Social-ecological system approaches for water resources management

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In the era of the Anthropocene, understanding the dynamic interactions between humans and water is crucial for supporting both human well-being and the sustainable management of resources. The current water management challenges are inherently unpredictable and difficult to control. Social-ecological systems (SESs) approaches explicitly recognize the connections and feedbacks between human and natural systems. For addressing the complex challenges of the Anthropocene, consideration of SES attributes such as causality (or interdependence), feedback, non-linearity, heterogeneity, and cross-scale dynamics is important. In addition, innovative qualtitative and quantitative methods such as Bayesian networks, agent-based modelling, system dynamics, network analysis, multicriteria analysis, integrated assessment and role-play games have recently been used in SES research. The overall goal of this review is to gauge the extent to which SES attributes and methods are considered within the current interdisciplinary water paradigm. The paper therefore develops the normative theoretical characteristics of SES in terms of its key attributes (i.e. causality, feedback, heterogeneity, nonlinearity, and cross-scale dynamics) incorporated in the water paradigm approaches. The paper then compares the methods applied in the interdisciplinary water paradigm and examines how they can complement each other. Finally, the paper reflects back on the usefulness of SES attributes and methods for assessing the interdisciplinary water paradigm and makes recommendations for future research

Keywords: social-ecological systems (SES); attributes; methods; water management paradigms; feedback; non-linearity

Introduction

Humanity is said to have entered a new geological epoch, the Anthropocene, during which human activity has become the dominant influence on climate and the environment. Within earth systems, humans are changing the global water system in a significant way without adequate knowledge of impacts. In the past, the science-based command-and-control approach to water management (e.g., structural flood control) proved to be efficient for achieving short-term economic goals. Based on the assumption of predictable uncertainty (or stationarity) and reversible trajectories of change within natural systems, the goal of the command-and-control approach is to maximize resource exploitation by reducing natural variability through limited involvement of stakeholders. However, the conventional approaches that have worked in the past seem inappropriate to deal with the challenges faced in the Anthropocene — resource constraints, financial instability, religious conflict, inequalities within and between countries, and environmental degradation. Mounting evidence of the failure of conventional approaches to successfully address few contemporary water management challenges has led to a discourse around newly emerging water paradigms (Schoeman et al. 2014). According to Pahl-Wostl Claudia et al. (2011), a water management paradigm refers to a set of basic assumptions: the nature of the system to be managed; the goals of management; and the steps for achieving the goals.

In the era of Anthropocene, understanding the dynamic interactions between humans and water is crucial for supporting both human well-being and the sustainable management of resources (Ostrom 2009; Liu J et al. 2015). The recently developed Sustainable Development Goals (SDGs) of United Nations have considered the synergies and trade-offs among different targets and goals. The interconnectedness (or synergies and trade-offs) of water (SDG 6) and non-water (other SDGs) related targets cannot be achieved with traditional disciplinary approaches alone. Instead, inter- and trans-disciplinary approaches are necessary to address complex interconnections and to identify effective solutions to sustainability challenges. Social-ecological systems (SESs) approaches therefore explicitly recognize the connections and feedbacks between human and natural systems (Holling 2001). A social-ecological system (SES) can be defined as a coherent system of biophysical and social factors that regularly interact in an adaptive and sustained manner (Holling 2001). The core SES attributes include causality (or interdependence), feedback, non-linearity, heterogeneity, and cross-scale dynamics (Preiser et al. 2018; Reyers et al. 2018). For addressing the complex challenges of the Anthropocene, consideration of these SES attributes is consequently important.

In the field of water management, the current inter-connected challenges are inherently unpredictable and difficult to control. For addressing these challenges, the UN's Sustainable Development Goals (SDGs), especially SDG 6, encompass multiple 'wicked' water-related issues, including water pollution, climate change, transboundary water management, water consumption (UN 2017). For addressing these challenges, there is a paradigm shift occurring in water management globally, whereby practice has moved away from command-and-control (or technocratic) approaches towards more SES thinking such as integrated water resources management (IWRM), the water-energy-food (WEF) nexus, the Nature based Solution (NbS) and socio-hydrology (SH) (Pahl-Wostl C. et al. 2007; Di Baldassarre et al. 2013; Benson et al. 2015; Cohen-Shacham et al. 2016). These approaches can be considered an interdisciplinary water paradigm whose goal is to make decisions for generating a broader spread of benefits for people and ecosystems through integration of issues, sectors and disciplines. Although the interdisciplinary water paradigm considers SES thinking, no specific theory of SES, comprised of normative criteria for implementation, exists making comparative analysis of effectiveness problematic. In addition, several advanced methods (such as Bayesian networks, agent-based modelling, system dynamics, network analysis, multicriteria analysis, integrated assessment, role-play games, scenario building workshops) recently used in SES research have high potential for both analysing and implementing interdisciplinary water paradigm approaches. However, the extent to which these methods are applied within the new water paradigm is largely unknown.

The overall goal of this review is to gauge the extent to which SES attributes and methods are considered in the interdisciplinary water paradigm. The paper therefore develops the normative theoretical characteristics of SES in terms of key attributes (i.e. causality, feedback, heterogeneity, nonlinearity, and cross-scale dynamics) incorporated in the water paradigm approaches. The paper then compares the methods applied in the interdisciplinary water paradigm and examines how they can complement each other. Finally, the paper reflects back on the usefulness of SES attributes and methods for assessing the interdisciplinary water paradigm and makes recommendations for future research.

SES Theory: Key attributes of SES

New paragraph: use this style when you need to begin a new paragraph. The concept of SES introduces the idea of understanding humans and nature through an interdisciplinary approach in which both are interdependent, integrated, complex and interactively shaped by each other (Berkes and Folke 1998). Since the introduction of the SES framework by , the growing number of published articles on SES (from ~3,000 to >15,000) between 2007 and 2018 indicates the influential role of this concept in academia (Partelow 2018). SES, as a complex adaptive system consisting of ecological and social processes and components (Figure 1) that interact (e.g. causal interaction), creates feedbacks, reflects heterogeneity and nonlinearity and adapts through cycles over time and across multiple scales (e.g., cross scale dynamics) (Preiser et al. 2018; Reyers et al. 2018). Figure 1 depicts a revised (based on Kay et al. (1999); Reyers and Selomane (2018)) conceptual framework of attributes in SES. In general, SES consists of five main attributes (Figure 1):

- *Causality:* referred to as causation, assumes changes in one process or state is the reason for changes in another process or state. In SES science, causality often refers to interactions among the variables within SES;
- *Feedbacks:* this attribute goes beyond the interactions among the variables of SES to provide a deeper dynamic view in which interactive relationships create a loop where their outcome links back to the origin of the initial trigger for these interactions;
- *Heterogeneity:* reflects variability in SES in space and/or time. Temporal and spatial heterogeneity is recognized as an early warning indicator of tipping points in SES;
- *Nonlinearity:* is defined as the disproportionality of inputs and outputs, or a situation where the results of the interactions among the processes and states are not proportional over time and can lead towards a tipping point or multiple states in SES;
- *Cross-scale dynamics:* highlight the feedbacks and interactions across time and space. The social and ecological connections among multiple scales are key features of the spatial dimension of cross-scale dynamics. This may also include temporality in terms of a time lag, which integrates the idea of a slow or delayed response of SES, as there may be a substantial time difference between the action and outcome.

[Figure 1 near here]

Interdisciplinary methods in SES

To foster a better understanding of the dynamics and complexity of social-ecological interactions, a variety of assessments methods are now available. These assessment methods can broadly be categorized into two groups: quantitative and qualitative. Quantitative methods include data-based or statistical approaches (e.g., Bayesian networks) and simulation based approaches (e.g., agent-based modelling, system dynamics). Qualitative methods include participatory mapping and role-playing games. Both quantitative and qualitative approaches are used together in some methods e.g.: system dynamics modelling, network analysis, agent-based modelling, multi-criteria analysis/indicator-based aggregation, and integrated assessment/decision support systems/coupled model frameworks (Filatova et al. 2013). We have selected these assessment methods for assessing the social-ecological interactions, because: (i) they are useful for assessing the variety of SES perspectives described above; (ii) they represent different typologies i.e., quantitative, qualitative, statistical, simulation based. These methods have rich multidisciplinary conceptual and technical histories and they have benefitted from recent developments in computational and modelling advances (Kelly et al. 2013; Martin and Schlüter 2015).

Methods

The team of authors were selected based on their experience to the fields: (i) SES theory (ii) interdisciplinary methods and tools for SES research; (iii) interdisciplinary water paradigms (Integrated Water Resources Management, Water-Energy-Food Nexus, Nature based Solutions and Socio-hydrology). The team of authors on SES theory developed a normative criteria of SES theory which includes following key attributes: causality (or interdependence), feedback, non-linearity, heterogeneity, and cross-scale dynamics. Similarly, the authors who have expertise on SES methods and tools identified interdisciplinary qualitative and quantitative methods. After identifying key attributes and methods, we review each of the water paradigms (Integrated Water Resources Management, Water-Energy-Food Nexus, Nature based Solution and Socio-hydrology) to evaluate the extent to which SES attributes and methods are considered. The extent of SES attributes refers following qualitative criteria:

- Limited evidence (implicit): available studies suggest limited evidence that the SES attribute (e.g., causality, non-linearity) is implicitly considered in IWRM approach;
- Limited evidence (explicit): Available studies suggest limited evidence that the SES attribute is explicitly considered;
- Robust evidence (implicit): Available studies suggest strong evidence that the SES attribute (e.g., causality, non-linearity) is implicitly considered;
- Robust evidence (explicit): Available studies suggest strong evidence that the SES attribute (e.g., non-linearity) is explicitly considered

The extent of SES methods refers following qualitative criteria:

- Limited use: Available studies suggest limited application of SES methods;
- Widely use: Available studies suggest wider application of SES methods;

Each of the authors has expertise in the respective section and hence, the selection of article and evidentiary criteria are based on author's experience.

Interdisciplinary Water Paradigms

For addressing current water management challenges we consider following interdisciplinary water paradigms: Integrated Water Resources Management (IWRM), the Water-Energy-Food (WEF) Nexus, the Nature based Solution (NbS) and socio-hydrology (SH) (Pahl-Wostl C. et al. 2007; Sivapalan et al. 2012; Schoeman et al. 2014).

Integrated Water Resources Management (IWRM)

Integrated water resources management (IWRM) is integral to the emerging SES paradigm (Benson et al. 2015). The most commonly cited conceptualization is employed by the Global Water Partnership, in which IWRM:

'… is a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems' (GWP 2017).

However, IWRM remains essentially a contested concept, with multiple definitions and institutional applications (Benson et al. 2015). One reason is its disparate roots, with integrated forms of water management dating back centuries. Modern interpretations are traceable to the United Nations Conference on Water, Mar del Plata 1977 , with a commitment to holistic approaches to water management that inter alia involve assessment of resources, water use efficiency, environmental protection, pollution control, integrated resource use, public participation, river basin planning and transboundary cooperation. Further normative principles (e.g., participation of multiple actors including women, the economic value of water) were elaborated at the Dublin Conference 1992. Collectively, these principles have informed a diffusion of IWRM, promoted by global and supranational bodies including the United Nations, GWP, the OECD and the European Union (EU), resulting in 80 per cent of countries now engaging in implementation~~ bb b b ~~. This expansion of practice is recognized by Sustainable Development Goal 6, for ensuring access to clean water and sanitation. Target SDG 6.5 obliges states to 'implement integrated water resources management at all levels' by 2030. The widespread uptake of IWRM has resulted in multiple national interpretations~~ ~~. However, seven core features are universally prevalent: integration between water and land based resources use; river basin, or catchment as spatial scale; multi-level governance; public participation; economic valuation of water resources; equity in water access; and finally, environmental or ecological protection (Benson et al. 2020). All of these features are evident in the European Union's Water Framework Directive (WFD), one of the most recognizable IWRM systems. The WFD model is now influencing IWRM practice on a global scale (Fritsch et al. 2017).

Water-Energy-Food (WEF) Nexus

Water, energy and food security, highly important for society and economy, are closely linked (Olsson 2013). The Water Energy and Food Nexus acknowledges the links between water, energy and food in management, planning and implementation. Whereas IWRM tries to engage all sectors from a water management perspective, the nexus approach aims at treating the three issues – water, energy and food security, as equally important~~-~~. The Nexus approach has a lot in common with IWRM (e.g., multi-stakeholder involvement, assessment and management at river basin scale, demand management), with a new focus on security concerns (Cook and Bakker 2012), and on the opportunity to create sustainable business solutions for green growth, though public-private partnership (Benson et al. 2015). Hoff (2011) states that given the interconnectedness across sectors (water, energy and food), space and time, a reduction of negative economic, social and environmental externalities can increase overall resource use efficiency and sustainability. For example, searching for efficiency in the water and food nexus means finding the optimal combination amongst the main factors ruling the systems of crop and livestock production.

Nature based Solution (NbS)

Nature based solution (NbS) is an umbrella concept which also include ecosystem based adaptation (EbA) and ecosystem based disaster risk reduction (Eco-DRR).In order to address the challenges posed by the impacts of climate change and environmental adversaries, applications of the NbS, EbA and EcoDRR is gaining policy and action momentum across geographic and governance scales (Renaud et al. 2013; Cohen-Shacham et al. 2016). The Convention of Biological Diversity (CBD) therefore defines EbA as “the use of biodiversity and ecosystem services (ES) as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change” (CBD, 2009, p. 41). The definition embraces the idea of using ecosystem and natural components and services (e.g. water bodies and pollination) for promoting human capacities to adapt with the adverse impacts of climate change whilst Restores, maintains or improves ecosystem health (Zölch et al. 2018).

NbS, EbA, Eco-DRR, Natural Flood Management (NFM), and Ecosystem based Mitigation (EbM) are all based on the basic principle of using ecosystem’s resources and services, provide alternative pathways to existing structural and engineering-based adaptation approaches (Jones et al. 2012). In addition to use of ecosystem services, NbS encourages the use of local and external knowledge about ecosystems, recognizes the diversity of local situations and creates a facilitating environment for Ecosystem-based Disaster Risk Reduction (Eco-DRR), water resource management, natural resource management and ecosystem management. NbS, in particular, EbA is particularly known for its “no-regret” and cost-effective approach to adaptation. NbS is simultaneously believed to contribute to shaping the core components of local wellbeing by providing multiple social, physical, economic and environmental co-benefits such as food security, water security, biodiversity, income and recreation.

Socio-hydrology (SH)

Work in socio-hydrology has built upon a long history of work in three related fields. The first is water resources systems (WRS) analysis that started with the Harvard Water Program in the 1960s (Kasprzyk et al. 2018) where the focus has mainly been on decision support by following a normative (optimization) route. The second is the aforementioned IWRM, which was more geared to actual implementation, by: i) involving integration across the entire hydrological cycle; ii) accommodating different water users and including engineering, economic, social, ecological and legal aspects; while iii) accounting for multiple spatial scales, such as upstream/downstream perspectives. The third is the more recent development of inter-disciplinary frameworks exploring the mutual shaping of society and nature (including water), such as SES, coupled human-nature systems (CHNS), and complex systems science described in this paper.

Socio-hydrological phenomena consist of paradoxical outcomes, counter-intuitive dynamics or unintended consequences that arise in water management and governance. They include, for example, the safe-development paradox, or levee effect, which was first identified by Gilbert White as early as the 1940s (White G. F. 1945): see below. The paradox describes instances in which protection measures, such as levees, generate a false sense of security (Ludy and Kondolf 2012), and trigger urban or economic expansion in risky areas (Burton and Cutter Susan 2008). As a result, paradoxically, risk can even increase after building such structural protection measures (Di Baldassarre et al. 2013).

Comparing water management paradigms based on SES attributes

Integrated Water Resources Management (IWRM)

To an extent, IWRM considers SES attributes of causality, feedback, heterogeneity, non-linearity and cross-scale dynamics. A qualitative judgement based on available studies is shown in Table 1. With regards consideration of causality, IWRM systems are invariably based upon generation of scientific evidence of causal processes on which to base planning. The UN, for example, highlights understanding of water use problems and the role of science as a key step in its guidelines for IWRM. Characterization of the watershed for problem identification is also considered an important precursor to development of planning goals and solutions. River basin management planning requirements under the WFD also explicitly maintain that protection of water resources is dependent on controlling pollution sources. Causality for water pollution is therefore assumed to be human-induced, providing a basis for remedial action. Establishing causality as a first step in IWRM processes is therefore evident in multiple contexts worldwide.

[Table 1 near here]

Consideration of feedback in SES is also a feature of IWRM processes. Integrated forms of water management often incorporate learning on implementation outcomes through adaptive management as a means of addressing complexity and uncertainty (Halbe et al. 2013). The UN highlights the importance of a ‘spiral model’ of ‘iterative, evolutionary, and adaptive management’ for IWRM, evolving through time in response to changing SES circumstances. Integration of adaptive management and IWRM is, to varying degrees of success, visible in multiple contexts. The WFD also explicitly considers feedback through its requirement for the review and updating of river basin management plans, in six year cycles beyond its initial implementation period.

Heterogeneity of SES is generally encompassed by IWRM, although is not explicitly a focus. By providing a general set of generalized principles for water resource management which can be adapted to suit specific contexts, IWRM can theoretically account for differing ecological, social and cultural conditions, allowing for spatial heterogeneity. As such, IWRM principles have been promoted by international organizations and donor agencies across the developing South, resulting in multiple variants to the IWRM approach that arguably reflect localized SES. Even the WFD, which provides a relatively prescriptive blueprint for IWRM is founded on the principle of subsidiarity, whereby national governments have interpreted implementation to fit indigenous conditions (Benson and Jordan 2008). However, distinct variability in the success of IWRM highlights its weakness in terms of compatibility with local conditions. Technocratic, top-down IWRM institutions may not match local political or cultural contexts, leading some to challenge its relevance for developing countries or to seek ways of modifying them for practical application (Al-Saidi 2017).

Non-linearity is not an explicit focus of IWRM. However, the adaptive water management approach in IWRM considers non-linearity through a learning process, taking into account the outcomes of implemented measures, intended to be an iterative process, involving ‘learning to manage by managing to learn’ (Pahl-Wostl C. et al. 2007). However, non-linearity has limited evidence in the IWRM literature.

Cross-scale dynamics are only partially addressed by IWRM. Scaling of water management tasks to the river basin is an important feature of IWRM systems (Hüesker and Moss 2015). However, despite the flexibility offered by the approach discussed above, such scaling can result in spatial mismatches with other institutional and socio-economic scales, particularly external institutional drivers of SES impacts. A fundamental scale mismatch is evident between the river basin oriented WFD and agricultural policy, a significant influence on non-point source water pollution, which is decided at national and European levels but implemented at sub-basin scales (Fritsch and Benson 2013). Rescaling of decision-making via IWRM may additionally result in only limited redistribution of power to local actors (McNeill 2016). Inter-jurisdictional conflicts over water use present institutional challenges to IWRM in multiple contexts, including Europe, Asia and Africa (for example, Huitema and Meijerink (2014)). Moreover, transboundary aspects of IWRM highlight scale contradictions between water management decisions taken in respect of national sovereignty and protection of basin wide water resources. The temporal scale of SES management is similarly difficult to resolve with IWRM. Assessing the effectiveness of integrated water management is considered problematic over the short term due to the long time periods associated with ecological recovery, for example from non-point source pollution of groundwater (Benson et al. 2013).

Water-Energy-Food (WEF) Nexus

In general, approaches making reference to the WEF Nexus take into consideration the various SES attributes (i.e. causality, feedback, heterogeneity, non-linearity, and cross-scale dynamics) in their attempt to represent and model the interconnections among the elements of the three sectors, which are evidently elements of SES in the studied areas, which could have varying amplitude and multiple scales. A qualitative evaluation, based on available studies, is shown in Table 2.

[Table 2 near here]

Causality is indeed the very basis of any attempt to describe SES behaviour as a prerequisite for approaching management challenges, but also feedback loops and non-linearity are fundamental features of complex systems, such as SES. Their consideration allows WEF nexus modelers to explore non-linearity and emerging properties. Heterogeneity is considered differently depending on the preferred methodological approach. For example, it is specifically considered by multi-agent modelling, while it tends to be neglected by other approaches that prefer aggregation and averages.

The WEF literature is now flourishing, with many papers being published, ranging from epistemological considerations, to methodological ones, to the presentation of case studies at various scales. Wicaksono and Kang (2019), for example, present a model to simulate the WEF Nexus at the national level, with a focus on identifying the relationships between supply and demand, and the reliability of the resources. They adopt a system dynamics approach (Water-Energy-Food Nexus Simulation Model; WEFSiM), with a focus on analyzing changes in energy policy in South Korea and on investment planning in Indonesia. They propose an aggregated reliability index of resources allowing evaluation of feedbacks among the most important elements.

Hussien et al. (2017), in contrast, utilize a modelling approach at the household scale, by means of an integrated model, applied to the city of Duhok, Iraq. They adopt a bottom-up approach to their analysis based on system dynamics methods, to estimate WEF demand and water and organic wastes generated, also including consideration of the impact of change in users' behaviours in terms of diet, under the effect of varying income, family size and climatic scenarios.

In another example, Zhang X and Vesselinov (2017) develop an integrated, multi-period socioeconomic model called WEFO, for exploring the management of

WEF demands, based on productions costs, socioeconomic demands and environmental controls, which includes consideration of interrelationships and trade-offs among system components, and environmental impacts. The management objective of the WEFO model is to minimize the total costs generated in the WEF system as a sum of energy supply, water supply, electricity generation, food production, and CO2 emissions mitigation.

Nature based Solution (NbS)

Although the Nature based Solution (NbS) is relatively a new approach in general, it considers aspects of SES attributes i.e. causality, feedback, heterogeneity, non-linearity and cross-scale dynamics to different extents. One particular obstacle to assessing the SES attributes in the NbS approach is the lack of adequate case studies, particularly on water resource management. Based on this review, the reflection of SES attributes in NbS is summarized in Table 3.

[Table 3 near here]

This review is hugely benefited from the “Room for the Rivers” programme implemented in the Netherlands for adapting with flood risks. Literature from the project case studies and other similar projects, e.g. “Making Space for Water” in England, demonstrates explicit evidence of causality (Buuren et al., 2015). Worldwide river restoration projects using different NbS and NFM techniques (e.g. rewilding, channel widening) have achieved considerable successes in managing flood risks for human and agricultural production (Keesstra et al., 2018). Eco-engineering; an earlier application of working with natural ecosystem such as putting sand into natural currents in the Dutch coast for coastal defense was used to prevent coastal flooding and erosion (Keesstra et al., 2018). Similarly, landscape-scale restoration of local water cycles and water resources in the Rajasthan state of India generated desired effects of a flowing river with fisheries, heightened ground-water levels, increasing agricultural production and reversals to environmental migration (WWAP, 2018). These large-scale case study findings are also supported by the small-scale studies of NbS showing explicit consideration of causality in the NbS approach.

The NbS approach also demonstrates feedback mechanisms beyond causality, although, exemplary case studies on water resources are again somewhat limited. Based on the limited evidence available, successful implementation of NbS for water resource management including flood resilience, water quality improvement and groundwater recharge and urban drainage management produces a strong feedback loop, which, in essence, enhances the desired outcomes of projects as well as accelerating the social-ecological co-benefits. For example, the “Room for the River” project generated integrated outcomes of increased water safety and spatial quality whilst increasing biodiversity richness by 50% along the floodplain delta, while improving socio-economic and environmental condition. Other examples include, among others, creation of circular economy in contrast to the current ‘take, make, dispose’ model of production; extending multi-folding life expectancy of hydroelectric scheme in addition to reducing nutrient run-off and increasing farm productivity in Brazil; and improved natural ecosystems in Rhein Delta. However, unintended negative uncertainties for both human and natural systems, for example, Mediterranean reduced base flow of the river in the summer months ~~-~~for reforestation in the Mediterranean region or trapping sands by the oyster reefs in the Nethe~~a~~rlands, unintentionally hampering coastal defense through increasing erosion.

Attributes such as non-linearity and uncertainty are only evident in limited case studies, however, both are normative characteristics of ecosystems and nature. Climate change and other anthropogenic stressors are supposed to create negative consequences on human and natural systems. For example, the “Room for the River” project considered the climatic and hydrological uncertainties that could increase future flooding problems. As a response, NbS accommodate enough flexibility in their design and institutional structures so that such uncertainties can be proportionately accommodated. A flexible management structure allows local institutions to integrate complexities and adapt to future needs for adaptation through resource management.

The other important SES attributes of spatial and temporal heterogeneity and spatial-temporal cross-scale dynamics are not as empirically evident in the approach as causality, and feedback. It should be acknowledged that inadequate numbers of case studies do not allow us to make normative judgements about the implicit or explicit consideration of these attributes in NbS. However, NbS activities require time to mature and efficient to provide intended benefits whilst normatively, working across landscape scale is one of the basic NbS/EbA principles.

However, both cross-scale dynamics (spatial and temporal) are somehow implicitly addressed in NbS approaches for water management. Cross-scale dynamics are often associated with benefits but also undesirable uncertainties and impacts. In many instances, downstream communities and natural systems have benefited from NbS upstream measures aimed at flood control, biodiversity conservation and agricultural water management. For example, the Nairobi Water Fund restored Kenya’s Upper Tana Basin which provides 95% of Nairobi’s drinking water using different NbS strategies which then eventually benefited both upstream and downstream communities through improved water and soil quality, health and agricultural production (WWAP, 2018). Similarly, it is reported in England upstream NFM measures, e.g. river naturalization, significantly reduce flood risks for downstream communities. NbS interventions require longer timeframes to produce the desired benefits including changes of governance, as well as predominant mindsets favoring traditional measures. The attribute of “temporal” dynamics is implicitly integrated in NbS philosophy, however, cannot be conclusively demonstrated due to a lack of relevant case-studies.

Socio-hydrology (SH)

Some authors argue that socio-hydrology can be seen as a special case of SES research with an emphasis on water (Troy et al. 2015). Indeed, socio-hydrology is also based on the fundamental premise that natural systems and the social systems that use and depend on them are inextricably linked (Folke et al. 2010). Socio-hydrology focuses on how feedbacks within and across natural and human components lead to self-organization of SES into one of multiple stable configurations or regimes. There are, however, subtle and important differences between the two fields. Because of its roots in ecology and resilience thinking, SES studies place heavier emphasis on nonlinear, abrupt shifts in qualitative system behavior (i.e., regime shifts), thresholds that separate such regimes, and adaptive management of SES in the face of uncertainty (Cosens et al. 2018). In comparison, socio-hydrology is more interested in emergent phenomena arising from human-water interactions at regional or basin scale in the long-run and the feedback mechanisms that might explain the phenomena (Blair and Buytaert 2016). Further, because of the prevalence of human engineered controls in water systems, the role of physical infrastructure tends to be more clearly present in socio-hydrology studies compared to those of SES (although see Yu DJ et al. (2017); Tellman et al. (2018)).

Socio-hydrology emphasizes the role of feedbacks and causality (or interdependencies) between human and water systems. Over the last six years, much of socio-hydrology research has focused on the explanation of phenomena that have arisen from these feedbacks and interdependencies in the context of floods (Di Baldassarre et al. 2013; Di Baldassarre et al. 2015), droughts (Di Baldassarre et al. 2018), groundwater exploitation (Marston and Konar 2017), water quality degradation (Giuliani et al. 2016), land degradation (Elshafei et al. 2016), farming and agriculture development (Fernald et al. 2015), and water resources development (e.g.(Mostert 2018). Based on a review of these studies (e.g. Blair and Buytaert (2016)), while non-linearity is only implicitly considered in SH, there is limited evidence that spatial and temporal heterogeneity and cross-scale dynamics are implicitly considered in SH. The summary evaluation is shown in Table 4.

[Table 4 near here]

Comparing water management paradigms based on SES methods

Integrated Water Resources Management (IWRM)

Methods for assessing SES vary significantly within the broad conceptual framework of IWRM, although this can be discussed in relation to the WFD, watershed planning and integrated water management in the global South. Commonalities between them in mainstream approaches include quantitative integrated assessments and participatory methods for supporting adaptive management, although other methods are employed.

Article 5 of the WFD requires that analyses are undertaken of the characteristics of river basins, human impacts and economic analyses of water use to support river basin management planning. For assessing river basins the European Commission consequently recommends the Driver, Pressure, State, Impact, Response (DPSIR) analytical framework. This framework, originally developed for assessing SES by the Organization for Economic Co-operation and Development and the European Environment Agency, integrates quantitative analysis of causes and effects for each of its five components. The approach is now widely deployed for not only analyzing water bodies in the WFD implementation but also integrated management globally. Article 4

WFD also maintains that disproportionate costs of measures can provide an exemption for states in meeting ‘good status’ deadlines or allow imposition of less stringent water quality objectives, leading to use of Cost Benefit Analysis (CBA) or stakeholders’ financial liability assessments (Feuillette et al. 2016) . Finally, Directive Article 14 mandates the ‘active involvement of all interested parties’ in the river basin management planning process. States have undertaken this requirement through different public participation methods, including stakeholder consultation processes (Jager et al. 2016).

Watershed planning in the USA employs multiple methods. Under Section 319 of the Clean Water Act 1987, states must identify sources of pollution and implement a Nonpoint Source Management Program in order to receive federal funding for pollution remediation of watersheds. Nonpoint source pollution is calculated according to a Total Daily Maximum Load (TDML) for each river, which is then used to inform watershed planning. A TDML is calculated according to the maximum level of pollution permissible which enables a waterbody to meet national water quality standards. No single method is employed for determining TDMLs, with the EPA noting multiple techniques, ‘from simple mass balance calculations to complex water quality modeling approaches’, depending on waterbody, flow conditions and pollutants. Guidance on watershed planning also recommends a collaborative and participatory approach through involving stakeholders in plan development. Academic studies record a variety of participatory methods in practice, including participatory rural appraisal and focus group discussion.

United Nations guidance for implementing IWRM anticipates participatory and integrated assessment approaches but does not provide specific methods. Indeed, IWRM guidance from other global bodies tend to focus on providing normative principles rather than method specification. However, integrated assessment and participatory methods are highly visible across the developing South, depending on national or regional context. For example, an integrated, hybrid methodology comprised of fuzzy programming, interval parameter programming and a general one-dimensional water quality model was developed to support regional water planning in China (Fu et al. 2017). Numerous examples of public participation methods, both through formalized institutions and informal practices, are recorded in the literature on IWRM (Yu H et al. 2014).

Use of other methods for IWRM is recorded in the academic literature, although does necessarily inform official IWRM practice. Role play games have been developed to support decision-making in river basin management (Craven et al. 2017). To a lesser extent, multi criteria analysis is utilized, often in combination with other techniques such a games or public participation (see Aubert et al. (2018)). Bayesian network analysis has also been applied to integrated water management in various national contexts (Xue et al. 2017). Other forms of network analysis are prevalent in this literature, for example network mapping of SES in watershed planning (Sayles and Baggio 2017), social network analysis of social capital in collaborative planning (Floress et al. 2011), and analysis of SES policy networks and institutions (Lubell et al. 2014). The interdisciplinary SES methods that are used in IWRM practice and studies are shown in Table 5.

[Table 5 near here]

Water-Energy-Food (WEF) Nexus

Zhang C et al. (2018) analysed the state-of-the-art of methodologies in the field of the WEF Nexus, starting from terminological clarifications and ending up with the comparison of eight nexus modelling approaches, providing a guidance on the selection of appropriate modelling approaches: investigation and statistical methods; computable general equilibrium models; econometric analysis; ecological network analysis; life-cycle analysis LCA); system dynamics models; agent-based modelling; and integrated indexes.

Albrecht et al. (2018) point out that, notwithstanding the success of the Nexus paradigm as a conceptual approach, comprehensive operational applications have been so far limited. They thus reviewed methodological proposals for Nexus thinking by examining 245 journal articles and book chapters and found that even if nearly three-quarters adopted a quantitative approach, less than one-third of them presented reproducible approaches and quite often did not meet the ambitions of the nexus in terms of capturing the most important WEF interactions. Moreover, they show that social science methods are limited and many are confined to disciplinary silos, with only about one-quarter combining methods from diverse disciplines and less than one-fifth integrating both quantitative and qualitative approaches. They conclude by selecting a subset of promising proposals, supporting the idea that mixed-methods and transdisciplinary approaches are needed, together with adequate engagement of stakeholders and decision-makers.

In their study, McGrane et al. (2018) share the opinion that a comprehensive WEF nexus tool is still lacking, primarily because of limitations in both available data and understanding of WEF systems. In particular, they point out the need to invest in approaches to deal with the plurality of scales (e.g., spatial, temporal, institutional, jurisdictional), from household to national levels. They also affirm the need to engage stakeholders, in order to contribute to our understanding of nexus dynamics.

Kaddoura and El Khatib (2017) review Nexus approaches for supporting integrated decision making as a means to optimize synergies and manage trade-offs, by examining existing modelling tools. They found that the six tools examined focus in particular on the understanding of Nexus complexity at different time scales, with the main limitations evident in the extensive data requirements of current tools, and the capabilities for assessing individual Nexus areas.

Salmoral and Yan (2018) explore the potential of life cycle analysis (LCA) for understanding complex WEF interlinkages, by focusing on the food dimension, with consideration of the upstream virtual water and embodied energy in food consumption patterns in an English catchment, with consideration of the origin (local or imported) of products. By adopting an LCA approach, they develop the analysis of causality to include the consideration of virtual elements along the whole supply chain. The SES methods that are used in WEF Nexus studies are shown in Table 6.

[Table 6 near here]

Nature based Solution (NbS)

SES are located in different landscapes and serve different groups of stakeholders (Andrade et al. 2011). Therefore, it is imperative to adopt a multidisciplinary and multiagency working approach with institutions, involving multiple stakeholders to strengthen efforts for adaptation and increase community and ecosystem resilience (Wilby and Vaughan 2011). Huq (2016) therefore identify 18 institutional criteria for NbS/EbA implementation. Among them, stakeholder involvement and institutional collaboration are considered highly important for successful implementation of NbS. Participation of a wide range of stakeholders such as communities, local informal and formal institutions and NGOs is argued to ensure that institutions devise the most suitable environment for implementing adaptation (Grantham et al. 2011). Institutional collaboration facilitates stakeholder engagement and promotes shared learning through horizontal, vertical or inter-sectoral communication (Dixit et al. 2012).

In implementing the project “Room for the Rivers” in the Netherlands, stakeholder participation was widely used, mainly in the form of participatory workshops. Participation, interactive designing and planning workshops were together considered an important policy instrument, collectively known as the Design Ateliers (DESA). As pointed out by Busscher et al. (2019) “DESA are a form of interactive planning and design workshops where policy makers, project managers and stakeholders co-design, discuss and debate local challenges and possible solutions. Such an interactive collaborative approach is focused on finding common ground between the parties involved”.

Integrated assessment of system dynamics are widely used strategies in NbS and its different variations in order to devise locally and culturally applicable measures. Because of its localized nature, its suggested that NbS is preceded by in-depth assessment of social and ecological systems in which interventions take place. The pretext of integrated SES analysis is to allow operational and design flexibility in order to accommodate uncertainties, calculate trade-offs, identify internal system inter-dependencies and promote adaptive management of resources against environmental adversaries (Accastello et al. 2019). Uses of technical methods and models such as Agent-based modelling, Bayesian Approaches or network analysis in NbS are found in limitation studies (Terzi et al. 2019). Stakeholder participation is central to NbS success and therefore open discussion methods with limited technical inputs including a wide range of stakeholders remain the most widely used method (Rijke et al. 2012). The SES methods that are used in NbS studies are shown in Table 7.

[Table 7 near here]

Socio-hydrology (SH)

As shown by recent reviews of socio-hydrological models (Blair and Buytaert 2016), most of them are based on the system dynamics approach rather than network analysis and agent based modeling. These models have been proposed as explanatory hypotheses for feedback mechanisms generating one or more observed classes of phenomena. The explanatory model is a system dynamics (stylized) model, based on coupled differential equations (Di Baldassarre et al. 2013), which aims to explain in a generic manner a phenomenon often observed in flood risk studies, i.e., the aforementioned safe-development paradox. In the same way, a (place-based) conceptual model depicts the human-water dynamics in the Murrumbidgee River basin in eastern Australia, including competition between humans and the environment that underlies the pendulum swing back and forth phenomenon. Similar place-based models have been developed for the pendulum swing phenomena documented in Western Australia (Elshafei et al. 2016) and the Tarim basin in western China (Liu D et al. 2015). The SES methods used in socio-hydrology are summarized in Table 8.

[Table 8 near here]

Di Baldassarre et al. (2017), for instance, develop a system dynamics model by capturing cognitive biases at the individual level in the management of droughts and floods, inspired by the idea of the availability heuristic in behavioral economics (Kahneman and Tversky 1979). The evolutionary game theory captures the social dilemma of how individually rational behavior can lead to collectively irrational outcomes of poor levee maintenance as well as how the removal of short-term flooding can lead to erosion of people's compliance to informal rules that regulate the social dilemma and, ultimately, erosion of community resilience to floods. Finally, Gunda et al. (2018) investigate the water stress response of the Valdez acequia in New Mexico (a community managed irrigation system) by linking a hydrological model to the system dynamics model of an acequia developed by Turner et al. (2016). They focus on the role that community social structure, in particular mutualism, plays in the ability of the acequia to maintain its functionality. They found that, while agricultural productivity declined, the community was able to maintain its functionality under streamflow declines due to adaptations like shifting crop selection.

Conclusion

The cause-effect relationships are ambiguous and nonlinearity and feedback are inherent in complex water management. Specifically, the synergies and trade-offs of water and other targets of SDGs cannot be achieved without considering interactions and feedbacks. The lack of recognition of complex SES interaction causes or reinforces many of water resources management challenges. Important attributes of social-ecological systems such as causality, feedback, non-linearity, heterogeneity, and cross-scale dynamics are therefore useful for addressing the challenges of water resources management. The extent to which SES attributes are reflected in the interdisciplinary water managements approaches such as Integrated Water Resources Management (IWRM), the Water-Energy-Food (WEF) Nexus, the Nature based Solution (NbS) and socio-hydrology (SH) is discussed in section 5 and summarized in Figure 2.

[Figure 2 near here]

Robust explicit evidence for causality (or cause-effect relationships or interdependencies between social and ecological sub-systems) is found in the IWRM and socio-hydrology literature. However, the evidence is robust but only implicit for causality in the WEF Nexus and NbS literature. In Socio-hydrology, feedback is explicitly considered with robust evidence, but the evidence is only robust and implicit in the IWRM and NbS literatures. Limited explicit evidence is found in published WEF Nexus research. Limited but explicit evidence of the SES attribute of non-linearity is evident in each of the four interdisciplinary water management approaches. Robust implicit evidence for heterogeneity is found only in the WEF Nexus literature, while limited evidence is found in the IWRM, NbS and Socio-hydrology literatures. Finally, an important SES attribute, cross-scale dynamics, is not well considered in interdisciplinary water management approaches.

The levee-effect and reservoir effect are two examples of feedback in water resources management. The levee effect (White G. F. 1945) refers to the construction of levees for reducing the frequency of flooding but can increase low frequent catastrophic flooding. Many societies build levees to protect floodplain areas and therefore reduce the frequency of flooding. This encourages human settlements in floodplain areas, which are then vulnerable to high-consequence and low-probability events. This has led to a complex web of interactions and feedback mechanisms between hydrological and social processes in settled floodplains (Di Baldassarre et al. 2013). Thus, the process of constructing levees often leads to a shift to potentially catastrophic flooding. Similarly, the reservoir effects (Di Baldassarre et al. 2018) refer to cases where over-reliance on reservoirs increases vulnerability, and therefore increases the potential damage caused by droughts. Without considering feedback mechanisms in both levee and reservoir effects, more damage can be expected by using traditional water management approaches.

Due to climate change and development pressures, non-linearity is present in complex water management, where a small change in one variable leads to a sudden transition or non-proportional change in the dependent variable. As a consequence, water resources management tends to be less predictable than linear systems. Heterogeneity and cross scale dynamics are essential for managing complex water resources problems. The dynamics and interactions across different scales, for example, spatial (e.g., river basin) and jurisdictional domains (e.g., national or intergovernmental) play crucial roles in water management. In the Anthropocene, the local is no longer local and the global is not just global, but, rather, is shaped by broader social-ecological dynamics and drivers (Reyers et al. 2018).

Cash et al. (2006) identified three main challenges related to heterogeneity and cross-scale dynamics: (i) ignorance – the failure to recognize important scales and their interactions together; (ii) mismatch – the persistence of mismatch between levels and scales in social-ecological systems; (iii) plurality – the failure to recognize heterogeneity in the way that scales are perceived and valued by different actors. A failure to consider these important SES attributes within interdisciplinary water management approaches could lead us to apply the wrong decision to a given problem.

In order to consider SES attributes in complex water management approaches, interdisciplinary methods and tools are needed. The methods and tools that are used in water managements are described in Section 6 and summarized in Figure 3. Participatory workshops are widely used in IWRM and NbS. System dynamics are widely used for the WEF Nexus, NbS and socio-hydrology, while, integrated assessments are widely used in IWRM, WEF Nexus and NbS. Other important methods and tools such as role-playing games, multicriteria analysis, network analysis, agent-based methods and Bayesian approaches are not widely used in interdisciplinary water management but feature in academic analyses.

[Figure 3 near here]

Our review suggests that important SES attributes such as non-linearity, heterogeneity and cross-scale dynamics are still not considered widely in the interdisciplinary water management approaches. In addition, innovative qualitative and quantitative methods such as role-playing game, multicriteria analysis, network analysis, agent-based model and Bayesian approach are not applied widely for addressing complex water problems. Therefore, a rethinking and reframing is needed to consider these SES attributes and methods for addressing complex water problems.

Acknowledgement

All authors would like to acknowledge anonymous reviewers and the editor. AK Gain is financially supported by EU funded Marie Curie Individual Fellowship (Project No. 787419). All authors equally contributed to the manuscript.

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Tables

Table 1. Reflection of SES attributes in Integrated Water Resources Management.

Table 2. Reflection of SES attributes in Water-Energy-Food Nexus.

Table 3. Reflection of SES attributes in Nature based Solution (NbS)

Table 4. Reflection of SES attributes in socio-hydrology

Table 5. Reflection of SES methods in the IWRM literature

Table 6. Reflection of SES methods in WEF Nexus literature

Table 7. Reflection of SES methods in Nature based Solution (NbS) studies.

Table 8. Reflection of SES methods in socio-hydrology studies.

Figures

Figure 1. Attributes in social-ecological systems (based on Reyers and Selomane (2018)).

Figure 2. Summary reflection of SES attributes in the water management approaches

Figure 3. Summary reflection of SES methods in the water management approaches