Mapping the Landscape of Water and Society Research: Promising Combinations of Compatible and Complementary Disciplines

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Conflict of Interest

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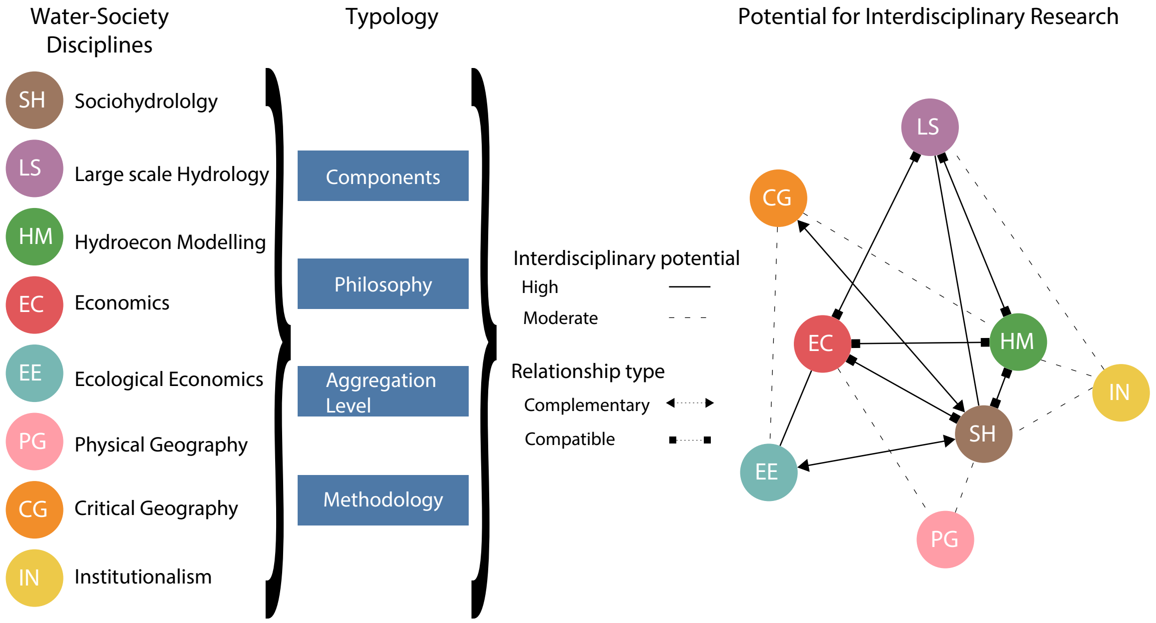
Abstract

Coupled human-water systems (CHWS) are diverse and have been studied across a wide variety of disciplines. Integrating multiple disciplinary perspectives on CHWS provides a comprehensive and actionable understanding of these complex systems. While interdisciplinary integration has often remained elusive, specific combinations of disciplines might be comparably easier to integrate (compatible) and/or their combination might be particularly likely to uncover previously unobtainable insights (complementary). This paper systematically identifies such promising combinations by mapping disciplines along a common set of topical, philosophical and methodological dimensions. It also identifies key challenges and lessons for multidisciplinary research teams seeking to integrate highly promising (complementary) but poorly compatible disciplines. Applied to eight disciplines that span the environmental physical sciences and the quantitative and qualitative social sciences, we found that promising combinations of disciplines identified by the typology broadly reproduce patterns of recent interdisciplinary collaborative research revealed by a bibliometric analysis. We also found that some disciplines are centrally located within the typology by being compatible and complementary to multiple other disciplines along distinct dimensions. This points to the potential for these disciplines to act as catalysts for wider interdisciplinary integration.

Graphical/Visual Abstract and Caption



Caption: A typology identifies promising combinations of disciplines for interdisciplinary research on water and society by mapping them along a common set of topical, philosophical and methodological dimensions.

1. INTRODUCTION

Coupled human-water systems (CHWS), where human activities and water resources interact dynamically in space and time, arise in a wide variety of settings that include flood protection (Di Baldassarre et al. 2013), agriculture (Giuliani et al. 2016; Grafton et al. 2018), urban water supply (Savelli et al. 2021; Srinivasan et al. 2013), catchment hydrology (Srinivasan et al. 2015; Van Emmerik et al. 2014) and transboundary water interactions (Penny et al. 2021; Mullen et al. 2022) among many others. This diversity of contexts has allowed CHWS to be studied by a wide variety of disciplines, which is both an opportunity and a challenge. It is an opportunity because complementary perspectives allow insights that could not be obtained by individual disciplines. For instance, hydrology, economics, and political ecology respectively describe the hydroclimatic drivers, misaligned incentives, and structural inequities that were simultaneously at play in Cape Town in the late 2010’s, before the city’s water reserves were depleted (see Box 1). Yet, understanding how these processes interact and compound to create the severe water crisis now known as “Day Zero" requires a process of interdisciplinary research, where concepts, methods or epistemologies are not only exchanged but comprehended by all parties to result in a mutual enrichment (Choi 2006). A comprehension of CHWS that is both specialized (e.g., how hydroclimatic drivers, misaligned incentives and structural inequities arose in Cape Town) and holistic (e.g., how these three processes are influencing each other) is necessary to generate actionable insights that address the systemic and operational issues that are often jointly at the root of an impending water crisis.

The need for interdisciplinary integration has long been recognized in the water research community, as seen in the variety of recent initiatives aiming to bridge disciplinary boundaries (Di Baldassarre et al. 2019; Brown et al. 2015; Vogel et al., 2015; Ross and

Chang 2020). Yet, despite notable successes in combining specific disciplines that have proven to be particularly *compatible* (e.g., hydrology and data science, Razavi et al. 2022), interdisciplinary integration continues to be an enduring challenge. This challenge has been particularly salient for disciplines whose perspectives on CHWS are the most *complementary* and prone to provide the most transformative insights. For example, a few exceptions notwithstanding (e.g., Savelli et al. 2021; Rusca et al. 2017), interdisciplinary research combining the physical environmental sciences and the critical social sciences is rare; and yet viewing water as both an environmental process and a socio-cultural vector can unveil crucial new insights, for example on the social justice implications on water security crises, and more recently on more-than-human (waste)water, soil and sediments waterscapes (de Micheaux, Mukherjee, and Kull 2018; McClintock 2015; Rusca et al. 2022; Hurst, Ellis, and Karippal 2022)). This tension between compatibility and complementarity, and the general barriers and requirements for interdisciplinary research, have been insightfully discussed elsewhere (e.g., Oughton and Bracken 2009; Rusca and Di Baldassarre 2019; Wesselink, Kooy, and Warner 2017; Lélé and Norgaard 2005). In particular, Wesselink, Kooy, and Warner (2017) argue that increased attention to knowledge paradigms and their four constitutive components (ontology, epistemology, axiology and methodology) is critical to find common grounds for interdisciplinary collaboration. However, these recommendations have yet to be operationalized to systematically identify combinations of disciplines that are particularly promising for interdisciplinary research and, more importantly, to characterize *how* these disciplines are complementary and compatible as a starting point to realize this potential. The typology presented in this paper seeks to fill this gap.

This paper accompanies and complements an ongoing community effort to synthesize progress during the Panta Rhei 2012-2022 Scientific Decade of the International Association of

Hydrological Sciences (IAHS). As part of that effort, the disciplines listed in Box 2 are presented in a synthesis book (Müller et al, 2024) with sufficient background to serve as a primer for anybody seeking to gain basic literacy in any of the related disciplines. Here, we complement that effort by focusing on the typology that we developed to organize and relate the different disciplines in the synthesis book. We discuss the potential to support interdisciplinary research in CHWS by identifying promising combinations of disciplines that are compatible (i.e. disciplines that can be mobilised together or combined without conflict) and complementary (i.e. disciplines that are potentially mutually enhancing) along different dimensions of the typology. Section 2.1 presents the four primary dimensions of the typology (topical focus, philosophy, aggregation and methodology) and applies them to map the eight disciplines in Box 2. Section 2.2 describes the metrics used to evaluate the compatibility and complementarity of disciplines across these dimensions. Section 2.3 describes a large (N>11,000 papers) bibliometric analysis of recent collaborative research papers that we use in Section 3 to discuss the compatibility and complementarity outcomes of the typology. Section 4 concludes by discussing the typology's potential, both to identify low hanging fruits for future collaboration and to address key barriers to particularly promising – but unlikely -- interdisciplinary collaborations. The typology that we propose points to key philosophical and methodological challenges for research teams involving researchers from multiple disciplines to elucidate in order to leverage these low hanging fruits as catalysts for actionable CHWS research.

Box 1: Interdisciplinary perspective on Day Zero

In 2018, the city of Cape Town experienced a severe water security crisis that became known as Day Zero and nearly caused the municipal water system to run out of water. Although triggered by a prolonged meteorological drought affecting the Western Cape region between 2015 and 2017, Day Zero emerged as a manifestation of a long-term historical process, where early investments in large water storage infrastructure allowed water availability to become increasingly decoupled from climate variability (Garcia, Ridolfi, and Di Baldassarre 2020). This fostered economic growth but also encouraged unsustainable water use and, paradoxically, decreased resilience to extreme droughts in a phenomenon known as the reservoir effect (Di Baldassarre et al. 2018). Within the city, the legacy of colonization, segregation, and neo-liberalisation caused the crisis to be experienced very differently across the city's social and racial divides. Although the experience of upper- and middle-class populations, whose lifestyle was threatened by water restrictions, was strongly emphasized in the media, the crisis disproportionately affected the water security of lower-class neighborhoods and informal settlements, where available coping options were severely limited (Savelli et al. 2021; Enqvist and Ziervogel 2019). The above example illustrates the tight interactions that often relate humans to water. Water flows are continually reshaped by social and economic relationships that they themselves contributed to create in a coevolutionary historical process. These complex temporal and spatial dynamics gave rise to the poorly resilient and unequal water security landscape of Day Zero.

2. Methods

2.1 Typology Dimensions

Our typology builds on the concept of interdisciplinary distance, that is the extent to which two disciplines rely on common assumptions about the nature of knowledge and acceptable way of accumulating it (Choi and Anita 2008). Such common grounds make collaboration across disciplines that are epistemologically close comparatively straightforward. Yet it is from the crossroads of epistemologically distant disciplines that the most insightful knowledge can arguably be gained, thanks to the multiplicity of perspectives at hand (Choi and Pak 2007; Rusca and Di Baldassarre 2019). Building on Wesselink et al (2016), we extend this concept beyond epistemology and define interdisciplinary distances along four primary dimensions that span what we believe are key features of disciplines studying CHWS: their topical focus, their philosophical paradigm (here consisting of their epistemology and axiology), their level of aggregation and their methodology. These dimensions, and their respective axes, have been identified within the context of the Panta Rhei synthesis effort first through electronic surveys within the multi-disciplinary author team of the book chapter that this paper builds on and complements (Müller et al 2024), and then through extensive consultation within the broader community of contributors to the synthesis effort (>100 authors). Each primary dimension is discussed in the following paragraphs with application to the eight CHWS disciplines in Box 2. Section 2.2 then discusses quantitative metrics to characterize the interdisciplinary distance between the disciplines within the two or three-dimensional spaces associated with each primary dimension.

Three caveats are important to note from the onset. First, the disciplines in Box 2 were selected based on their inclusion in the Panta Rhei synthesis book (Müller et al, 2024). While they span the environmental, and quantitative and qualitative social sciences, and represent a wide variety of approaches to study coupled human-water systems, these disciplines are by no means exhaustive but are constrained by the range of expertise available within the authors team. Second, we use the term ‘discipline’ within the context of this paper to represent families of approaches that are located at identical positions within the typology. This definition may not map one-to-one to traditional scientific fields. For example, different subfields of hydrology (e.g., socio-hydrology and large scale hydrology) occupy distinct locations within our typology and are therefore distinguished as separate disciplines. Conversely, distinct fields within the broad umbrella of the critical geographies (e.g., political ecology, environmental justice or hydrosocial science) use comparable conceptual outlines to examine human-water interactions and therefore have an identical location within our typology. Third, the short description of each discipline given in Box 2, and the typological mapping described in the following paragraphs, represent our own interpretation. While we root this interpretation firmly in an extensive review of the literature, it remains subjective and we refer the reader to the online platform discussed in Section 2.2 to revise it as they see fit.

Box 2: Considered disciplines

Socio-hydrology (SH): Subfield of hydrology seeking to understand the coevolution between hydrological and social systems across spatial and temporal scales. Key references: Murugesu Sivapalan, Savenije, and Blöschl (2012); M. Sivapalan and Blöschl (2015); Pande and Sivapalan (2017); Murugesu Sivapalan (2015)

Hydro economic modeling and water systems analysis (HM): Engineering discipline focusing on the analysis of water systems and the quantitative modeling of socio-economic and water resources interactions in order to guide water management or policy. Key references: Harou et al. (2009); C. M. Brown et al. (2015); Kasprzyk et al. (2018); Pablo Ortiz Partida et al.(2023).

Large scale hydrology and land surface models (LS): Subfield of hydrology seeking to predict the spatial distribution of water resources at a large (regional to global) scale and its evolution through time under climatic and anthropogenic forcing. The category includes large scale hydrological models used for water resources assessments and land surface models used to represent the terrestrial component of fully coupled earth system models. Key references: Pokhrel et al. (2016); Wada et al. (2017).

Economics (EC): Quantitative social science that generally relies on utility maximization principles to understand how agents (individuals, households, farmers, firms, and institutions) make decisions that can influence water systems, and vice versa. Focus areas concerned with water resources include agriculture and resource economics, environmental economics, general equilibrium, development economics, health economics and political economy. These subfields respectively consider water in the context of non-market valuation, economic production, household income, public health and externalized costs. Key references : Hanemann (2006); Dinar and Tsur (2021); Müller and Levy (2019).

Physical geography and the spatial sciences (PG)**:** Set of approaches treating the social-physical co-created space as the core object of interest. Frameworks from physical geography and the spatial sciences generally seek to map the landscape, and understand its emergence, by collecting, analyzing and modeling geolocated information about water resources, human-built infrastructure and the communities served by them. The category includes agent based models, geographic information systems, environmental geography and geospatial analysis among others. Key references: Gaile and Willmott (2004).

***Ecological Economics and Social Metabolism (EE)*:** Interdisciplinary field focused on characterizing energy and matter (including water) exchanges between societies and their environments, and on understanding the implications of these flows for the structure and function of both socioeconomic and ecological systems. The category includes social metabolism, water footprint accounting, and virtual water among others. Key references: Daly (2000); Giampietro et al. (2014); Madrid, Cabello, and Giampietro (2013); Hoekstra (2011).

***Institutionalism (IN)*:** Interdisciplinary school of social science focusing on the justice, sustainable, efficient and effective management of common pool resources -- which can include water -- as rival and non-excludable goods. Of particular interest are the challenges of designing cooperative institutions, managing information and resolving conflicts. The category includes the socio-ecological systems (SES) and the Institutional Analysis and Development (IAD) frameworks which both arose within the Workshop for Political Theory and Policy Analysis under the leadership of Elinor Ostrom. Key References: Elinor Ostrom (1990); Schlager and Cox (2018).

***Critical geography (CG)*:** Set of critical social science paradigms that generally consider water and society as part of a single integrated socionatural system, continually reshaped by power choreographies. They posit that researchers are themselves part of that system, meaning that they are both influencing and influenced by the system that they are studying. Critical geography also emphasizes how different cultures, religions and societies attribute different meanings and values to water. The category includes a variety of paradigms, such as Political Ecology, Hydrosocial Cycle, Multiple Ontologies of Water and Water Justice, among others. Key references: Bryant (1992); Boelens et al. (2016); Sultana (2009); Swyngedouw (2004); Linton and Budds (2014) Zwarteveen and Boelens (2014).

2.1.1. Dimension 1: Starting point

The first dimension concerns the topical focus *(*or ‘starting point’ in Wesselink, Kooy, and Warner (2017)) of the disciplines in their approach to CHWSs. Conceptualizing CHWSs in terms of constitutive components (humans and water) and domains of dynamic interactions (time and space) allows us to define two axes along which to organize the disciplines.

Broadly speaking, the first axis tends to separate disciplines rooted in the environmental versus social sciences (Figure 1A, x-axis). On one end of the spectrum, Large Scale Hydrology (LS) generally integrates human processes (e.g., irrigation withdrawals) with the explicit purpose of improving hydrological predictions. Conversely, Critical Geography (CG) studies often take power relations governing water governance at different scales as the entry point of their analysis. Hydrological principles are mobilized with the explicit purpose of better understanding the associated social processes and uneven outcomes. Most disciplines lie between these ends of the spectrum. For example, Hydroeconomic (HM) and Sociohydrologic (SH) models are rooted in water management and hydrology but also seek to predict and optimize social and economic variables (e.g., welfare, costs or resilience), in addition to environmental ones. Similarly, Economics (EC), Ecological Economics (EE) and Institutionalism (IN) often consider social processes (e.g., incentives, supply chains and institutions) from the perspective of resource sustainability and/or environmental conservation.

The second axis (Figure 1A, y-axis) distinguishes disciplines that predominantly focus on the temporal versus spatial dynamics of water-human interactions. HM and SH often represent system components as potentially multiple, spatially lumped, entities and focus on characterizing their response to time-varying (generally stochastic or non-stationary) climate or anthropogenic forcing. This places these disciplines on the temporal side of the axis, whereas, in contrast, Physical Geography (PG) and Ecological Economics (EE), e.g., studies mapping social metabolism (Huang et al. 2013) or virtual water flows (Lenzen et al. 2013), often predominantly focus on the spatial dynamics of fluxes and stocks, whether virtual water, energy or people.

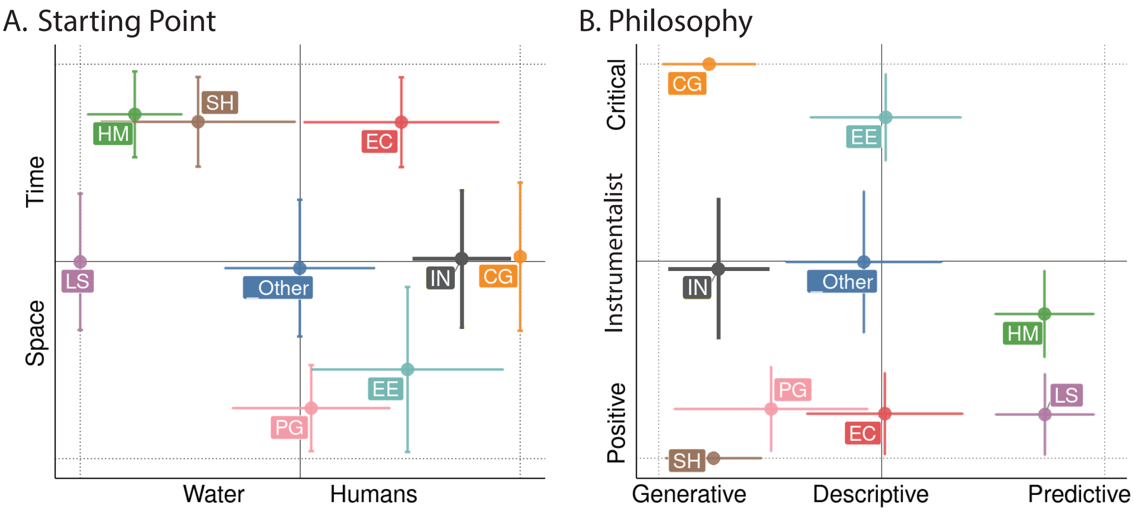


Figure 1. Typology dimensions 1 and 2: Starting point and philosophy. Symbols and error bars for each discipline represent their mean location and standard deviation across N=1000 Monte Carlo simulations. Discipline acronyms are defined in Box 2.

2.1.2. Dimension 2: Philosophical paradigm

The second dimension concerns the *philosophical paradigm* of the discipline as described in its epistemological (‘what can we know about the world?’) and axiological (‘why should we gather knowledge’ and ‘what should we do with the knowledge?’) tenets. This dimension is conceptualized as a pair of orthogonal axes, each containing three discrete categories.

The first axis portrays the knowledge-action paradigm of each discipline and is discretized into *positive, instrumentalist* and *critical* approaches. The distinction between positive and instrumentalist approaches is an axiological one. Positivist approaches (e.g., socio hydrology) “seek to understand the dynamics of coupled human-water systems, as opposed to normative (here referred to as instrumentalist) approaches (e.g., water systems analysis) aimed at solving concrete water management problems" (Pande and Sivapalan 2017). This distinction broadly separates the sciences that seek to test theoretical hypotheses (SH, PG, EC, LS) from the engineering and policy fields that seek to address specific management problems, whether through system optimization (HM) or institutional design (IN). Rather than fixing a specific water management problem, Critical Geography (CG) scholars use a commitment to social justice, unsettling oppressive power structures and the promotion of transformative social change as starting points to critique the way water management problems are framed in the first place (Blomley 2006; Painter 2000; Mustafa and Halvorson 2020). These approaches, which we refer to as *critical*, are also distinguished by their epistemological view: they hold that the researcher is an integral part of the system that he/she is studying, so the knowledge that they gather is situated and what they perceive as the optimal solution to the problem, or indeed their very framing of the problem itself, can be subjective and therefore critiqued (see Wesselink, Kooy, and Warner 2017). This critical stance is a defining characteristic of CG. It is also often adopted within EE through critiques of market-based assumptions and arguments about the incommensurability of values and the need for non-monetary valuation tools (Martinez-Alier, Munda, and O'Neill 1998).

The second axis -- *epistemic perspective* -- determines whether the knowledge is predominantly gathered to predict the future (*Predictive*), describe the present (*Descriptive*) or understand the current state of the world by studying its past evolution (*Generative*). Predictive disciplines often include scenario analysis to characterize the response of CHWS to counterfactual climate or anthropogenic forcings. For example, LS models have been used to predict future water availability under climate change using different representative concentration pathway (RCP) scenarios (Pokhrel et al. 2021), and HM models have been used to evaluate the effect of alternative management options on future hydroclimate resilience (Brown et al. 2012; Kryston et al. 2022). Descriptive disciplines might similarly focus on policy evaluation, but often from an ex post perspective using observational data (e.g, Cabello Villarejo and Madrid Lopez 2014 for EE). Finally, generative studies use historic analysis to either explain current paradoxical phenomena (e.g., "levee effect" in HS, Di Baldassarre et al. 2013), understand the emergence of current issues (e.g., water injustice in CG (Zwarteveen and Boelens 2014; Sultana 2018) or draw lessons learned to improve current practices (e.g., common pool institutions in IN, E. Ostrom 1965).

2.2.3. Dimension 3: Level of Aggregation

The third dimension concerns the level of aggregation of the discipline. Here we distinguish disciplines that view CHWS as two systems (humans and water) that are coupled but distinct from each other. These disciplines generally seek to represent the lump state of each system and its spatial and temporal dynamics as they interact with each other (Fig 2A negative y axis). For example, SH and HM often represent CHWSs as dynamic systems with coupled differential equations representing the time variations of spatially lumped state variables. In HM and EC, these state variables might also be formulated in the context of a maximization problem seeking to optimize the system according to one or more objectives describing its aggregate state. In contrast, other disciplines view CHWS as a single integrated 'socionatural' continuum, in which the 'socio' and 'natural' elements cannot be separated or even distinguished (Linton and Budds 2014). As a corollary, these disciplines generally focus on characterizing heterogeneities within that system (Fig 2A, positive y axis). For example, the political ecology or water justice frameworks within CG predominantly focus on describing and addressing inequities and asymmetrical power dynamics within a hydrosocial continuum

(Ranganathan and Balazs 2015; Boelens et al. 2022; Hommes et al. 2018; Correia 2022). Similarly, EE and PG describe heterogeneities and patterns in terms of resources and fluxes (e.g., water, energy, money, power or people), either across the integrated CHWS system or across the physical space.

The distinction between a focus on aggregate or disaggregate outcomes in the spatial domain can be extended to the temporal domain. Some disciplines predominantly focus on describing the time- aggregate state of a system. For example, water footprint assessments of, say, food production within EE often represent time-averaged crop water use within a given period and do not account for inter-annual variations associated with climate variability (Tuninetti et al. 2017). In contrast, other disciplines focus on time disaggregated behavior, for instance by seeking to characterize the robustness and resilience of systems to extreme events (HM, Reed et al. 2022).

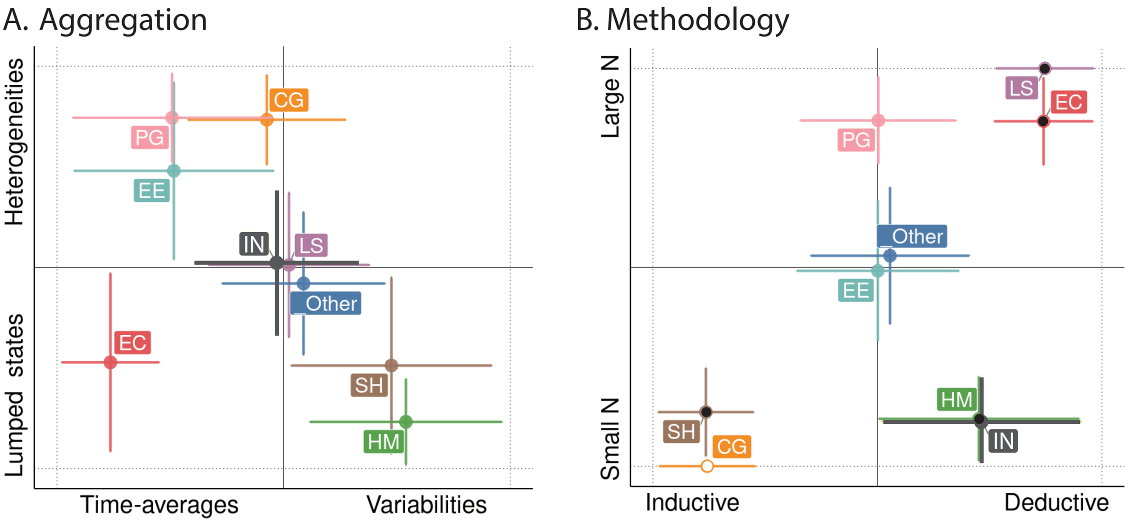


Figure 2. Typology dimensions 3 and 4: Aggregation and Methodology. Symbols and error bars for each discipline represent their mean location and standard deviation across N=1000 Monte Carlo simulations. Discipline acronyms are defined in Box 2. On Panel B (Methodology), black and white symbol colors indicate

disciplines that are predominantly quantitative and qualitative, respectively. Any other color indicates disciplines that are neither predominantly quantitative nor qualitative.

2.1.4. Dimension 4: Methodology

The final dimension concerns the methodological characteristics of the discipline, which determines how knowledge is being gathered. Here the distinction operates along three axes. The first relates to sample sizes and differentiates between disciplines focusing on a small number of case studies or a large statistical sample. Broadly speaking, the former focuses on the specificity of each CHWS and seeks to elucidate its constitutive causal relationships. Small sample studies generally work under the assumption that observations are determined by the unique contextual setting of each case, from which they can hardly be decoupled (see, e.g, (Beven 2000). This approach is prevalent in CG, IN and HM, where the local context plays a key role in determining the relationships between humans and water, the institutions that regulate these relationships and the infrastructure settings that optimize their outcome. Small sample studies are also prevalent in SH, where the process of generating transferable theoretical insights from place-based observations has long been discussed as a major challenge (Pande and Sivapalan 2017; Müller and Levy 2019; Bertassello, Levy, and Müller 2021). In contrast, large sample studies generally focus on similarities across individual CHWSs. They generally rely on statistical analyses to evaluate persistent CHWS relationships (whether causal or correlational) that hold ‘on average’ across a large number of contexts (Addor et al. 2020). These statistical relationships might be used for inference and hypothesis testing (EC) or for model validation (LS, PG , Galán and López-Paredes 2009). These so-called “small-N” and “large-N” approaches have been alternatively described as Newtonian vs Darwinian in the hydrology literature (e.g., Harman and Troch 2014) and put the emphasis on internal (causality) and external (sample representativeness) validity, respectively.

The second axis differentiates between disciplines where deductive or inductive reasoning is the norm. Broadly speaking, deductive reasoning uses theory to generate predictions that are then validated against empirical data (LS, HM) or, alternatively, to generate hypotheses that are then tested against empirical evidence. This latter approach is favored by disciplines (such as IN and EC) where policy evaluation takes a central role: theoretical frameworks are used to design policy which is then evaluated using causal empirical inference (Müller and Levy 2019). In contrast, inductive reasoning uses empirical analysis to identify patterns that are then explained through theory development. This approach is favored by disciplines such as SH (Troy, Pavao-Zuckerman, and Evans 2015) and CG (Meehan et al. 2023), where theory is often developed through the synthesis of place-based empirical studies. Finally, the third axis differentiates between disciplines relying primarily on qualitative (CG), quantitative (SH, EC, LS and HM), or mixed methods.

2.2. Interdisciplinary distances

2.2.1. Position and uncertainty

We assign a compatibility score and a complementarity score for each pair of disciplines according to their relative position in the spaces corresponding to each primary dimension of the typology (Figure 3). The axes corresponding to each primary dimension are normalized between -1 and 1 and each discipline is placed at any of the three possible integer positions (-1, 0, 1) for each axis. For example, disciplines focusing on the spatial and temporal dynamics of coupled human water systems will be respectively placed at -1 and 1 on the corresponding axis. Disciplines ascribing approximately an equal weight to temporal and spatial dynamics will be placed at a value of 0 on that axis. This system allows a very diverse set of disciplines to be systematically positioned and compared, but offers a somewhat reductionist perspective on each discipline. First, each discipline is clearly made up of a diverse set of studies that are unlikely to map to the same location in the typology. Second, each researcher might have a different subjective opinion on the location of their discipline that may differ from that of our author team. We address these two challenges -- diversity and subjectivity as follows.

We mitigate the diversity challenge by assigning to each discipline a set of discrete probabilities along each axis, rather than a deterministic position. We assign a weight w_i to each integer position $i \in \{-1,0,1\}$ on each axis based on three parameters (mode μ, minimum m and maximum M) that we determine for each discipline to represent its central tendency and range for that axis:

$$w_i = \begin{cases} 1 & if\ i \in [m, M] \\ 2 & if\ i = \mu \\ 0 & otherwise \end{cases}$$

For example, infrastructure operations that hydro-economic models seek to optimize are often set to address *time* variations in water availability (floods and droughts) and demand (Harou et al. 2009). However, in some cases water system outcomes are governed by *spatial*, rather than temporal, dynamics (Mullen et al. 2022). HM might therefore be represented as $\{w_{-1},w_0,w_1\} = \{2,1,1\}$ on the time-space axis of the *"Starting point"* dimension of the typology. The probability P_i associated with each position i is then obtained as

$$P_i = \frac{w_i}{\sum_i w_i}$$

We use a Monte Carlo method to propagate the uncertainty on the position of each discipline in the typology. This distribution is visualized on Figure 1A for HM, where the symbol is squarely in the upper quadrant of the graph ('time') with an error bar representing the standard deviation of the Monte-Carlo generated distribution around its mean value. At each run, we (1) generate an independent instance of position $i \in \{-1,0,1\}$ for each discipline along each axis of the typology according to the corresponding probabilities; and (2) compute the compatibility and complementarity scores between each pair of disciplines as described below. We finally compute the ensemble-mean compatibility and complementarity scores across the N=1000 runs of the Monte Carlo analysis.

We mitigate the subjectivity challenge by encoding the typology into an interactive web-based tool that is openly accessible at https://mfmul.shinyapps.io/TypologyOfDisciplines/. The tool can be used to adjust weights w_i for combinations of dimensions and disciplines and observe the ensuing effect on the compatibility and complementarity scores (Figure 3A). Broadly speaking, we find that the qualitative results discussed in Section 3 are robust to small deviations from the default weights provided in Table S1.

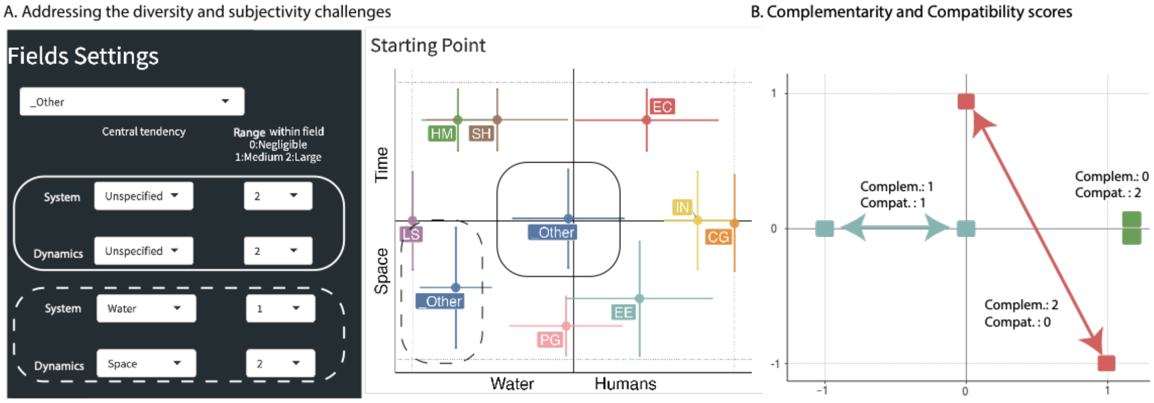


Figure 3. A. Illustrative use of the interactive webtool to affect the location and error bars of disciplines within the typology. In the plain circles, a fictitious "other" discipline is placed at a central point along the "starting point" dimension (system and dynamics are "unspecified") of the typology with large uncertainties represented by a range (M - m) of 2. The dashed circles, the fictitious discipline is located at the lower left quadrant of the dimension (system: water, dynamics: space) with a lower level of uncertainty (spread=1) associated with the

"system" axis. **B.** Examples of determination of complementarity and compatibility scores based on the relative location of disciplines within a dimension of the typology.

2.2.2. Compatibility and complementarity scores

The compatibility score $S_{//}\in[0,1]$ is intended to represent the topical, philosophical, aggregational and methodological overlaps between two disciplines. For each primary dimension, we define the compatibility score as the proportion of secondary dimensions along which the two disciplines 'overlap' (i.e. they are separated by a distance of zero). Two disciplines located at the exact same position in the space corresponding to a primary dimension of the typology will have a maximum compatibility score of 1. The compatibility score will be 0.5 if two disciplines have the same position along one of the two axes of the primary dimension, and zero if they do not share any common coordinates (Figure 3B).

The complementarity score $S_{\perp}\in[0,1]$ is intended to represent the extent to which two disciplines cover the typological space that we associate with each primary dimension. We define it for each primary dimension as the maximum normalized distance between two disciplines along any of the secondary axes. Accordingly, two disciplines located at the same position in the space will have a complementarity score of zero. Two disciplines located at opposite ends of one of the axes will take a complementarity score of 1, no matter their location along the other axis (Figure 3B). Our metric for $S_{\perp}$ allows for the axis along which two disciplines are most complementary to be specifically identified for each dimension of the typology. We believe this has high practical value by allowing multi-disciplinary teams to identify specific dimensions for which interdisciplinary research has the highest potential. This axis-specific information would be lost by more common distance metrics (e.g., the Euclidian distance) that aggregate coordinates from all axes.

Compatibility ($S_{//}$) and complementarity ($S_{\perp}$) scores are computed independently for each of the four primary dimensions of the typology, which are then averaged to obtain overall values of $S_{//}$ and $S_{\perp}$ for each combination of disciplines. As before, computing $S_{//}$ and $S_{\perp}$ separately for each dimension has the practical benefit of allowing key barriers to, and areas of potential for, interdisciplinary research to be identified.

Overall scores were finally obtained as the average between $S_{//}$ and $S_{\perp}$ for each combination of disciplines. This implies that complementarity and compatibility are weighted equally within the context of this analysis. This is, of course, a subjective choice that we believe is the most parsimonious approach. Nevertheless, alternative weights that ascribe a higher virtue to either of the two characteristics can be assigned in the interactive web-based tool ("Score Weight" slide bar at the bottom of the side panel on the left hand side).

2.3 Bibliometric analysis

The outcomes of the typology are discussed in relation to a large bibliometric analysis of historic research collaborations. We obtained paper references from Clarivate's Web of Science database through separate queries for each of the eight disciplines using the keywords provided in Table S2. We restricted our search to peer-reviewed research papers published in the English language, excluding preprints, conference proceedings, book reviews and meeting abstracts. We aggregated the output of each query to obtain a final database of 11,885 papers, 8,633 of which have been published in the 2012-2022 period. Each paper is assigned a "home" discipline based on the particular query that identified it, i.e. all papers appearing in the query corresponding to "SH" in Table S2 are assigned to the discipline of sociohydrology, and so on. About 1.7% of papers appeared in two or more of the eight queries, in which case one of the corresponding disciplines was assigned randomly. The sample of papers represents 29,021 distinct authors, 23,287 of which have published queried papers in the 2012-2022 period. We assigned to each author a "home" discipline based on the query containing the highest number of their papers. For example, M. Rusca appears on 9, 3 and 1 papers in the queries corresponding to CG, SH and EC respectively and is therefore assigned CG as a home discipline (which corresponds to her self-identified affiliation). About 2.3% of authors have equal numbers of papers in two or more disciplines, in which case one of the corresponding disciplines was assigned randomly. After assigning a discipline to each author and paper, we characterize interdisciplinary collaboration by computing the proportion of papers in each discipline that include authors from other disciplines. Note that this outcome-focused metric uses co-authorship as a sole measure of interdisciplinary success. This is undoubtedly reductionist and fails to capture important outcomes of interdisciplinary research beyond publications -- a caveat that needs to be kept in mind while interpreting the results. We focused on the set of papers published during the 2012-2022 period, which corresponds to the IAHS Panta Rhei scientific decade (Montanari et al. 2013).

3. Results and discussion

The outcomes of the typology mapping for the disciplines in Box 2 are displayed on Figure 4A. The boxplots represent the distributions of overall scores for each discipline, which vary between 0.5 (or 50%) and 63% for all considered interdisciplinary combinations. This narrow range is not surprising perhaps, as disciplines that are less compatible intuitively tend to be more complementary. Nonetheless, the value of the typology lies in the non-linear nature of that tradeoff along the different dimensions of the typology: disciplines that are simultaneously compatible along some dimensions and complementary along others are particularly propitious for interdisciplinary collaborations. Consequently, the remainder of the discussion focuses on the relative disparities between the scores attributed to different combinations of disciplines, rather than seeking to interpret their absolute value. Accordingly, the size of pies corresponding to each combination of disciplines on Figure 4A were scaled to match the range of total scores in the boxplots and represent the relative affinity between disciplines. Section 3.1 discusses the extent to which this affinity predicted by the typology matches historic patterns of interdisciplinary collaborations revealed by the bibliometric analysis. The relations between disciplines within the typology and the respective contribution of compatibility and complementary characteristics across its dimensions (colors in the pies of Figure 4A) are discussed in Section 3.2.

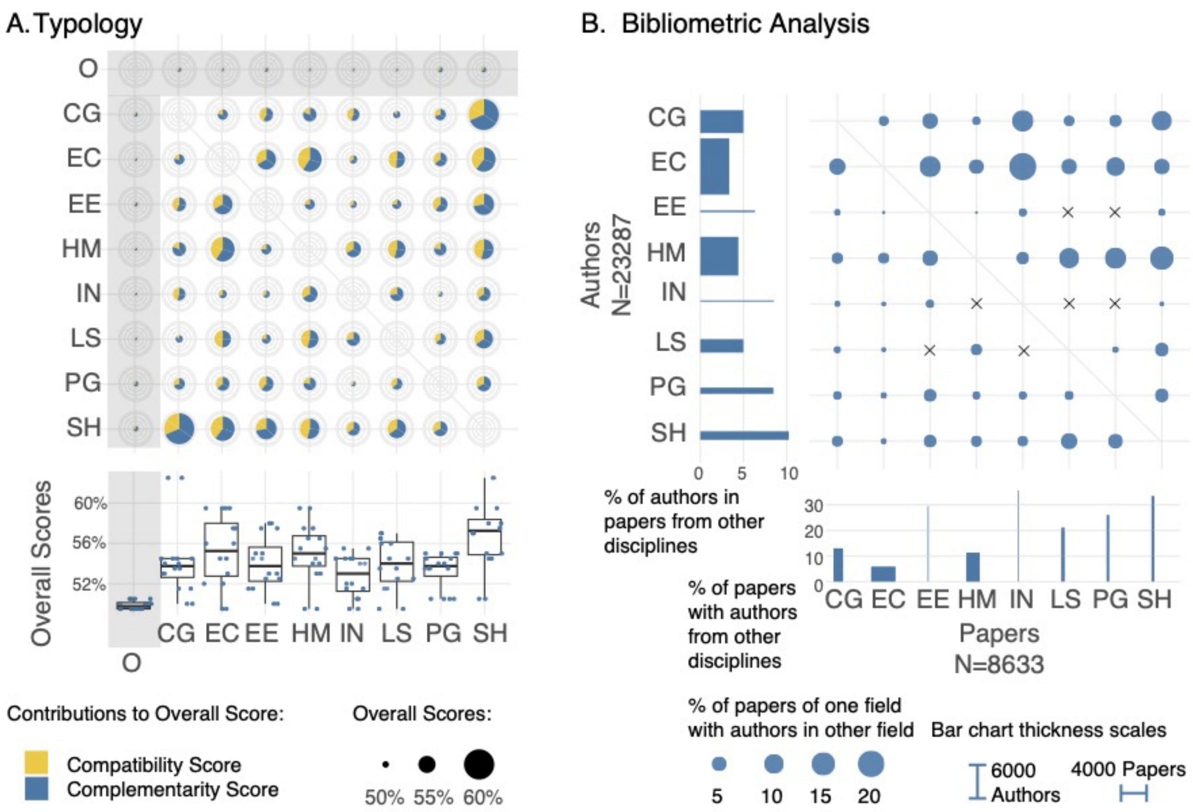


Figure 4. A. Outcome of the typology classification. Boxplots represent the distribution of overall scores associated with the combinations between each discipline and all the other disciplines. Pie sizes represent overall scores (scaled between 0.5 and 0.65) for each combination of discipline, with colors representing the respective contributions of the compatibility and complementarity scores. Combinations with an additional fictitious discipline located at the center of each dimension in the typology are highlighted in gray. **B.** Results of the bibliometric analysis of interdisciplinary papers published in each of the 8 disciplines between 2012 and 2022. Vertical bars represent the proportion of papers from each discipline with authors from other disciplines; horizontal bars represent the proportion of authors from each discipline who co-author papers in other disciplines. Thickness of bars are proportional to the number of authors (horizontal bars) or papers (vertical bars) sampled for each discipline. Symbol sizes represent the proportion of papers in each "column" discipline with authors from the "row" discipline. Cross symbols represent a proportion of zero. Discipline acronyms are defined in Box 2, with the exception of "O", which represents a fictitious "other" discipline located at the center of the typology (see Section 3.2).

3.1. Typology predictions and past interdisciplinary research

Results of the bibliometric analysis are displayed on Figure 4B. Vertical bars represent the proportion of papers in each discipline that include at least one author from another discipline during the 2012-2022 period. Horizontal bars represent the proportion of authors from each discipline who have served as co-authors on papers in other disciplines during the 2012-2022 period. Symbol sizes represent the proportion of papers in each discipline (columns) that include authors from other disciplines (rows).

Comparing Figures 4A and B suggest a broad consistency between predictions from the typology and outcomes of the bibliometric analysis. Both analyses point to SH as having the highest average level of affinity with the other disciplines (Fig 4A, boxplot) and the highest propensity for recent interdisciplinary research, both in terms of publishing in papers hosted in other disciplines (Fig 4B, horizontal bars) and including authors from other disciplines in SH publications (Fig 4B, vertical bars). Care must be taken in interpreting these absolute results, however, because the analysis is limited to the 8 particular disciplines in Box 2. These disciplines might have a high affinity with other disciplines that have been omitted from the analysis, so a comparatively lower average affinity in Figure 4 does not mean a lower absolute affinity for interdisciplinary research. This limitation is less likely to affect the *relative* levels of affinity between individual combinations of disciplines that were included in the analysis. Indeed, patterns of symbol sizes within individual columns of Fig 4A also parallel corresponding patterns in Fig 4B, suggesting that the relative affinities between disciplines predicted by the typology is consistent with historic patterns of collaborations, measured in terms of the number of authors from other disciplines that participate in papers from each discipline. Comparing the ranking of symbol sizes within each column for the theoretical

(Figure 4A) and empirical (Figure 4B) outcomes yields a median Spearman correlation coefficient of 0.52 (Quartiles: 0.21, 0.73) across disciplines. For example, consistent with the typology in Figure 4A, interdisciplinary co-authorship to SH papers is dominated by authors from CG and, to a lesser extent, HM and EC (Fig 4B, last column) with comparatively little participation by authors from IN. In the social sciences, participation in EE papers is dominated by EC with almost no participation by LS and IN (Fig 4B column 3).

Beyond these broad similarities, there are specific differences between the typology prediction and bibliometric analysis that are important to point out. These differences are not surprising and arise from the fact that factors other than the theoretical affinity considered in the typology determine the feasibility of interdisciplinary research. Some of these factors are rooted in the historic evolution of the disciplines. For example, IN and EE exhibit high levels of interdisciplinary integration, both in terms of the propensity for their own authors to participate in papers in other disciplines, and in terms of the inclusion of authors from other fields in their own papers. Yet (according to our typology) neither field has a comparatively strong theoretical affinity for interdisciplinary research with other disciplines in Box 2, or has authors contributing to a substantial share of papers in other disciplines (Fig 4B, rows 3 and 5). Both disciplines emerged within the last 50 years and evolved in association with journals (e.g., Ecological Economics) and workshops (e.g., the Ostrom workshop at Indiana University) that are themselves interdisciplinary with researchers predominantly from CG, EC and HM. As a result, an outsize number of researchers contributing to IN and EE are rooted within -- and predominantly publish in -- these three fields (Fig 4B columns 3 and 5). As a corollary, a comparatively small number of researchers publish a predominant number of their papers in IN or EE and were attributed these fields as their “home” discipline, hence the narrower horizontal bars in Figure 4B.

Structural norms within disciplines and institutions are also well-known barriers to interdisciplinary research (Boden and Borrego 2011). For example, the typology identifies EC as having a high potential for interdisciplinary research with an average affinity score second only to SH (Fig 4A boxplots). This prediction is consistent with the fact that EC authors participate in a substantial share of papers from other disciplines (Fig 4B, row 2). Yet these contributions can be traced to a small subset of authors, as the overall share of EC authors participating in interdisciplinary research is the smallest among the 8 considered disciplines. Similarly, the share of EC papers that include authors from other disciplines is the smallest among the considered disciplines. These results echo previous findings about the propensity for economics to simultaneously serve as a source of interdisciplinary knowledge for other disciplines while not building substantially on insights from them (Pieters and Baumgartner 2002). They also reflect strong disciplinary norms incentivizing publication in a small number of disciplinary journals, with comparatively much smaller weights placed on interdisciplinary publications for promotion and tenure evaluations (Heckman and Moktan 2020; Jaeger et al. 2023). While perhaps extreme in economics, structural barriers to interdisciplinary research are certainly not unique to that field. A pattern that is comparable to EC also emerges for HM in our results, namely a high potential for interdisciplinary research outlined by both the typology and contribution to research in other disciplines, and yet a comparatively low rate of participation to interdisciplinary research both in terms of authors and papers. The isolation of these disciplines might also be partly attributed to power dynamics at play within academic and policy circles that restrict or de-incentivize the large potential for EC and HM to contribute to interdisciplinary research. For instance, academic culture and water practitioners tend to value quantitative methods and economic assessments over qualitative methods and socio-political analyses (see for instance Budds, 2009; Zwarteveen et al., 2017; Rusca and Di

Baldassarre, 2019), placing disciplines like EC and HM in a position of power. Qualitative social sciences, on the other hand, are often marginalised (Seidl et al. 2017; Hesse-Biber, 2010; Connelly and Anderson, 2010). These types of power asymmetries are often reproduced in interdisciplinary research projects, where qualitative social sciences are at times placed in a "service" (Viseu, 2015, p. 291) or "end-of-pipe" role (Lowe, 2013 p. 207). The large untapped potential for an increased contribution of EC and HM to CHWS knowledge could perhaps be leveraged with more explicit structural incentives for interdisciplinary research within these fields.

3.2. Compatibility and complementarity across typology dimensions

The typology is based on the premise that combinations of disciplines that are compatible along some of its dimensions, while being complementary along others, have a particularly high affinity for interdisciplinary research. To characterize this tradeoff and its implications for the disciplines in Box 2, we conceptualize the typology as a network with links characterized by the degree (described as the quantile of overall score) and type (complementarity vs compatibility) of relationship that it assigns to each combination of disciplines. This network is depicted in Figure 5 for the overall score representing the general affinity between the disciplines (panel A) and the specific score corresponding to each of the four dimensions of the typology. Dashed and plain edges represent significant relationships with scores higher than the median and 75th percentile (respectively) of all 45 possible combinations of discipline pairs. The subset of solid links with arrows or square symbols respectively represent significant relationships that are either mainly complementary or compatible, which occurs when either the complementarity or the compatibility score (but not both) is higher than its corresponding 75th percentile. For the purpose of this analysis, the network in Figure 5 also contains a fictitious 9th discipline in addition to the 8 disciplines in Box 2. This additional discipline (labeled "O" as "other" in Figure 5 and Figure 4A) is located at a central location within each dimension of the typology and serves as a baseline in the discussion.

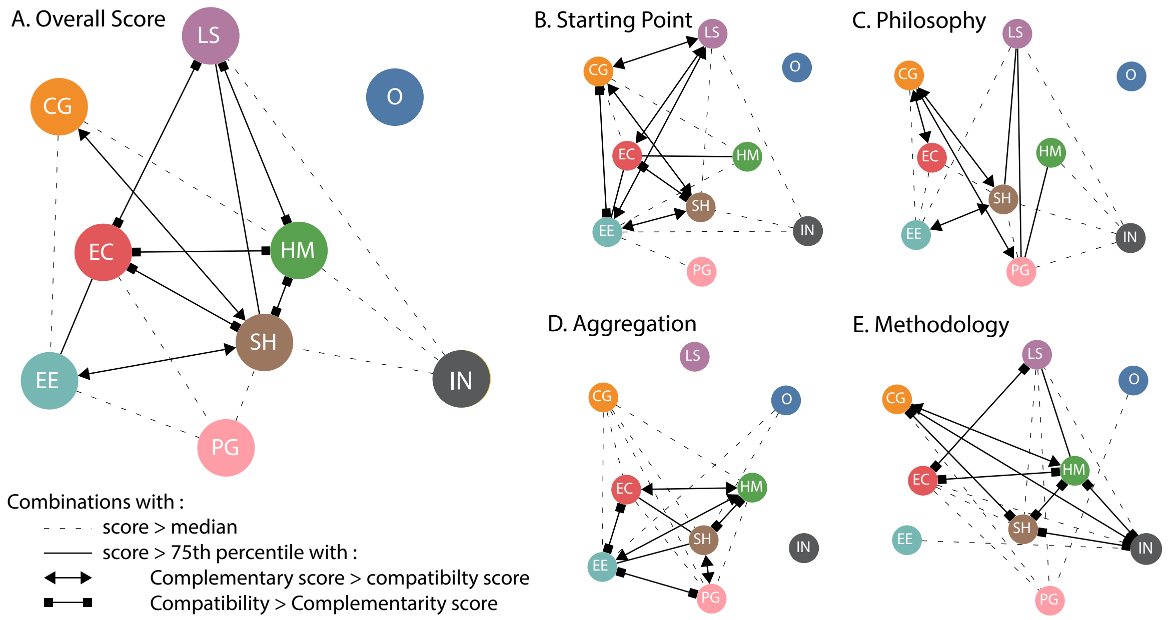


Figure 5. Relational network between disciplines for the overall score and the individual dimensions of the typology. For each network, overall scores larger than their median and 75th percentile are represented as dashed and solid lines, respectively. Edges with compatibility or complementarity scores larger than their 75th percentile values are marked with arrow and square symbols, respectively. Discipline acronyms are defined in Box 2, with the exception of “O”, which represents a fictitious “other” discipline located at the center of the typology (see Section 3.2).

The analysis identifies SH and EC, followed by HM and LS, as occupying central locations within the typology with the largest degrees of connectivity, with respectively 5, 4, 3 and 3 solid edges on Figure 5. These four disciplines form a cluster with high degrees of compatibility or connectivity along *different* dimensions of the typology, as seen in the insets in Figure 5, which allows for large overall scores (pie sizes in Figure 4A) . Specifically, HM, LS and SH take water as a starting point, whereas EC takes a complementary perspective rooted in the social sciences; yet a different combination of three disciplines (HM, SH and EC) predominantly focus on temporal dynamics that complement the spatial dynamics captured by LS. With regards to philosophy, LS and HM are both oriented towards prediction, whereas EC and SH are respectively predominantly concerned with description and generation; finally, HM takes an instrumentalist perspective that complements the positivist perspective of LS, SH and EC. Methodologically, although all four approaches are compatible in their quantitative approach, two of them (LS and EC) are data-intensive disciplines (large N) that complement the site-specific (small N) approach often adopted by the two others (HM and SH). Finally, three (HM, LS and EC) of the four disciplines are deductive in the sense that they rely on theory to make predictions, which complements the observation-based inductive approach often adopted by SH researchers.

These tradeoffs translate in a high degree of interdisciplinary connectivity for SH, which sits at the center of the typological space occupied by the four fields along most considered dimensions (Figure 5). This stands in sharp contrast with the baseline discipline "O", which stands as the most poorly connected in the typology (Figure 5) despite its central location along each dimension (see Figures 1 and 2). This apparent paradox illustrates the advantage of being simultaneously complementary and compatible to different disciplines along different dimensions, rather than being moderately close to all disciplines along all dimensions. A high degree of connectivity within the typology does not only point to a discipline's high affinity to connect with other individual disciplines but also its potential to act as a bridge between (i) multiple and (ii) diverse disciplines. Regarding multiplicity, SH has both the highest degree of connectivity (Figure 5) and the largest proportion of papers with authors hailing from three or more disciplines (Table 1). Regarding diversity, the compatibility -- or even overlap -- between SH and other disciplines that occupy a similarly central location in the typology has been extensively discussed in previous reviews (see, e.g., Madani and Shafiee-Jood (2020); Pande and Sivapalan (2017) for HM, Müller and Levy (2019) for EC and Wada et al. (2017) for LS). Yet, remarkably, the largest overall affinity score predicted by the typology relates SH to CG, a qualitative critical social science that is philosophically and methodologically very distinct from the centrally located disciplines of the typology. This complementary perspective offers outsize potential to generate the type of holistic and actionable knowledge necessary to understand and govern complex CHWS, as argued in Wesselink, Kooy, and Warner (2017) and illustrated in Savelli et al. (2021). Here the typology suggests that SH and CG are not only complementary but also compatible along -- different -- key dimensions that can serve as a starting point for interdisciplinary research. Namely, both disciplines tend to take a generative perspective and a place based (small-N) methodology based on inductive reasoning in the sense that theory development is driven by empirical observations (Fig 1 and 2). These commonalities can serve as a cornerstone for interdisciplinary research between the two fields.

	CG	**EC**	**EE**	**HM**	**IN**	**LS**	**PG**	**SH**
R1	0.02	0.00	0.01	0.01	0.02	0.04	0.03	0.07
R2	0.13	0.05	0.05	0.11	0.07	0.18	0.13	0.20

Table 1. Fraction of papers in each discipline with authors from 3 or more disciplines. R1 represents the ratios of all the papers queried for each discipline. R2 represents the ratio of the subset of papers of each discipline that are interdisciplinary, i.e. that have authors from 2 or more disciplines.

4. Conclusion

This paper proposes a typology to map and relate key disciplines focusing on CHWS. This process comes with a certain level of subjectivity in both the selection of disciplines and their placement within the typology, which we mitigate -- but not eliminate -- using a Monte Carlo analysis and an interactive web platform. In addition, the typology itself can be further developed to capture application constraints and opportunities that are not currently accounted for. For example, the unit of analysis and its associated spatial and temporal scales might vary substantially across disciplines: LS might considers hourly variations over ~100km^2 grids; SH might consider long term >10 years coevolving catchment-scale phenomena; GC might take individual-level personal experiences as units of analysis. These aspects affect the compatibility and complementarity of interdisciplinary combinations and need to be further studied. With these caveats in mind, application to 8 specific disciplines allowed us to identify particularly promising combinations of disciplines that stand out for their high degree of compatibility and complementarity. The typology can, in particular, be used to discern areas of compatibility between disciplines such as SH and CG, which have a particularly high potential to generate new insight due to their high degree of complementarity. Conversely, the typology also identifies dimensions along which disciplines such as SH and HM, which have been argued to be overlapping and redundant, can be used to complement each other and generate new insights. More broadly, the typology also outlines important features of the landscape of CHWS research where some disciplines (e.g., SH and EC) occupy a central location within the typology. These disciplines are compatible and complementary to a large set of disciplines along different dimensions of the typology and can potentially serve as catalysts for broader interdisciplinary research. While specific to coupled human-water systems, these findings also point to the potential for a comparable typological approach to be used to support interdisciplinary research on other topics that have been the focus of extensive -- but separate -- traditions of research in multiple disciplines.

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