights on how to operationalize this, mainly through measurement rather than methodological tools. The Data Cube technology could overcome current limitations and offers reliable avenues to test hypothesis about the dynamics of social-ecological systems and water security by offering to combine spatial and time data with no major technical requirements for users. We pose water security as an illustration of this analytical and methodological perspective because it is conducive to analyze human and nature interdependencies (Dadson et al., 2017; Gerlak and Mukhtarov, 2015) to highlight the spatial and time dimensions of SES. Indeed, water availability changes over space, time, and quality in consequence of human and natural trends.

First, we propose an institutional and cognitive model of change to feed the social-ecological system framework and frame analysis about SES evolution. Then, in section 3, we discuss the current methodological barriers to accumulate knowledge about SES evolutions and share recommendations to overcome them. We present the Data Cube technology and approach in section 4 as a promising to put in practice our recommendations and test the proposed model of change. Finally, we conclude by identifying the next steps and avenues.

2 SES and Evolution: Theoretical Framework

2.1 SES: Origins and Scope

A Social-Ecological System (SES) is "*an ecological system intricately linked with and affected by one or more social systems*" (Anderies et al., 2004). The Social-Ecological Systems framework further elaborates Elinor Ostrom's Institutional Analysis and Development (IAD) framework and the framework developed by Marty Anderies and colleagues (2004) (Ostrom et al., 2007; Schlager and Cox, 2018). It was intended to specify the biophysical aspects of the IAD framework (see Schlager and Cox (2018) for a more detailed comparison of the two frameworks). The framework has been updated through a rearrangement of the list of relevant attributes of governance systems to make it applicable to broader policy settings (McGinnis and Ostrom, 2014). Some emerging research aims to combine or integrate the IAD and SES frameworks to help overcome their individual limitations (SES framework as too static and the IAD framework as underspecified) and offer a more powerful framework that allows for deeper multilevel analyses of dynamic changes in social-ecological circumstances by making direct connections between institutional changes and social-ecological outcomes (Cole et al., 2014).

The SES perspective is closely linked to the resilience thinking. While the SES framework relates to the structure of a system, resilience focuses on evolution. SES and resilience thinking conceive systems as moving across stability domains according to internal and external disturbances. Key variables of interest are interlinkages among the components of the system and the adaptation of the later according to its resilience. We adopt the third generation of resilience thinking, that is called socio-ecological (Folke, 2006). Resilience is the magnitude of disturbance that can be absorbed before the system changes its structure by changing variables and processes that control behavior (Holling, 1996, p.33). Social-ecological resilience extends the ecological resilience, first generation (Holling, 1973), to the social world and distinguishes from engineering resilience, second-generation (Pimm, 1984).[1]

The SES framework and resilience thinking together provide a consistent set of concepts for the analysis of co-evolution between humans and nature. As a consequence, most researchers use these frameworks as a "*checklist of concepts from which they could qualitatively or quantitatively measure their variables for the sake of case descriptions, case comparisons, or statistical analysis*" (Schlager and Cox, 2018, p.243). To move toward more explanatory power, there is a need for internal theoretical models, especially regarding evolution and change (Fath et al., 2015; Lubell et al., 2014).

2.2 An institutional and cognitive model of change

2.2.1 Evolution through an adaptive cycle

The global dynamics of a SES follows an adaptive cycle that frames the co-evolution between humans and nature (Gunderson and Holling, 2002; Ostrom and Janssen, 2005). The adaptive cycle consists of a process of destruction-creation that drives the potential and the connectedness of the SES (Figure 1). SES's potential and connectedness increase within a stability domain until saturation, i.e., occurrence of non-absorbable disturbances. Then the SES adapts and reorganizes to move toward a new domain of stability. Two phases form the pattern of any adaptive cycle: the saturation and the reorganization phases. The first is a phase of growth until a turning-point where the SES becomes unstable because saturated. Mostly, this turning-point corresponds to a regime of over-exploitation without any additional or external stocks of resources. The next phase is marked by a release and a reorganization of the SES toward a new stability domain. After that, a new adaptive cycle starts.

[1] Engineering resilience considers changes as predictable and focuses on stability near to steady-state equilibrium. The key variable of interest is the recovery time, i.e., the speed of return to the steady-state equilibrium after a disturbance. In that perspective, the system does not change its structure.

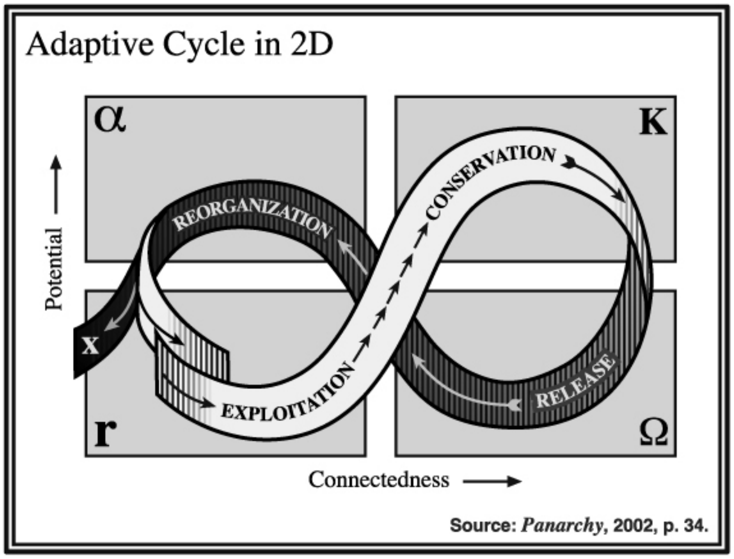

Figure 1: Heuristic scheme of an adaptive cycle (Gunderson and Holling, 2002)

The adaptive cycle heuristics is widely used, but lacks of internal explanations of the patterns and triggers of change. Regarding the defined scope of SES, we propose a model of change that combines four central ontological axioms: co-evolution between human and nature, adaptation within multiple stability domains, polycentricity, and path-dependency. We offer a theoretical background to the two main phases of an adaptive cycle – saturation and reorganization. We use the concepts of rigidity trap and institutional complexity trap to explain the phases of saturation, and draw on the adaptive governance literature to explain the phase of reorganization.

2.2.2 Explaining the saturation of an SES

The rigidity trap reflects the equilibrium where the SES's internal controls lock the system into a pathway that reinforces undesirable outcomes (Fath et al., 2015; Stedman, 2016). It is a dynamic leading to an organizational status-quo which produce a vicious circle. It is a particular setting where the refinements of the management model and of the institutional design have organized exploitation of the resource characterized by a low natural diversity and a low variation in resource dynamics to maximize the economic use of the resource (Carpenter and Brock, 2008; Gunderson and Holling, 2002). The governance design appears robust because institutions are highly connected, self-reinforcing, and inflexible which constrains the innovation ability of the SES (Carpenter and Brock, 2008). Even if the outcome reveals to be undesirable, the SES is unable to explore any alternative patterns, increasing its vulnerability to disturbance. As a result, the system could not evolve anymore within the same stability domain and is likely to experience a structural crisis (Carpenter and Brock, 2008; Fath et al., 2015; Stedman, 2016). For example, a rigidity trap may be a SES organizing an ecologically clean over-exploitation of the resource, which is frequent when public policies do not distinguish the resource from its uses (Gerber et al., 2009; Varone and Nahrath, 2014).

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The institutional complexity trap concept puts forward that the extent of the regulatory scope of a given SES has a decreasing marginal impact on its coordination efficiency (Bolognesi and Nahrath, 2018; Bolognesi et al., 2017). The governance of any environmental resource is a regime of multiple public policies and property rights specific to different uses of the same shared-resource (Gerber et al., 2009; Vatn, 2005). The regime efficiency (integration) to govern behaviors depends on the scope of regulated uses (extent) and the coherence of the public policies and property rights that structure the regulation. Together extent and coherence increase the integration of the regime, and thus the potential efficiency of the governance design.

Bolognesi et al. (2017) show that this relation is not linear, the marginal impact of extent on integration is decreasing (Figure 2). Indeed, the increase of the regime extent impacts negatively on its coherence because of institutional overlaps and frictions. As an illustration, water uses are regulated by policies specific to agriculture, environment, urban planning, energy, among others; but these policies could be conflictual or not consistent while overlapping. These overlaps correspond to transversal transaction costs that reduce the efficiency of the coordination and lock the SES in a state of non- feasible additional progress under the same structural conditions. The SES becomes vulnerable to disturbances, opening the room for a release and marking the end of the saturation phase. Over time, expertise in governance stresses the increase of transversal transaction costs by developing siloization and uncoordinated extension of the regime (Cejudo and Michel, 2017).

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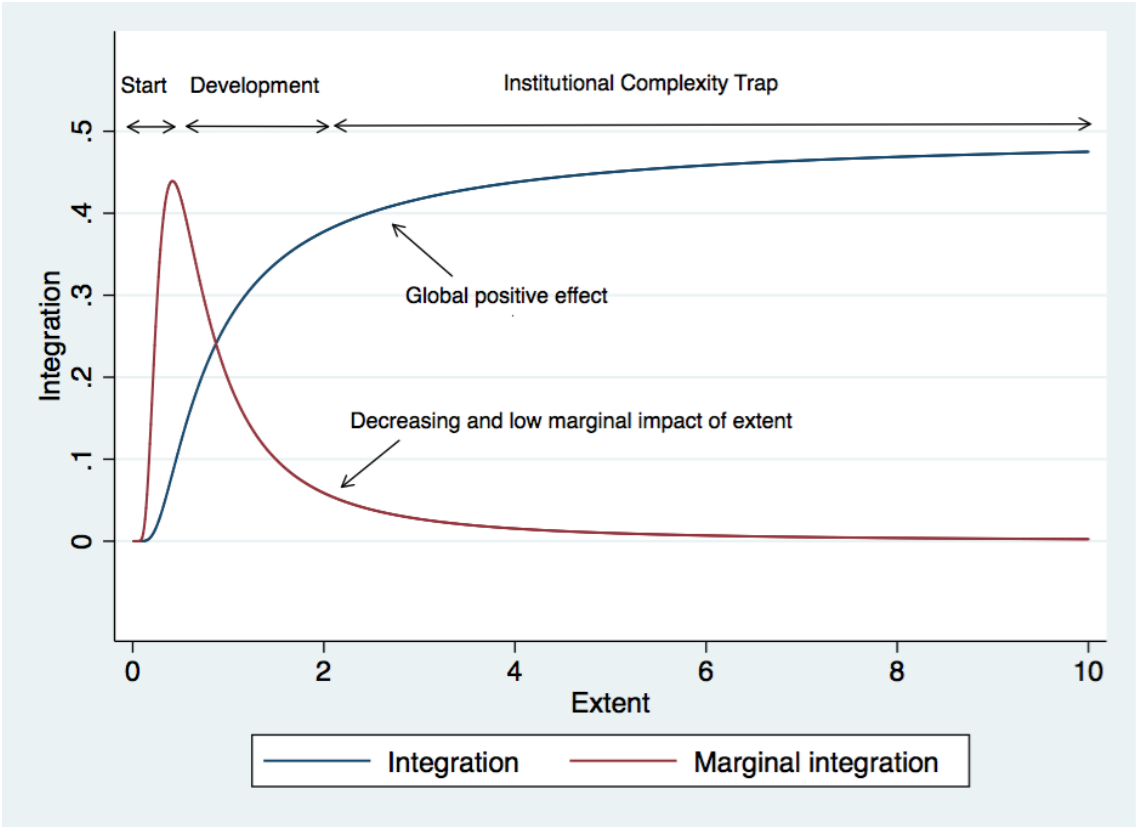

Figure 2: The saturation process through an Institutional Complexity Trap (Bolognesi and Nahrath, 2018)

The rigidity trap produces a lack of adaptive capacity and the institutional complexity trap constrains the ability to refine coordination mechanisms. Taken together, these traps drive the SES to a state where it is robust to shock but not necessarily resilient anymore. The SES is vulnerable to disturbances and likely to know a structural crisis, entering into the phase 2 of an adaptive cycle.

2.2.3 Explaining the reorganization of an SES

Phase 2 of the adaptive cycle is the reorganization, including a release and a reorganization process (Gunderson and Holling, 2002). SESs reorganize following the patterns of four ideal-types: integrative-synchronous regime, entrepreneurial-synchronous regime, resilient-synchronous regime, transformative-synchronous regime (Renou and Bolognesi, 2018).[2] Each model has its logic of action and structuring principles depending on nature (control vs. self-determining) and goal (poietic vs. dissipative) of the coordination (Table 1).

Integrative synchronous regimes are problem-solving oriented, and change remains under control. The logic of action is to integrate the SES to reduce the misalignment between the different levels and scales of the SES (Teisman and Edelenbos, 2011). Even if this pattern implies changes in

[2] These four pathways draw ideal-types, the observed pathways should be hybrids of these.

the structure of the SES, integrity remains an important goal. Entrepreneurial synchronous regimes are problem-solving oriented and evolve according to iterative change of components of the SES following a logic of effectuation that seek to minimize losses (Sarasvathy, 2009). It is an organized form of micro-trial-error learning. Therefore the structuring principle is subsidiarity. Actors impulse reorganization in resilient synchronous regimes by seeking a new balance of the SES functions through reframing problems (Adger et al., 2005). The logic of action is resilience, and adaptability the structuring principle. Transformative synchronous regimes follow the most significant change, regarding structure, by reducing the role of control and reframing problems. Reflexivity is the structuring principle of this change.

	Autopoietic cohesion	Dissipative cohesion
Extension by control	Integrative synchronous regime Logic of action: integration Structuring principle: integrity	Entrepreneurial synchronous regime Logic of action: effectuation Structuring principle: subsidiarity
Extension by self-determination	Resilient synchronous regime Logic of action: resilience Structuring principle: adaptability	Transformative synchronous regime Logic of action: transformation Structuring principle: reflexivity

Table 1: Ideal-types of reorganization patterns

These ideal-types involve different logic of action, structuring principles, and institutional levels. Nonetheless, three mechanisms could explain this diversity in reorganization patterns: institutional crafting, learning, and complementarities within a polycentric system of institutions.

In environmental governance, polycentric governance systems, involving multiple overlapping centers of decision-making interacting within an overarching set of rules, are thought to help address the complex interrelationships within our social and environmental systems (Heikkila et al., 2018). Polycentric governance systems exhibit enhanced adaptive capacity (Pahl-Wostl and Knieper, 2014; Silveira and Richards, 2013), adapting by changing rules and behavior as they gain experience. Learning can help support a governance system's adaptive capacity (Folke et al., 2005).

Learning is an important pathway toward adaptation and responsiveness to changing environmental and social conditions. Rules structuring an environmental governance process can enable or constrain the institutional work of learning, and serve as a critical pathway toward institutional change (Heikkila and Gerlak, 2018). Heikkila and Gerlak (2018)'s recent work suggests that openness in boundary, scope, information, and choice rules may support learning across a variety of contexts and institutional arrangements, but attention is needed to the different issue contexts and types of learning when thinking about specific design features. The deliberate creation of forums, for example, can bring together decision-makers to share information and learn (Galaz et al., 2012). But beyond the structure of the institutional design itself, the personal interrelationships and communication patterns, or social dynamics, can play a key role in promoting and inhibiting learning (Heikkila and Gerlak, 2013). Although a deliberate push for polycentric resource management can help encourage rule experimentation, some researchers found that it may not necessarily encourage adaptation and learning (McCord et al., 2017).

There are different types learning that can influence reorganization. Newig et al. (2016) distinguish serial learning (sequential) from parallel learning (simultaneous) and emphasize the source can be endogeneous or exogenous, i.e. others jurisdictions or policy fields. In addition, the concept of triple-loop learning allows for identifying the level of learning, and thus the impact of learning on the SES reorganization (Pahl-Wostl, 2009). Single-loop learning is incremental; it proceeds of the same pattern of SES dynamics (integrative and entrepreneurial synchronous regime). Second-loop learning leads to question the cause effect relationship between components of the SES (resilient synchronous regime). Triple-loop learning is paradigmatic change and allows for deep transformation and reorganization of the SES toward a new equilibrium (transformative synchronous regime). The challenge to reorganize an SES is to develop channels for triple-loop learning.

Learning can support innovation in the SES as its implementation reorganizes the SES and proceeds through institutional bricolage or crafting. Actors use the learning in problem-solving perspective solving to improve governance and decision-making(Cleaver, 2002; Ostrom and Basurto, 2011; Poteete et al., 2010). Learning can result in a change of the structure of the linkages between resource uses and institutions. The network turns from a closed-loop – characterized by rigidity and institutional complexity traps - to more open ones (Fath et al., 2015; Heikkila and Gerlak, 2018; Lubell et al., 2014).[3] As a consequence, reorganization of an SES necessitates triple-loop learning in association with an opening of the network of uses, resources and institutions.

Figure 3 synthesizes our institutional and cognitive model of change of an SES. The attraction into a rigidity trap or an institutional complexity trap saturates SES over the years. The SES becomes vulnerable to external disturbances and is likely to experience a crisis. The crisis opens a phase of release that ends-up with the reorganization of the SES. The reorganization consists of embedded pathways of change (multiple spatial and time scales) and is driving by individual learning, innovation, and diffusion. These three drivers allow for a paradigmatic shift of the SES structure, opening the network of actors. It defines a new equilibrium with a more balanced relationship between ecological and social systems, and with more flexibility and adaptability.

[3] "*Characteristics of a rigid system include very few key nodes with a high concentration of influence, and low diversity both in nodes and pathways*" (Fath et al., 2015, p.4).

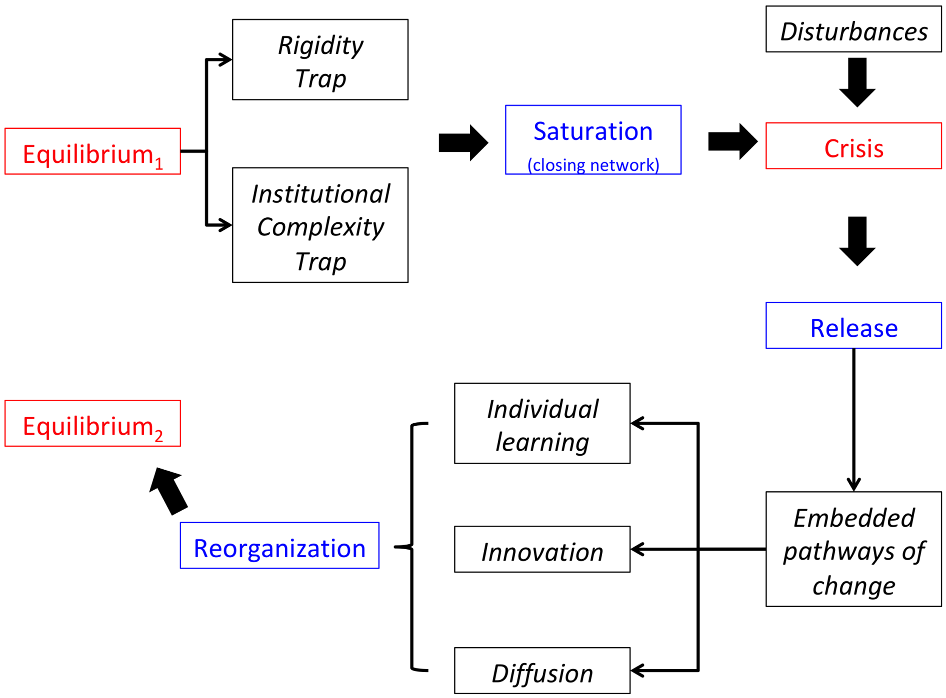

Figure 3: An institutional and cognitive model of change for SES

3 SES Evolution and Measurement: insights from the case of water security

In section 2, we proposed a model to understand the dynamics of SES, which is crucial in a context of global transformations. In this section, we shed lights on key methodological limitations that prevent reliable tests of the institutional and cognitive model of change of SES, and knowledge accumulation. We put forward recommendations to tackle these methodological issues. We use the case of water security as an illustration of SES measurement. Water security makes for a good illustration given its high-priority in the political agenda, its fundamental social-ecological essence, and its multi-level and multi-uses perspective.

3.1 Limitations to general knowledge about water security: measurement heterogeneity and time-limited analyses

Over the past decade, water security has emerged as a new currency of the international water community (Cook and Bakker, 2012). It can broadly be seen as an extension of sustainable development thinking to water resources with the focus on the quantity and quality of water supply for societal and ecological needs (Gerlak and Mukhtarov, 2015). There is an extensive and growing body of scholarship examining the adoption of and application of water security in a wide array of journals and from a diverse set of authors across diverse geographic regions and scales around the world (Gerlak et al., 2018; Huai and Chai, 2016). In bridging both the environmental and social spheres, water security can be seen a tool for the adaptive management of an institutional water regime and contribute to improved governance (Bolognesi and Kluser, 2018). But knowledge accumulation is limited in that area of research.

We argue that there are three primary factors that limit knowledge accumulation around water security and thereby, hinders its ability to serve as a tool for adaptive management of SESs: large diversity of methodology, case specificity, and cross-sectional studies. The two first limitations prevent comparability and thus the external validity of findings. The former is a matter of internal validity; dynamic mechanisms are not properly observed or tested which prevents inferential and causal claims.

The first limitation that limits knowledge accumulation around water security is heterogeneity of measurement of water security. There has been an explosion of assessments of water security and the adoption of indicators to operationalize water security varies considerably around the world (Gerlak et al., 2018). The authors report the use of 15 sub-indicators, and that the majority of the studies use only two of them: sufficient quantity (91% of the studies) and acceptable quality (51% of the studies). This large methodological diversity is also characterized by a diversity of conceptual frameworks, which serves to limit comparison. Indeed, they are generally characterized by a high subjectivity which can reduce the relevance of their normative use (Bolognesi and Kluser, 2018). For instance, Bolognesi and Kluser (2018) highlight that water security scores of Vietnam, Thailand, the Philippines, and Kyrgyzstan are contradictory in the literature, being good or weak depending on the study. This heterogeneity is consequential considering the current evidence-based policy-making paradigm. What "evidence-based" means regarding such an extensive range of appraisal? In addition, it actively prevents the growth of a Scientific-common knowledge because opposing measures of common observation units are shared with the same label – without mentioning this diversity.

The second limitation is case specificity in terms of how we study and understand water security. There is a growing body of place-based research that investigates how water security is adopted, engaged, and implemented in various environmental and social contexts around the world. 21% of peer-reviewed studies published between 2010 and 2015 and dealing with water security are place-based cases (Gerlak et al., 2018). The persistent diversity in perspectives and applications of water security suggests that scholars adapt the concept to the contexts of the cases they are studying. Gerlak et al. (2018) found that 60% of the studies using a definition of water security offer a new

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definition, and thus are case-based. While this can suggest the need for a more community-context view to understand and realize water security, it might also suggest a limited generalizability of water security and hinder our knowledge of water security.

Finally, the third limitation of knowledge accumulation around water security focuses are static, or measuring cross-sectional, meaning that samples cover only one period of time (mostly a year). It prevents the study of water security evolution, and of SESs more generally. As an illustration, a significant strength of water security in comparison to Integrated Water Resource Management (IWRM) and nexus -competing concepts – is that water security is thought as a lever of development and transitions (Bolognesi and Kluser, 2018; Dadson et al., 2017). IWRM and Nexus consist mostly of refining an existing situation without any systemic change in most cases (Al-Saidi and Elagib, 2017; Wichelns, 2017). IWRM and nexus-based governance concepts are prone to institutionalizing the saturation of the SES. Regarding our institutional and cognitive model of change, we could assume that they frame integrative and entrepreneurial synchronous regimes mainly. Existing dataset prevent to test this core assumption which impedes to analyze the impact of social reforms on the ecological outcome of an SES.

3.2 Dealing with measurement disparity and evolution: recommendations to reinforce external and internal validity

To overcome methodological heterogeneity and case-specificity that constrain external validity of studies, we recommend to (1) enlarge the N of analysis; (2) carry out a replicable empirical strategy; and (3) include a time dimension. First, increasing the number of observations and cases automatically increase the external validity as it reduces to the case-dependency of results. In addition, it makes easier the identification strategy and to delineate impacts of contextual variables (climate, economic activity, etc.) from effects of explanatory variables (learning processes, institutional setting, resource uses, etc.). Ratajczyk et al. (2016) provide recommendations for large N studies focusing on SES. They identify seven prominent databases that contain SES or Commons related dataset. These datasets cover about 2000 cases, and coding strategies are all based on the SES or IAD framework, which limits inconsistency among studies.[4] The literature on water security should gain in developing this kind of common research practice and data sharing.

Second, replicable research design is a necessary condition for expending datasets over time, by adding new observations or variables and by facilitating merging dataset. The choice of raw data and coding strategy are critical. We recommend using data that are reliable, free and "protected" to ensure their accessibility over space and time. Coding strategy contributes to reach this goal. It should be clear, not case-dependent and easy to replicate over a large number of observations.

[4] Two important meta-database initiatives include (1) SESMAD, 2014. Social-Ecological Systems Meta-Analysis Database: Background and Research Methods. Available from: http://sesmad.dartmouth.edu/; and (2) Resilience Alliance and Santa Fe Institute. 2004. Thresholds and alternate states in ecological and social-ecological systems. Resilience Alliance. (Online.) http://www.resalliance.org/index.php/thresholds_database.

In this regard, automated-coding looks necessary. It is widely used to analyze the resource and its characteristics but remains rare and difficult in the study of institutions and actors relationships. Recent methodological progress in social sciences enables (semi) automated-coding of institutions-actors attributes. Heikkila and Weible (2018) study polycentricity across 11 Colorado oil and gas regulations by creating a dataset that links actor, rule, and the deontic categories of Ostrom's institutional grammar (Ostrom, 2005). In that way, they produce a convincing measure of polycentricity and other network attributes that could be transposed to the analysis of the rigidity trap. Discourse network analysis (Leifeld, 2013) techniques could be used to appraise the degree of institutional innovation and its diffusion to depict the logic of actions SES pathways of change (Renou and Bolognesi, 2018) and reorganization of an SES. Finally, inferential network analysis (Cranmer et al., 2017) methodologies permit tests of causality between these institutional characteristics and actor attributes with environmental outcomes in a pervasive manner. (Lubell et al., 2014) highlight the impact of geographical factors in an SES. Gerlak et al. (2018) confirm that space and scale play a critical role in the water security. As a consequence, SESs studies must have a spatial dimension and ideally include GIS information into databases. It is decisive to identify central actors, rules, context path-dependencies and scale-related non-linearity.

Finally, analysis of change necessitates including time-related variables like date, time lag, event history. While it seems to be a commonplace, it is not a trivial challenge. Methodologies to study ecological patterns in SES exist (Epstein et al., 2015, 2013; Janssen et al., 2007; Vogt et al., 2015) but measuring and observing social components over the years remains difficult. As a consequence, a very few studies manage with change over the time. Dadson et al. (2017) offer a first attempt to model feedback between water security, risk and economic growth. (Robinson et al., 2018) draw eight lessons from their experience in modeling coupled human-natural systems.[5] It is consistent with our previous recommendations: common language, open-access code, considering spatio-temporal mismatch, homogeneous units reveals indispensable. (Bolognesi and Nahrath, 2018) transpose qualitative materials into quantitative materials to study water resource regimes extent, coherence and integration over centuries. Coupling these types of analyses with environmental outcomes seems promising to the analyses of SESs evolution and the identification of global changes as exogenous shocks. Consequently, we recommend including a time-variable in each study even if the research is time invariant. This would facilitate future aggregations of existing studies and enable dynamic analysis of SES evolution.

[5] "*The following eight lessons were identified that if taken into account by future coupled human–natural-systems model developments may increase their success: (1) leverage the power of sensitivity analysis with models, (2) remember modelling is an iterative process, (3) create a common language, (4) make code open-access, (5) ensure consistency, (6) reconcile spatio-temporal mismatch, (7) construct homogeneous units, and (8) incorporating feedback increases non-linearity and variability.*" (Robinson et al., 2018, p.896).

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4 Earth Observations for Water Security: The Data Cube

We identify three primary methodological limitations to testing our institutional and cognitive model of change of SES. The case of water security studies highlights significant issues related to measurement heterogeneity, case specificity and static perspective. The Data Cube technology could help overcome current limitations and offer reliable avenues to test hypothesis about the dynamics of social-ecological systems and water security by combining spatial and time data with no major technical requirements for users.

4.1 Earth Observation data to consider the spatial dimension of SES and water security

Remotely-sensed Earth Observations (EO) data appears to be necessary materials to take into account the spatial dimension of water security, and SES in general. Acquired by satellites together with in-situ measurements, they are a source for effective, quantitative and integrated capabilities (e.g., social and ecological) to monitor trends and variability for social-ecological systems. Regarding water security, authors already scrutinize water quantity and quality (Lawford et al., 2013; Lehmann et al., 2014). With EO data, one can map and monitor water bodies. Optical and radar sensors help identifying changes in area and water quality information can be obtained by applying algorithms to retrieve information (e.g., total suspended matter, chlorophyll content) from water colour (Concha and Schott, 2016).[6]

One of the main advantages of using EO data is that it provides information at the pixel level and therefore it can be then aggregated or disaggregated according to ecological or social variables to ensure the spatial fit of the components of an SES. For example, a network of actors can be represented following its spatial perimeter and then can serve as the basic statistical unit from which pixel values can be aggregated and various statistical information can be derived using zonal statistics. Such an approach suits for analysis of spatial mismatch between actors, institutions and resource (Ingold et al., 2018), but with large N dataset which allows inferential analysis. As a consequence, the analysis is not framed by administrative boundaries but by the footprint of the variables of interest. In addition, this strategy of data collection could be use for treatment effect research design by allowing to test the treatment in space or over time. As an illustration, the impact of the institutional complexity trap on resource use could be tested robustly..

Two principal missions allow retrieving EO data related to water security. Firstly, the Gravity Recovery and Climate Experiment (GRACE) mission allows tracking anomalies of the Earth's gravity field and consequently extract information on groundwater resources. Secondly, the Soil Moisture and Ocean Salinity (SMOS) mission enables mapping soil moisture and can provide useful information for monitoring droughts and extreme events. Other information can be generated

[6] Usually, spatial resolution is about 10-30m ; and temporal resolution is about 5-15 days.

from EO data such as precipitation, evapotranspiration, land cover, snow, temperature, that are all important variables to monitor the water cycle (Lehmann et al., 2014). Usually EO data are processed to generate information products that describe real-world variables, and these products are in turn converted into evidence-based information for decision support (Giuliani et al., 2017b).

4.2 The data cube to make EO-based research replicable over time and space

Measurement heterogeneity and non-replicability are significant limitations to the study of SES dynamics. EO Data Cubes overcome these limitations. EO data, that are increasingly available from a number of freely and openly accessible repositories, can provide an efficient and effective mechanism to support water security monitoring. However, the full information potential of EO data has not been yet realized. They remain still underutilized mainly because of their complexity, increasing volume, and the lack of efficient processing capabilities (Lehmann et al., 2017). Consequently, new approaches are required to rapidly analyze data in a transparent and repeatable manner and to facilitate the transformation of large amounts of EO data into actionable information and decision-ready products (Giuliani et al., 2017b). Data cubes are part of these new approaches.

To tackle these issues and bridge the gap between users' expectations and current Big Data analytical capabilities, EO Data Cubes (EODC) are a promising solution to store, organize, manage and analyze EO data. The main objective of EODC is to facilitate EO data usage by addressing Volume, Velocity, Variety challenges, and providing access to large spatio-temporal data, for a given geographic area over a specified time period, in an analysis ready format (Giuliani et al., 2017a). EODC reveals to be a promising tool for analyzing SES dynamics and testing the institutional and cognitive model of change.

With EODCs, researchers could address the current methodological limitations enabling reliable and causal analysis of SES dynamics. It constitutes a data infrastructure offering: open access materials, systematic measurements and sample combination in a versatile format. As a consequence, it facilitates replicable empirical strategies, common measurements and enlarging sample size by including new geographic areas and new time periods. Because of the versatility of EODC, EO data can be merged with social data, we can build an integrative dataset of SES. For instance, with EODC, a discourse network analysis dedicated to grasp degrees of institutional innovation in learning process could be combined with water flows and water quality information over years.

There are four different technologies currently operational namely the Open Data Cube supported by Digital Earth Australia (Lewis et al., 2017), the EarthServer (Baumann et al., 2016), or the Google Earth Engine (Gorelick et al., 2017), and E-sensing (Maciel et al., 2018). These initiatives are paving the way to broaden the use of EO data to larger communities of users; they represent about 50 different implementations worldwide supporting decision-makers with timely and actionable information converted in meaningful geophysical variables; and ultimately are unlocking

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the information power of EO data. For example, the Swiss Data Cube holds currenlty 34 years of Landsat (1984-2018) and 3 years of Sentinel-2 (2015-2018) Analysis Ready Data (ARD)[7] over Switzerland (Giuliani et al., 2017a). This corresponds approximately to 7000 scenes for a total volume of 4TB and more than 110 billion observations that can be converted in different environmental variables (Figure 4).

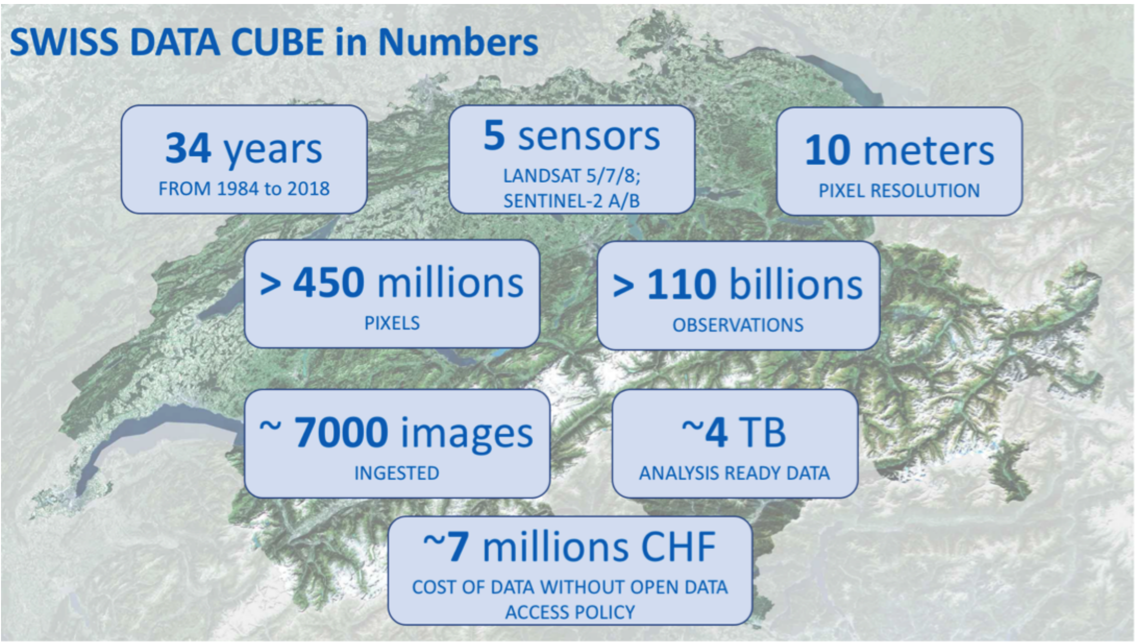

Figure 4: Swiss Data Cube in Numbers (as of October 2018)

Most of these EODC implementations are using Landsat data, partly because it is the oldest EO program.[8] In addition, since 2008 the entire data archive is freely and openly accessible (Wulder et al., 2012). This creates an unprecedented opportunities to use Landsat data in different contexts such as land cover changes, ecosystem mapping or water monitoring (Pasquarella et al., 2016; Tulbure et al., 2016). Besides Landsat, the Sentinels program, operated by the European Space Agency (ESA), forms another valuable EO data source. Sentinels are part of a satellite's constellation for the operational need of the European EO program called Copernicus. This two exhaustive sources favor establishing common, reliable and precise measurements that minimize the risk of missing data over time and space.

Among the major benefits of EODC is that it makes data analysis easier, facilitating data access and distribution and lowering the technical barriers for managing and processing large amounts of

[7] An essential pre-condition to support user applications and generating usable information products is to facilitate data access, preparation, and analyses. The systematic and regular provision of Analysis Ready Data (ARD) can significantly reduce the burden of EO data usage. To be considered as ARD, data should be processed to a minimum set of requirements (e.g., radiometric and geometric calibration; atmospheric correction; metadata description) and organized in a way that allows immediate analysis without additional effort. ARD correspond in optical imagery to surface reflectance products.

[8] It has been initiated in 1972 and provides continuous observations for more than 45 years.

EO data (Figure 5). Traditionally, satellite imagery is downloaded, processed and provided to users on a custom basis. This process serves a single purpose each time analyzing data locally (e.g., desktop computer) and downloading data on scene-based file. With the paradigm shift advanced by EODC information becomes available more rapidly, the burden of data preparation and usage is drastically reduced (Dhu et al., 2017; Lewis et al., 2017). Consequently, the widespread availability of EO data, the advent of Analysis Ready Data, and the large processing capabilities provided by High Performance Computing (e.g., clouds, clusters) allow envisioning supporting policy frameworks like the SDGs (Anderson et al., 2017). EODC can provide the long baseline required to determine trends, define present, and inform future, and thus provide a good fit between the analytical scope of SES evolution and empirical tests.

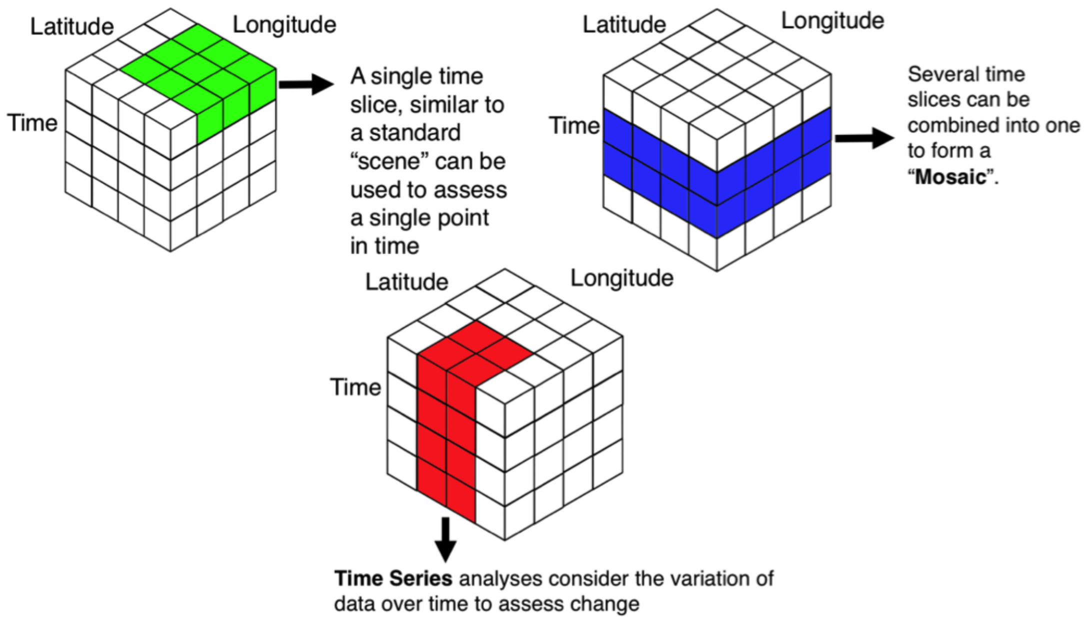

Figure 5: Sampling in a Data Cube (modified from B.Killough, 2018)

4.3 Avenues for implementing an analysis of water security dynamics through Data Cube

Currently, the most advanced EODC implementation is represented by Digital Earth Australia (DEA) that already developed some interesting information products related to water management. In particular, using the Water Observations from Space (WOfS) they map the presence and extent of surface water over the entire country using 27 years of Landsat observations (Lewis et al., 2016). It allows for flood risk assessment, agricultural water tracking, and mangrove monitoring. Similarly, Australia has developed an algal bloom early warning alert system informing the SDG 6 (clean water and sanitation). This initiative contributes to build common and replicable measurements of the water security ecological system.

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These measurements of the ecological system could then be combined with variables about the social system related to water security, namely institutions and actors. As an illustration, similar dataset as Heikkila and Weible (2018) about the polycentricity of regulation could advantageously be merge with ecological dataset. For instance, it enables to link characteristics of polycentricity with water quality. Then, because the dataset has a time dimension, it becomes possible to analyze patterns of change. For example, such approach can be used to determine the Water Security Index (WSI) (Gain et al., 2016) at various scales and over the times. Gain et al. (2016) used a quantitative and integrated (e.g. physical and socio-economic) approach to develop a spatial multi-criteria analysis framework. They measure water security as a function of 'availability', 'accessibility to services', 'safety and quality', and 'management'. The index is generated by aggregating indicator values on a pixel basis using an ordered-weighted average method allowing exploring the sensitivity of produced maps to different policy makers behaviors.

With EODC, it is possible to replicate the measure of Gain et al. (2016) with time coverage of several decades and to include general institutional variables in the dataset, such a count of water policies in each pixel. We could also focus on some given geographical area in order to have accurate measure of the social system. The former research design allows for testing structural patterns of SES evolution in the case of water security, the latter allows for specific hypotheses testing by offering a reliable identification of the causal mechanism we propose in our institutional and cognitive model of change.

5 Conclusion and next steps

Our contribution to the literature on SES is threefold. First, we provided an institutional and cognitive model of change to enable causal hypothesis on the evolution of SES. Second, we identified three methodological limitations preventing from reliable and generalizable results on the evolution of SES through an illustration of water security. Finally, we propose new tools through the Earth Observation Data Cubes to overcome these limitations and enable an easy combination of social and ecological data over space and time.

The institutional and cognitive model of change for SES, that we proposed, provides the adaptive cycle heuristics (Gunderson and Holling, 2002) with three institutional causal mechanisms about the saturation and the reorganization of a SES. We discuss how Rigidity Traps (Fath et al., 2015; Stedman, 2016) and Institutional Complexity Traps (Bolognesi and Nahrath, 2018; Bolognesi et al., 2017) drive the saturation of an SES until a crisis. Rigidity traps reduce adaptive capacity (i.e. the ability to explore alternative patterns) while institutional complexity traps reduce the ability to refine coordination mechanisms (i.e. the marginal effectiveness of new institutions). After a crisis, four ideal-types grasp the SES's diversity of reorganization patterns (Renou and Bolognesi, 2018). Transformative and resilient synchronous regimes are more likely to frame a rebound (Adger et al., 2005; Geels, 2010). We argued that learning processes are pivotal in defining the ideal-type of reorganization pattern that the SES is likely to follow (Heikkila and Gerlak, 2018). Learning mechanisms and capacities contribute to determine the level of innovation and its scope of diffusion in a reorganizing SES (Newig et al., 2016; Pahl-Wostl, 2009; Poteete et al., 2010).

This model of change offers many testable propositions but there are three main methodological limitations that prevent hypothesis testing and results-comparison. We highlighted these limitations using the water security case. They include: heterogeneity of measurement, case specificity and static perspective (Bolognesi and Kluser, 2018; Gerlak et al., 2018). These methodological limitations bound the external validity and reproducibility of research designs that address SES dynamics. We suggest three primary recommendations to overcome these limitations: (1) increase number of observations and the geographic scope; (2) provide replicable measurements regarding both data availability and method transparency; and (3) include time variables in the analysis – even in the case of panel dataset.

Finally, we put forward Earth Observation Data Cubes (EODC) as a promising avenue to address these methodological limitations and recommendations, and thus to contribute to a better understanding of SES dynamics. Earth observations enable focusing on the spatial dimension of SESs and water security, but they are difficult to perform. Data cubes provide Earth Observations through a handy interface, excluding complex technical knowledge from the users, and combine data over the years reduced (Dhu et al., 2017; Lewis et al., 2017). They make easier the combination of social and ecological data over a large number of observations and facilitate broadening the space and time coverage; which makes it a unique tool for testing generalizable propositions of SES change. Moreover, they enable the data structure fits with the theoretical unit of analysis. Indeed, the basic unit of EODC is the pixel, but then pixels could be aggregated according to the analytical needs (Giuliani et al., 2017b). It means the dataset is less dependent of administrative boundaries but could stick with the resource footprint for instance.

As next steps, we foresee two primary way to combine social and ecological datasets. The first way consists involves building a georeferencing social network and linking this with ecological system (Lubell et al., 2014). The second way is to give a spatial perimeter to institutions and to link this with the ecological system. This has been recently done to highlight spatial misfits (Ingold et al., 2018), but it could be used to analyze institutional complementarities, in relation with the institutional complexity trap mechanism, or mechanism of learning and diffusion to studies reorganization patterns in a dynamic way. However, with only four operational Data Cubes in Australia, Colombia, Switzerland and Taiwan (but with many more appearing[9]), there remain

[9] Recently, the African Regional Data Cube has been launched covering Kenya, Senegal, Sierra Leone, Ghana, and Tanzania. Other EODC are under development in Vietnam, Uganda, United Kingdom, Georgia and Moldova and more that 30 other countries have expressed interest. The long-term objective is to have continental or even global coverage.

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challenges to their extensive use. Further, harnessing the full potential of EO data for supporting informed decision-making on water security requires developing new algorithms (e.g., water related indices, aggregations methods) and tailored applications specific to the water security domain. Finally, we invite researcher to share their data in a common and free access repository to accelerate knowledge accumulation by favoring comparison, cross-analysis, and collaboration.

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