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Research, part of a Special Feature on Convergent Science for Sustainable Regional Systems

Facilitating convergence research on water resource management with a collaborative, adaptive, and multi-scale systems thinking framework

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ABSTRACT. Water resource systems display complex behavior that challenges our ability to identify paths toward improved management. Such behavior can arise from unanticipated feedbacks between social, ecological, and technological components that are conventionally studied and managed in disciplinary silos, often with limited consideration of interactions across scales of space and time. Convergence research driven by deep integration and co-production of knowledge within research teams is needed to better anticipate water resource system behavior and identify new approaches. We developed and applied a new framework—the Collaborative, Adaptive, and Multi-Scale (CAMS) systems thinking framework—to build a convergence research team around the task of characterizing a watershed as a complex system and hypothesize associated water management dynamics. The CAMS framework applies systems thinking methods within a broader integrated approach to engage and synthesize the knowledge and interests of an intellectually diverse research team and model a water resource system across spatial and temporal scales. Our case study of the Santa Fe Watershed in New Mexico reflects challenges and opportunities to manage water in the western United States of America. The specific methods applied within the framework included a six-session workshop on systems thinking, conceptual model development exercises with a longer-term subgroup, a structural analysis of system variables, and classroom-based projects. We discuss the successes, limitations, and potential of each method and how they interacted within the CAMS framework. We found that use of multiple systems thinking methods within the open-ended, iterative design of the framework provided a structure for long-term use that integrates disparate ideas, hypotheses, and findings from water sustainability research. Creating an inclusive environment within the research team was critical to the framework's successful application and will remain a core consideration for ongoing work aimed at broader participation.

Key Words: *convergence research; system dynamics modeling; systems thinking; water resources*

INTRODUCTION

Billions of people and critical ecosystems rely on managed water resource systems (Jackson et al. 2001, Cosgrove and Loucks 2015). These systems involve the storage and transport of water through some combination of seasonal snowpacks, constructed reservoirs, groundwater aquifers, lakes, rivers, aqueducts, and pipes—facilitated by both human activities and hydrological processes. Water resource systems are designed to buffer human communities, and in some cases, ecosystems, from hydrologic extremes such as drought and flooding (Loucks and van Beek 2017). However, many contemporary water resource systems were designed for different conditions than we have today (Woodhouse et al. 2005, Rao et al. 2018, Chen et al. 2021, Siirila-Woodburn et al. 2021), and now climate change, shifting land use, and rising water demand are diminishing their buffering capacity (Viviroli et al. 2011). The need to adapt water resource management to new conditions is increasingly acute, yet the complexity of doing so remains a formidable challenge.

Water resource management is widely acknowledged to be a "wicked" problem because it is replete with uncertainties and risks and lacks one clear path or point of resolution (Rittel and Webber 1973, Liebman 1976). However, the nature of wicked problems—having multiple paths toward multiple forms of resolution—can be viewed as an opportunity if only the paths and points of resolution can be identified and agreed upon (Reed and Kasprzyk 2009). A major barrier to realizing this opportunity is effective integration and co-production of knowledge across and beyond academic disciplines (Reed and Kasprzyk 2009, Montanari et al. 2013). Given the complex social, ecological, and technological interactions that define water resource systems (Markolf et al. 2018, Gittins et al. 2021), reaching beyond conventional disciplinary training to find new, integrated approaches is vital.

Convergence research is an emerging approach that draws on the traditions of multi-, inter-, and transdisciplinary research (e.g., Nikitina 2006, Yong et al. 2014, Gilligan 2021) to promote new thinking and innovation through novel framework development and deep integration of knowledge, tools, and modes of thinking (Gropp 2016, Tornow et al. 2018, Peek et al. 2020, Angeler et. al 2020). According to Gropp (2016), a convergent approach "augments a more traditional transdisciplinary approach to research by framing challenging research questions at inception." Its focus on "specific and compelling problems" and "pressing societal needs" (Tornow et al. 2018) makes convergence research well suited to the wicked problem of adapting water resource management to new conditions. Convergence research is also meant to augment other approaches with focus on "fostering the

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collaborations needed for successful inquiry" (Gropp 2016). In this way, convergence research builds on the traditions of team science and team building research that study approaches and efficacy of collaboration in research teams (Fiore 2008, Klein et al. 2009). Convergence research, however, is more acutely confronted with the cognitive and epistemic difficulties researchers experience in non-conventional research teams (Boon and van Baalen 2019) due to its emphasis on deep integration across disciplines.

Elsewhere in this Special Feature, we identify systems thinking as a core approach for convergence research (Morgan et al. 2025). Systems thinking is a body of theory and practical application that aims to infer how systems behave by gaining a deeper understanding of their underlying structure (Richmond 1994). In this definition, a "system" is defined as a collection of interconnected elements that generate behavioral patterns over time (Meadows 2008). Systems thinkers have developed a constellation of modeling approaches (Box 1), ranging from conceptual and qualitative to computational and quantitative, where "models" refer to any stylized representation of a system (Frigg and Hartmann 2006) and "modeling" refers to the formulation of models with the purpose of exploring systems' underlying structures. System dynamics modeling is one such set of approaches that emphasizes the interactions of stocks (elements that can accumulate or be depleted) and flows (elements that make stocks increase or decrease) to describe system behavior (Richmond 1994). System dynamics modeling is intuitively useful for describing water resource systems because water stocks (e.g., reservoirs) and flows (e.g., rivers) are key elements. However, stocks and flows can also be used to describe less physical elements, such as the accumulation and loss of trust in water management authorities among members of a population (Richmond 1994). Even so, system dynamics modeling conventions can be limiting, so systems thinkers deploy a variety of other modeling approaches to meet different needs. Here, we use "system dynamics modeling" to refer to qualitative and quantitative models that emphasize stocks and flows, and "system modeling" to refer to all other modeling approaches used by systems thinkers. Systems thinking can advance the development of convergence research programs because it provides a breadth of methods that are accessible to a range of users and relevant to a range of knowledge types (Morgan et al. 2025), but which all facilitate the formation of explicit agreements within research teams about interconnections between elements of a system (Richmond 1994, Meadows 2008).

Despite its promise for convergence research in general, we suggest that current methods in systems thinking are incomplete for convergence research on water resource management specifically. First, it is difficult to understand the behavior of water resource systems without acknowledging that they are multi-scaled, with processes at fine spatial and temporal scales influencing processes at coarse scales and vice versa (Ostrom 2009, Sivapalan and Blöschl 2015, York et al. 2019). Systems thinking should ideally reflect this multi-layeredness to accurately model different behaviors observed at different scales and to preserve relationships between the nuances available at finer scales and the abstractions necessary at coarser scales (Famiglietti and Wood 1994, Madrid et al. 2013, Belmont and Foufoula-Georgiou 2017). Yet, most system modeling methodologies start with delineating one set scope and scale for practical purposes (Midgley and Rajagopalan 2021). Second, water resources research often stands out for the number and diversity of perspectives and priorities involved from both stakeholders and outside researchers (Sivapalan and Blöschl 2015, Flint et al. 2023*a*), which would ideally be well represented in a convergence research program (Morgan et al. 2025). Although collaborative modeling across and beyond academic disciplines has long been a core idea in systems thinking (Box 1; Vennix 1996, Lamb and Rhodes 2010, Hovmand et al. 2012, Langsdale et al. 2013), modeling teams are usually convened for a single project, causing models to represent a snapshot in time from the perspective of a particular group of participants (e.g., Tidwell et al. 2004, Dhirasasna and Sahin 2019, Luna-Reyes et al. 2019). Ongoing collaboration, when it occurs, is not formalized in the modeling process, and emerging ideas or questions from evolving community partnerships and research collaborations are typically treated as new projects rather than continuations. Although this research approach may lead to broad knowledge shifts over time, it hinders integration of diverse perspectives into addressing a specific problem, as a convergent approach demands. Moreover, we posit that a convergent approach will only be effective if it prioritizes creating a culture of belonging (inclusion) and removing barriers for participation in research teams (equity), as doing so will allow deeper integration of knowledge. Although systems thinking commonly asks who was included and excluded from a project (Midgley and Rajagopalan 2021), it only very recently has begun asking explicitly about how its collaborative approaches might address issues of equity and inclusion (e.g., Polaine et al. 2022, Isar 2023). Third, these limits on collaborative and multi-scale approaches together limit the adaptiveness of a systems thinking project to new ideas, new questions, and new collaborations that may change the design, scope, or scale of models. Adaptive approaches are necessary to address the rapidly changing conditions that water resource systems are experiencing (Pahl-Wostl 2007), but are currently lacking in system modeling.

To address these limitations, we propose a new framework aimed at making systems thinking more broadly collaborative, adaptive, and multi-scalar for applications to convergence research on water resource systems. Here, we describe how we developed and applied the Collaborative, Adaptive, and Multi-Scale (CAMS) systems thinking framework to build a convergence research team around the tasks of characterizing a water resource system and hypothesizing water management dynamics there. The CAMS framework applies systems thinking as a method to engage and integrate the knowledge and interests of an evolving research team and to build models of a water resource system across spatial and temporal scales. We used the Santa Fe Watershed in New Mexico, USA as a case study system due to the confluence of opportunities and challenges there that reflect water management issues throughout the western USA (Box 2). We asked the following research questions:

1. Does the CAMS framework effectively facilitate the process of building a convergence research program on water resource management through its collaborative, adaptive, and multi-scale design?
2. What disciplinary and epistemological divides are bridged with the CAMS framework, and which are not?

3. Is the CAMS framework inclusive to diverse teams of researchers, and can it be used to foster inclusive and equitable collaboration with others in the future?

Our first question asked how and to what extent the collaborative, adaptive, and multi-scalar features of the framework contributed to the goals of convergence research in general and to addressing our identified limitations of systems thinking for water resources specifically. Our second question asked this in more depth by focusing on the frameworks' contribution to addressing the cognitive and epistemic difficulties inherent in a convergent team science approach. Our third question about inclusive and equitable collaboration uniquely focused on whether the framework was able to create a culture of belonging and remove systemic barriers for participation, which we believe is central to fully realizing its collaborative and adaptive design.

Our overarching hypothesis was that the multi-scalar and adaptive design of the CAMS framework would provide more and deeper opportunities for collaboration and allow more insightful characterization of water resource systems than other systems thinking methods alone, thus making it an effective approach for convergence research on water resources. We further hypothesized that the use of systems thinking in a multi-scalar and adaptive framework would facilitate an inclusive environment for participants by bridging divides formed by disciplinary-specific and scale-dependent knowledge. Following the practice of collaborative inquiry (Bray et al. 2000, Walther et al. 2017), we drew on the collective experience of the coauthors to investigate these research questions. The coauthors include participants from all modeling stages of the framework application, represent a broad set of expertise and relationships to water resources research, and were therefore able to reflect on the research questions from a variety of perspectives. Below, we describe the framework design and the methodology of its first set of applications. We then discuss the research questions in relation to this first application of the framework as well as its potential for ongoing use.

Box 1:

A brief history of systems thinking theory and practice

As a field, systems thinking has undergone several paradigmatic waves (Midgley and Rajagopalan 2021) that are useful to consider to understand the current state of the field and its limitations for convergence research on water resources. Starting in the 1940s–1960s, early users of systems ideas broke down barriers between conventional disciplines by generalizing the unique modeling traditions of different disciplines into a common set of practices. These practitioners emphasized producing quantitative models designed to represent reality, and judgements about how to define the boundaries or scale of the system and the scope of the modeling project were set by loosely defined "experts." Critiques in the 1960s–1980s pushed the field to consider models more as aids for the development of understanding between people with different perspectives, rather than as representations of reality. This led to the development of more qualitative and conceptual approaches and an emphasis on developing a shared understanding of the meaning of model elements and behavior. However, scale and scope judgements were still set in a top-down manner, leading to a third paradigmatic wave that emphasized acknowledging and critiquing how such judgements are made, particularly from the perspectives of marginalized members of the system. This third wave also embraced the idea of methodological pluralism, which seeks to mix the quantitative and qualitative approaches of the first two waves into a flexible and responsive systems thinking practice (Midgley and Rajagopalan 2021).

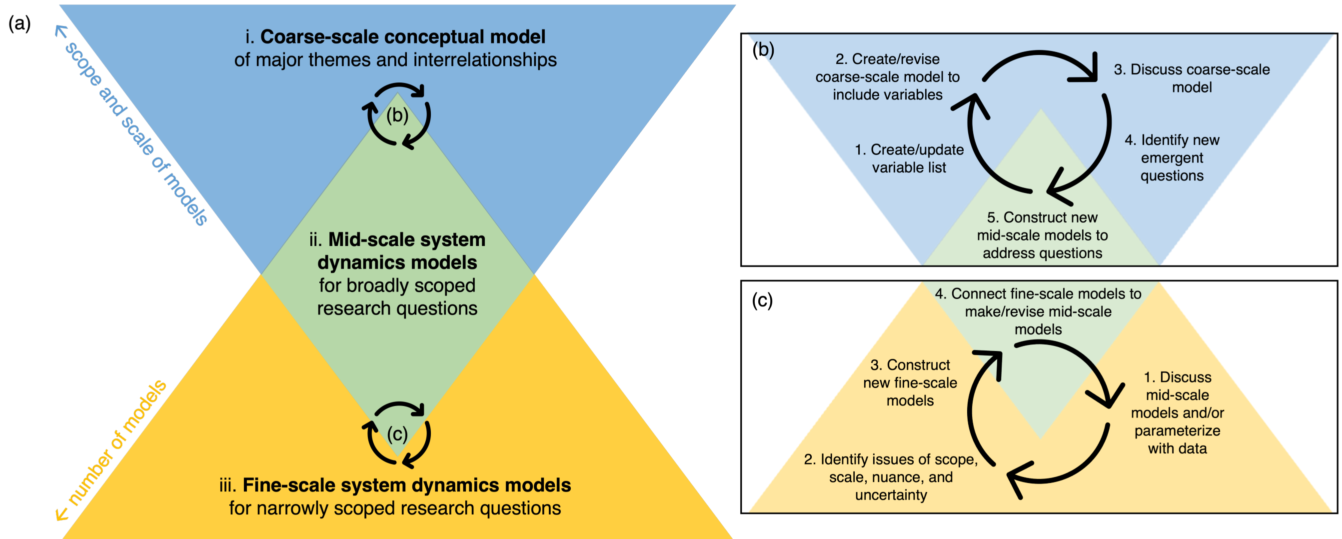
A FRAMEWORK FOR COLLABORATIVE, ADAPTIVE, MULTI-SCALE SYSTEMS THINKING

The first feature of the framework we describe is its multi-scale design, which allows users to combine individual systems thinking methods and models into a common framework over time. Models are organized across three levels: (1) a coarse-scale level containing a single conceptual model that describes major themes of interest within a system and their interrelationships (Fig. 1*a*(i), in blue), (2) a mid-scale level containing a set of system dynamics models that address more broadly scoped research questions and represent intermediate spatial and temporal scales (Fig. 1*a*(ii), in green), and (3) a fine-scale level containing a set of system dynamics models that address narrowly scoped research questions and represent fine spatial and temporal scales (Fig. 1*a*(iii), in yellow). The framework is depicted as two intersecting triangles, one with a broad base at the top and the other with a broad base at the bottom, to emphasize that it is bidirectionally hierarchical. By bidirectionally hierarchical, we mean that it is hierarchical from the bottom to top in that the scope and scale of any one model increases in this direction, and it is hierarchical from the top to bottom in that the number of models needed to represent the system increases in this direction (Fig. 1).

The framework's multi-scale design allows research teams to start model development at any level. We recommend a "middle-out" modeling approach wherein modeling begins at the mid scale, following previous analyses of multi-scale modeling approaches across the fields of physics, engineering, nanoscience, and biology (Batterman and Green 2021). A "middle-out" approach is both practically and epistemically preferable for several reasons. First, mid-scale modeling does not require the level of detailed information necessary to model at the finest scale, which may not be available at the start of a project and may not reflect the scope of initial research questions. Second, "bottom-up" approaches starting at the finest scale are likely to fail to capture the behavior of multi-scale systems because they inevitably miss factors that uniquely emerge at coarser scales (Batterman and Green 2021). Finally, "top-down" approaches are likely to overlook important elements because of the cognitive constraints of considering the complexity of a system at a broad scope and scale. In contrast, a "middle-out" approach allows a team to start with a level of complexity appropriate for a new collaboration, provides the raw material needed to model at other scopes and scales, and provides points of connection between models at other scopes and scales, as we detail below.

The framework's adaptive design becomes apparent as modeling progresses beyond the initial level. Starting from one or more mid-scale models, a set of processes embedded in the framework guide

Fig. 1. (a) The Collaborative, Adaptive, and Multi-Scale (CAMS) systems thinking framework and (b, c) embedded processes to create and revise models across levels of varying scope and scale.



the creation of coarse- and fine-scale models and encourage revision of models over time (Fig. 1*b*–*c*). We generalize these processes in Fig. 1 and provide specific examples of systems thinking and team science methods we used to accomplish these steps in the following section. Regardless of the exact methods used, these processes cause the creation or modification of models at any level to feedback to models on other levels by initiating a reevaluation and possibly a reformulation of models at those levels. These feedbacks make all models included in the framework adaptive to new information, collaborations, and questions and allow consideration of dynamics that interact across scales. Together, the three levels of modeling and embedded revision processes allow for flexible and interacting levels of different scope and scale while providing practical limits and tools to allow modeling at each level to proceed.

The collaborative design of the framework comes from the use of collaborative system modeling methods, but deepens the potential of these methods through adaptive and multi-scaled features and through a focus on creating an inclusive environment. Specifically, the embedded revision process provides explicit opportunities for the research team to add new members as additional questions and gaps in knowledge are identified, and the use of models at multiple scales encourages inclusion of team members whose expertise applies better to coarser or finer scales. These features build on the rich tradition of collaborative methods in system modeling (e.g., Vennix 1996, Tidwell et al. 2004, Lamb and Rhodes 2010, Hovmand et al. 2012, Langsdale et al. 2013) by removing barriers created by a potential team member's scale-dependent knowledge or time-dependent availability to participate and contribute. Collaborative activities then employ techniques such as individual self-reflection, structured sharing activities, and discussion of participants' relationship to the research to break down power structures and encourage a sense of belonging within research teams (Hovmand et al. 2012, Hattery et al. 2022).

THE FRAMEWORK IN ACTION

A workshop to jumpstart the research team at the mid-scale

We emphasize that the CAMS framework can be initiated through a variety of methods, as long as it uses systems thinking concepts and tools. Here, we describe how we initiated the process at the mid-scale (Fig. 1*a*(ii), in green) with a 5-d workshop series using techniques from the Group Model Building literature (Richardson and Andersen 1995, Vennix 1996, Hovmand et al. 2012, Rouwette 2016). The Group Model Building literature describes a family of group facilitation techniques that are linked to computer models and developed with a group in a meeting setting. Our workshop brought together 28 researchers from a wide range of disciplines and levels of expertise to learn about system dynamics modeling, hypothesize dynamics in the Santa Fe Watershed (Box 2), and model those dynamics.

Box 2:

The Santa Fe Watershed as a water resource system facing change

The geographic bounds of the Santa Fe Watershed in New Mexico, USA as considered in this study are generally the topographic and hydrologic boundaries of the Santa Fe Watershed from its headwaters to its confluence with the Rio Grande (Fig. 2). However, we treated this as a soft boundary, and included lands, waters, people, and infrastructure that extend beyond this boundary that are significant to the management of water in the Santa Fe Watershed. This includes adjacent land in the Pojoaque Basin and the Pecos Wilderness, and the Colorado River Basin, which is connected to the watershed through transbasin diversions. We also acknowledge that several Native

American Pueblo nations are connected to the study area beyond what is reflected in current property rights. For example, lands in the upper Santa Fe Watershed are part of the homelands of people from Tesuque Pueblo, and much of the lower watershed is part of the homelands of people from Cochiti Pueblo.

The City of Santa Fe and surrounding communities rely on water supply from four sources: the headwaters of the Santa Fe River Watershed (the municipal watershed), two groundwater well fields, and a surface diversion from the Rio Grande (Buckman Direct Diversion project) (Fig. 2). Water sources supply primarily municipal use, with lesser amounts supplying industrial and agricultural water demands. All of these water sources are vulnerable to drought, wildfires, population growth, and over-extraction of groundwater. First, the headwaters (municipal watershed in Fig. 2) supply up to 50% of municipal water demand, depending on the year. This high elevation snowmelt-dependent portion of the watershed is mostly forested and within federally protected wilderness, with the largest landowner being the U.S. Forest Service. As a result of historic fire suppression and drought conditions, the headwaters and their contribution to downstream water supplies are highly vulnerable to wildfire. A recent modeling study found post-fire debris flow probability to be >90% across the municipal watershed for all but the lowest severity fire and precipitation scenarios, with many scenarios causing debris flow volumes capable of completely filling the channel and two reservoirs that store water for downstream use (Lopez et al. 2024).

Water supply from the Rio Grande upstream of Cochiti Dam comprises another approximately 40% of municipal supply but is vulnerable to severe drought. In several recent years, streamflow has reached lows that prohibited the City of Santa Fe from physically drawing water from the Buckman intake structure. On paper, the water supply is part of the Colorado River system and specifically is imported from the San Juan River via the San Juan-Chama Diversion Project. This water supply is relatively reliable, but vulnerable to severe drought and wildfires in the San Juan Mountains.

Groundwater sources (wells in Fig. 2) make up approximately 20% of the municipal supply and have been viewed as reliable water supply, capable of buffering the region from hazards such as wildfires and droughts. However, the water table in the Santa Fe Basin has declined significantly when in high use in recent decades and the recharge process is poorly understood due to complex geology (Manning 2011). Furthermore, the City of Santa Fe's well fields have never been tested to the degree of providing the region's full water supply without supplementation from the municipal watershed or the Rio Grande.

Finally, there are important issues to be addressed around decision-making processes in the Santa Fe Watershed. Historical and ongoing inequalities, inconsistent acknowledgment of Tribal sovereignty, and uneven access to water due to position in the watershed (high to low elevation), have resulted in processes that benefit some groups over others (Flint et al. 2023*a*).

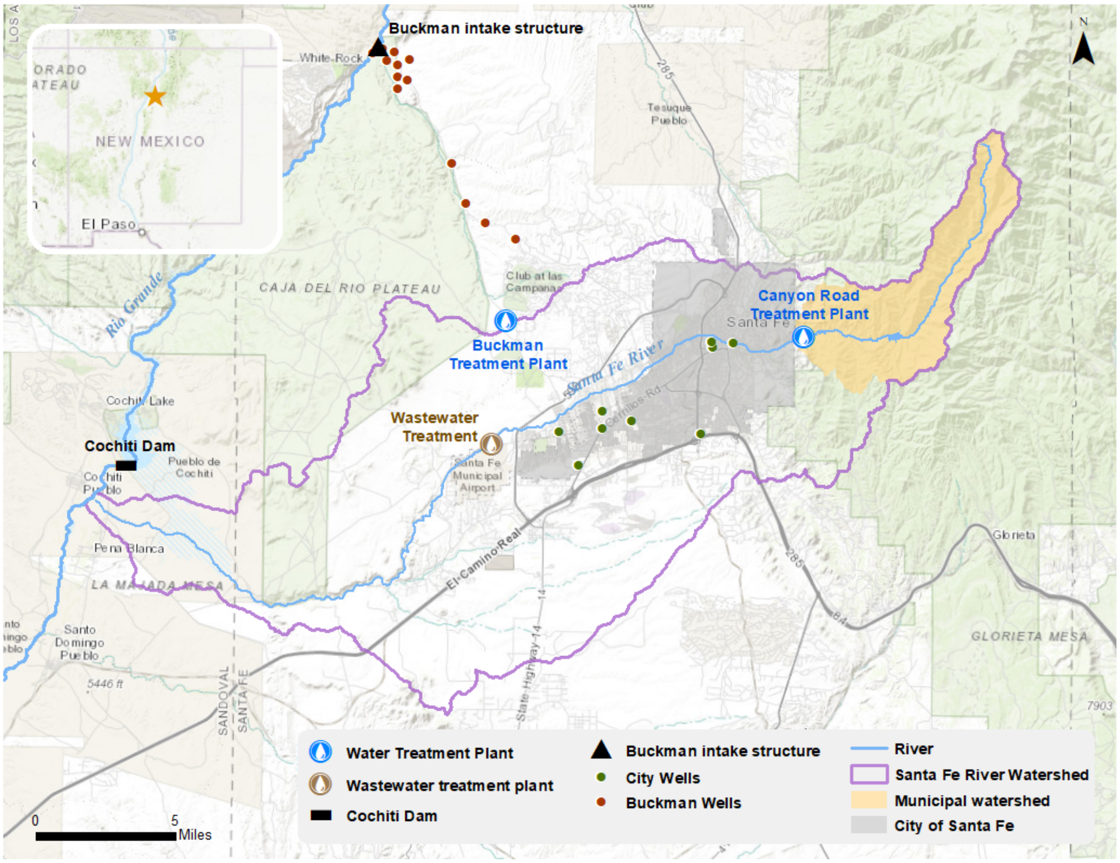
The workshop is described in detail in Append. 1*A* and summarized in Fig. 3. Briefly, academic disciplines represented by participants included biology, economics, geoscience, law, education, engineering, geography, health sciences, journalism, communications, planning, hydrology, agronomy, social psychology, and policy, although this list does not reflect all spheres of knowledge that participants identified with. Participants were not funded. Activities on day 1 supported participants in taking ownership of the workshop by (a) discussing and revising themes related to water management and (b) learning about each other's expertise and relationship to the Santa Fe Watershed. On day 2, participants brainstormed and defined elements influencing water management in the Santa Fe Watershed, where "elements" were defined as parts of the system that are in some way quantifiable and can change over time (Anderson and Johnson 1997). On day 3, participants broke out into four teams and co-produced research questions that reflected the interaction of elements they individually found most interesting. On day 4, teams classified elements as stocks and flows and began building system dynamics models around their research questions. On day 5, participants discussed and revised their models, articulated the stories these models told to the larger group, and discussed points of connection between the four models. Finally, on day 6, participants reviewed results and discussed continuation of the research team into next steps. Much of this discussion centered on challenges around defining scope and scale in system dynamics models to accurately represent their hypotheses and research questions. Participants concluded that important next steps should include (a) synthesizing the four mid-scale models and other elements discussed in the workshop into one conceptual model and (b) creating opportunities to refine parts of the four models into more detailed, finer-scale models. These discussions led directly to the development of the CAMS framework and the creation of models at coarser and finer scales.

Revising mid-scale system dynamics models into a coarse-scale conceptual model

Twelve participants of the workshop, including the two facilitators, continued to work together after the workshop with the objective of synthesizing the four mid-scale models and other elements discussed in the workshop into one coarse-scale conceptual model (Fig. 1*b* [Steps 1–2], in blue). Participants represented seven academic disciplines, including biology, geoscience, engineering, geography, policy, planning, and social psychology. We developed the conceptual model using (a) a series of group exercises to define coarse-scale elements and (b) a structural analysis to hypothesize and visualize the interrelationships of those elements.

First, several group exercises focused on synthesizing all 293 elements used or discussed in the creation of the four mid-scale system dynamics models into a list of 20 themes. Themes were identified by participants individually sorting the 293 elements into categories of their choosing via an asynchronous open card sort activity using online software (https://provenbyusers.com), followed by the team reconvening to reconcile differences in category choices, further refine the themes, and create a shared understanding of their meaning. Activities to create a shared understanding of their meaning resulted in the creation of a related framework (Fuzzy Social-Ecological-Technological Systems (Fuzzy SETS)) and is

Fig. 2. The Santa Fe Watershed and surrounding areas.

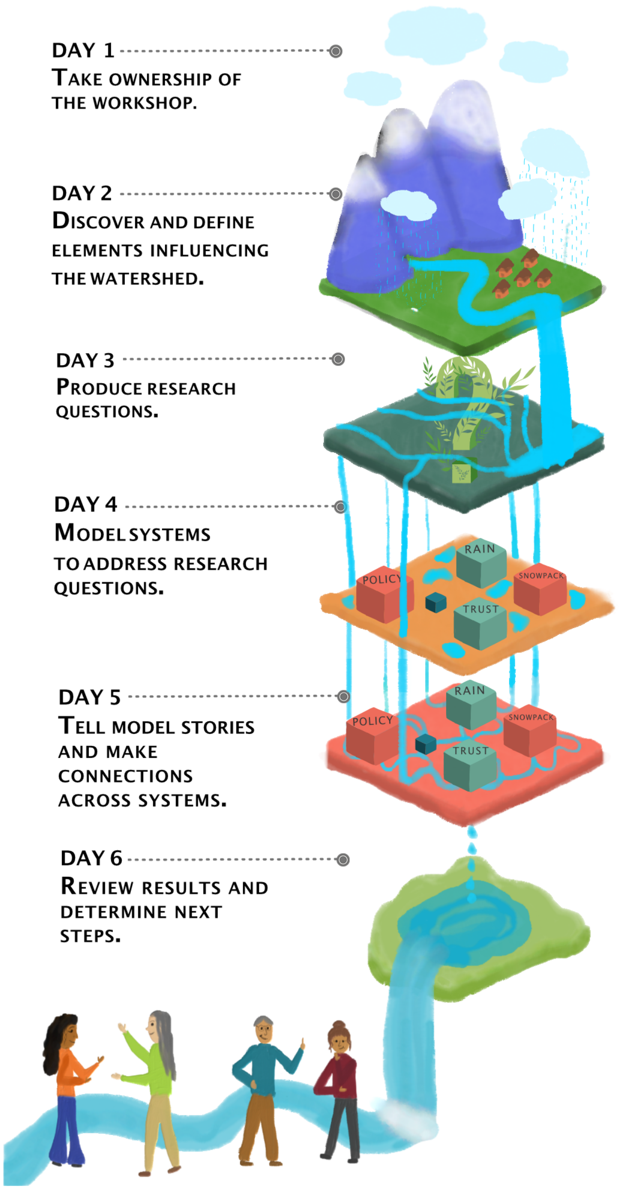


described elsewhere in this Special Issue (Lin et al. 2025). The 20 final themes (Append. 1*B*) then became elements to include in the coarse-scale conceptual model.

Second, we used structural analysis to define how the 20 elements may relate. In the context of systems thinking, structural analysis refers to a series of techniques that define the dependencies and influences of elements in a system based on surveys of participant knowledge (Duperrin and Godet 1973, Godet 1986, Arcade et al. 1999, Bashir et al. 2020). Structural analysis is often used to inform development of causal loop and stock-and-flow diagrams. Here, we introduce a novel application of the structural analysis technique Cross-impact Matrix Multiplication Analysis (MICMAC) to create a coarse-scale conceptual model that represents a series of hypotheses about drivers and dependencies in the Santa Fe Watershed from the perspective of our research team. The method and results are described in detail in Append. 1*B*. Briefly, participants received a survey for each element x asking "If (element x) changed, what could be its direct influence on (element y)?" for every possible element y. Participants answered on a scale of 0 (no influence) to 3 (high influence), and also indicated their confidence about the relationships on a scale of 0 (not confident at all) to 3 (very confident). This resulted in 20 surveys of 19 questions each, which participants completed based on their interest and expertise in each element. We used each element's mean influence vs. dependence in the system to categorize elements that describe their role in the system (Arcade et al. 1999). MICMAC categorizes elements into four main types and eight subtypes (Table 1) based on their mean location on an influence vs. dependence biplot, and we additionally used mean confidence and variability of responses to aid interpretation into types (Fig. B7 in Append. 1*B*). To create the conceptual model, we first interpreted MICMAC element types into a conceptual model template that highlights exogenous vs. endogenous vs. "core" endogenous elements and their interrelationships (Fig. 4*a*). Finally, we mapped our structural analysis results onto this template (Fig. 4*b*).

The MICMAC method provides insights into system behavior by interpreting influences and dependencies in light of systems thinking theory. In the context of our research team, these insights provided emergent team-level ideas and hypotheses to explore further. For example, the analysis found that the Santa Fe Watershed system has many possible core endogenous elements (Fig. 4*b*), which indicates an unpredictable and unstable system (Fig. B7, B8 in Append. 1*B*; Arcade et al. 1999). Contributing to possible instability is the fact that we identified no possible determinant elements (Fig. 4), which are those that can act as easy-to-access intervention points in the system to influence its

Fig. 3. Summary of the activities in a six-part workshop used to initiate model development at the mid-scale of the CAMS framework. This graphic was designed by an undergraduate researcher and coauthor (Kremer) who attended the workshop and translated it into visual media as part of a science communication fellowship program described in Donohue et al. (2023).



behavior (Arcade et al. 1999). The closest element to the determinant element range was "incorporation of traditional watershed knowledges [into watershed management]" (Fig. 4*b*), which was defined by the team as the extent to which the knowledge, histories, innovations, and practices of Indigenous and local communities are incorporated into shared public understanding about a watershed, as well as systems of formal and informal governance, policy, management, and other activities in a watershed (adapted from Secretariat of the

Table 1. Types of elements based on their location on an influence and dependence biplot as per the MICMAC structural analysis method. Summarized from Arcade et al. (1999).

Element type	Element sub-type	Description
Influent		Very influential with little dependence. Can act strongly on the system. Can be considered input variables
	Environmental	Conditions the system and cannot be controlled
	Determinant	Some dependence. Key factors influencing the system
Relay		Very influential and very dependent. They have a consequence on other variables if impacted
	Stake	The "potential breakpoint of the system" due to their strong simultaneous influence and dependence. Can have a strong influence on the system as a whole
	Target	More dependent than influential, resulting from system evolution. Can strongly influence the system if guided through strong action
Dependent		Little influence and very dependent, sensitive to changes of influent and relay variables
	Exit	The outcomes or results of system dynamics
Excluded		Relatively disconnected from system dynamics
	Disconnected	Mostly autonomous; may be in system but does not strongly guide or result from its dynamics
	Secondary levers	More influential than dependent. Can serve as secondary leverage points to change system outcomes
Regulating		May weakly act as secondary levers, targets, stakes, or determinants.

Convention on Biological Diversity (SCBD) 2023). However, this element also had the lowest mean confidence in responses. Insights from this analysis are discussed in Append. 1*B* and below.

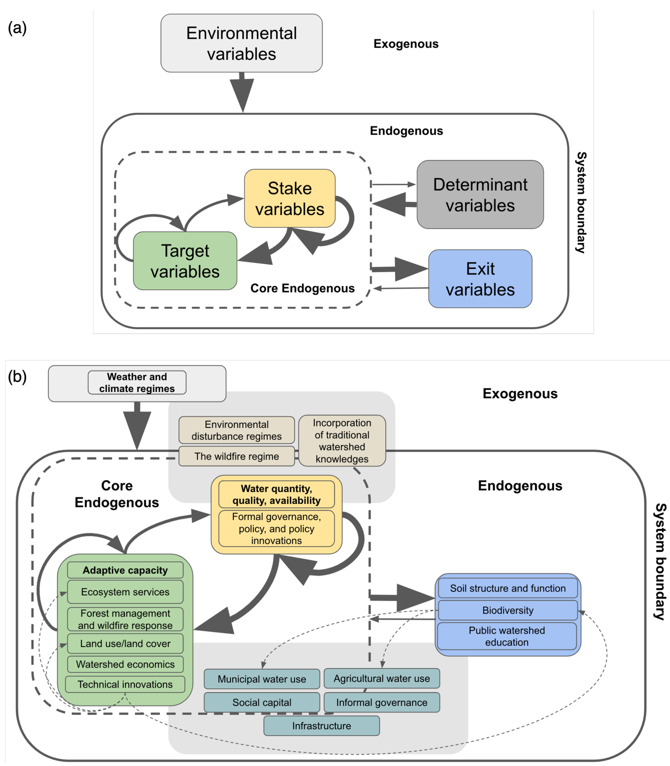
Revising mid-scale models into fine-scale models

Coarse- and mid-scale models inevitably obscure nuances that may be important to explore to address research questions and/or management challenges. Coarse- and mid-scale models can also be difficult to parameterize with data and empirical relationships because elements are sometimes too broadly defined to match to observational data sets. Fine-scale models, in contrast, allow detailed consideration of the dynamics implicit in coarse- and mid-scale models, and can be linked together to inform existing mid-scale models or define new ones.

There will likely be many options through which to develop greater detail to move from a mid-scale to fine-scale model. One potential pathway is to engage groups of researchers to select a specific element, or connection of elements, at the mid-scale, conduct a detailed literature review of that element, and construct a detailed system dynamics model (Fig. 1*c* (Steps 1–3)).

We implemented this approach within groups of graduate students as part of a course in environmental systems modeling (see Append. 1*C* for details). Graduate students came from a variety of disciplines, including engineering, geoscience, geography, anthropology, and planning. Students learned system dynamics modeling principles and implemented fine-scale models in GoldSim software (GoldSim, Seattle, Washington, USA). An example fine-scale system dynamics model that was created through this pathway is shown in Fig. 5. We stress that this is just one potential pathway for fine-scale model creation and revision. A similar process could be conducted with groups of researchers and/or community members.

Fig. 4. (a) Interpretation of element types from the MICMAC structural analysis method classification system into a conceptual model template. Element classification into types (shaded boxes) is based on elements' relative influence and dependence on other elements, whereasthe weight and direction of arrows correspond to the level and direction of influence of element types. The model template highlights exogenous vs. endogenous vs. "core" endogenous elements and their interrelationships: exogenous elements are relatively independent of the system and condition it; endogenous elements are influenced by other elements in the system; core endogenous elements are those most central to the internal dynamics of the system. (b) Interpretation of coarse-scale elements into a conceptual model based on total mean influence and dependency scores from surveying the research team and performing structural analysis on survey results. Weight and direction of arrows are the same as in (a) based on element types' level and direction of influence. Dashed arrows are important indirect relationships identified from structural analysis. Bolded elements are those with the least ambiguity in classification into an element type based on influence and dependency scores, variation in responses, and confidence of responses. Elements in gray boxes had high ambiguity in classification and were positioned spanning the categories they were most closely related to.



The ongoing revision process

Initial models at each level of the CAMS framework provide the raw materials for ongoing revision. Revision of mid-scale models can occur by connecting fine-scale models through common elements, incorporating new elements that were identified in fine-scale modeling activities into existing mid-scale models, or both. The process of connecting fine-scale models can also highlight additional elements needed to make connections. When all new elements identified through these activities are incorporated into existing or new mid-scale models, we can identify new feedbacks and system behaviors relevant to intermediately scoped research questions (Fig. 1*c* (Step 4)).

New mid-scale models created from fine-scale models can initiate the revision of coarse-scale models (Fig. 1*b* (Steps 1–2)). Existing coarse-scale models can also initiate the revision of mid-scale models (Fig. 1*b* (Steps 3–5)). In the former, revision of mid-scale models provides new elements to consider for inclusion in the coarse-scale model if the team determines that they are not already represented. This can be done by repeating or amending the MICMAC method, or by ad hoc additions of new elements to the model through team discussion. In the latter, the team can discuss the coarse-scale model and identify new questions and modeling needs prompted by its emergent dynamics. For example, we identified the incorporation of traditional watershed knowledges into watershed management as a likely important but uncertain element in our initial coarse-scale model. This prompted a discussion about how our coarse-scale modeling team lacked members with deep knowledge on this topic, and it was decided that the next formulation of a modeling team must prioritize inclusion of community members and researchers with understanding of traditional watershed knowledges and their role in watershed management.

Ongoing modeling and revision will be supported by the storage of detailed model descriptions, metadata, GoldSim player files, and reproducible code in a public repository that is currently under development (tnatlas.erams.com). These materials are also available by contacting the coauthors.

DISCUSSION

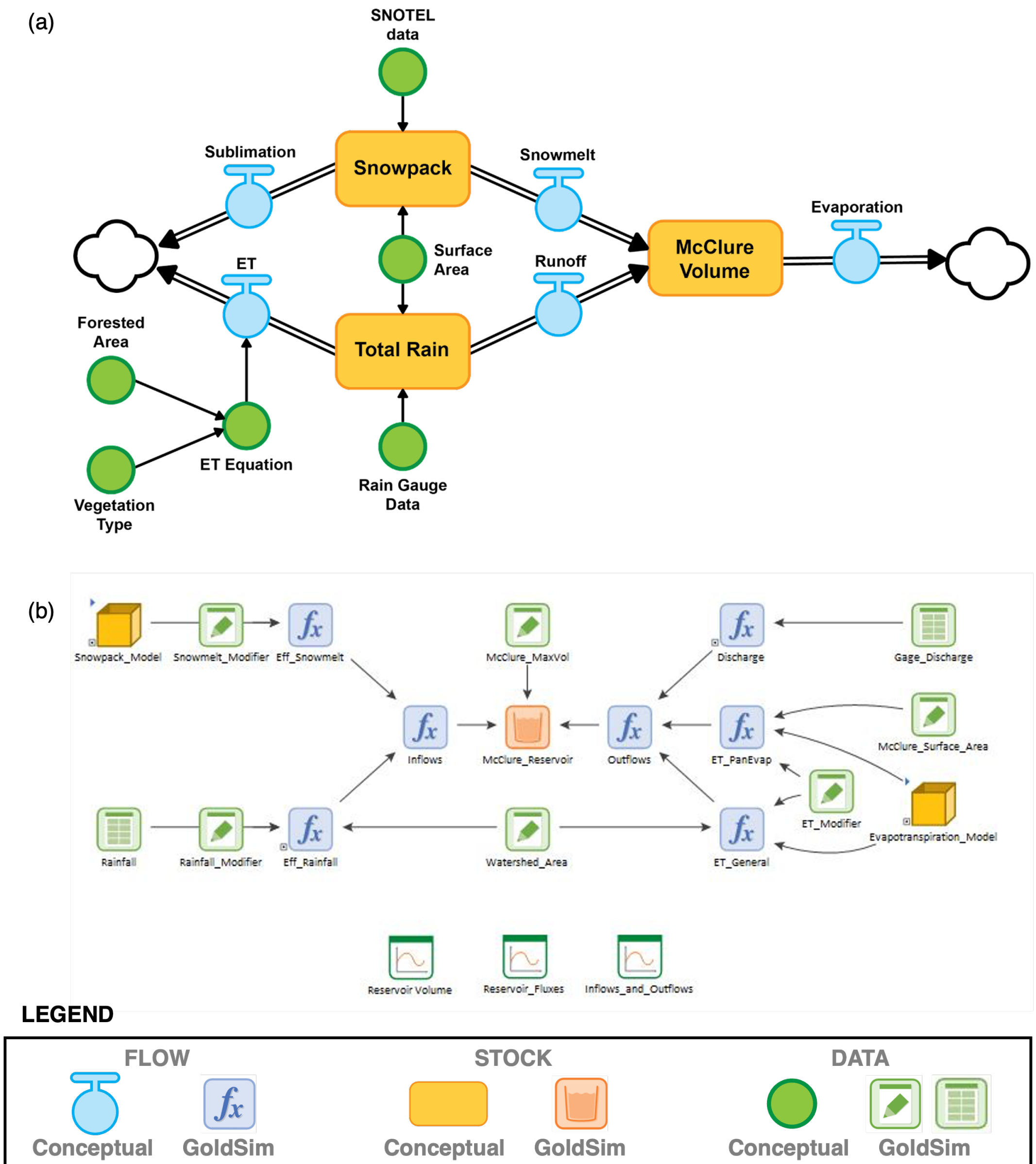
The CAMS framework represents a novel perspective in water resource management by integrating collaborative, adaptive, and multi-scale approaches into a flexible system modeling platform designed for long-term, iterative use. The framework's ability to engage and integrate knowledge across diverse and evolving research teams and model water resource systems across spatial and temporal scales is an important advancement in modeling complex and multi-scale systems. This approach is particularly relevant given the dynamic nature of water resource systems facing unprecedented social, ecological, and hydrological change (Carpenter et al. 2011, Viviroli et al. 2011). The Santa Fe Watershed, with its vulnerability to drought, wildfires, and over-extraction of groundwater, served as an excellent case study for initiating the CAMS framework. The framework's application in the Santa Fe Watershed demonstrated its utility in understanding complex interactions within a water resource system and identifying potential intervention points.

The novelty of this approach also opens considerations for future work. Below, we discuss the framework's strengths and limitations in response to our original research questions, synthesized from reflections of the coauthors.

Strengths: the CAMS framework effectively facilitated cross-discipline convergence research on water resources through its collaborative, adaptive, and multi-scale design

The CAMS framework has the potential to adeptly address the "wicked" nature of water resource management—characterized by uncertainties, risks, and lack of clear resolution paths—by guiding the use of systems thinking methods in convergence

Fig. 5. Example fine-scale system dynamics model investigating the effect of snowpack and rain on reservoir water supply. (a) Conceptual model. (b) Model implemented in GoldSim.



research. One of the most challenging aspects of convergence research and characterizing the multi-faceted nature of wicked problems is the handling and integration of knowledge from many sources about many topics (DeFries and Nagendra 2017, Peek et al. 2020, Morgan et al. 2025). The CAMS framework introduced methodological innovations to address this challenge, including structuring models across three levels (coarse-, mid-, and fine-scale) and employing a "middle-out" approach for model development. This approach balanced the need for detailed information from bottom-up approaches and the cognitive constraints of top-down approaches, allowing for a more nuanced understanding of the system at the early stages of an ongoing research program.

The CAMS framework demonstrated the utility of a multi-scale, multi-model approach in integrating complex information by providing insights that would have been unlikely to emerge from independent modeling projects. One such insight was the role of trust in the Santa Fe Watershed. Trust between various parties was included in three of the four mid-scale models created in the system dynamics modeling workshop, reflecting the important role that workshop participants believed it to play in water resource management (Append. 1*A*). This outcome echoes other research that has identified human relationships as key to successful river management (e.g., Flint et al. 2023*b*). The role of trust in mid-scale models was then synthesized into the coarse-scale model as the concept of social capital (Append. 1*B*).

Notably, the coarse-scale modeling team identified social capital as influential on water resource management but also highly dependent on other factors in the system. This dynamic suggests that it would be a challenging intervention point for changing water management because modifying it could require whole-system change (Arcade et al. 1999). Thus, although trust or social capital is potentially impactful on water management, our results suggest that more research is needed on how to effectively influence highly embedded factors in a deeply interconnected system. Only by considering multiple models across scales did this future research direction become clear.

The framework's collaborative and adaptive design allowed the modeling team to evolve, and this provided important opportunities for convergence. Specifically, the intellectually diverse nature of the modeling teams at every stage of the project tested the framework's ability to deeply integrate varied knowledge. As we expected, the use of multiple system modeling methods harnessed intellectual diversity by mixing quantitative and qualitative approaches. Less expectedly but equally important, we found that working across multiple system modeling methods had the advantage of developing participant's metacognitive skills. Developing metacognitive skills—the process of thinking about one's own thinking and learning—is essential to conducting convergence research because it helps participants understand how other disciplines construct knowledge and thus bridges epistemological divides (Boon and van Baalen 2019). Specifically, the CAMS approach introduced systems thinking to each modeling team by emphasizing the concept of systems as composed of elements and relationships, and prompted discussion of boundary judgements and team members' perspectives on the modeling process throughout. This approach provided a common ground that was understandable from varied disciplinary perspectives and which is shared across systems thinking approaches (Cabrera 2006, Midgley and Rajagopalan 2021), thereby allowing participants to work together using multiple systems thinking tools. Modeling with this foundation developed participant's metacognitive skills by helping participants become aware of how they were setting system boundaries, seeing how elements combined into systems, and appreciating the implications of including and not including different perspectives (Cabrera 2006). The framework thus made use of systems thinking's tradition of methodological pluralism (Box 1) but went beyond it to provide a new convergence-minded approach in "third wave" systems thinking (Midgley and Rajagopalan 2021) by emphasizing metacognitive skills.

Limitations: bridging disciplinary divides is an important first step for convergence research on water resources, but not the last

A central characteristic of contemporary systems thinking is evaluating how the scope and boundaries of a project are set (Box 1), generally referred to as "boundary critique" (Midgley and Rajagopalan 2021). The present study addressed this topic in a novel way by asking if the CAMS framework was inclusive to diverse teams of researchers. In addition, our question about equity acknowledges that future participants—particularly those outside academia—may face considerable systemic barriers that need to be addressed to allow effective and ethical participation in a research team (Hattery et al. 2022).

The coauthors found the CAMS framework inclusive of the disciplinary and epistemological diversity as applied here, which was broad in an academic sense but not in other ways. This was facilitated by the design of the framework as collaborative across disciplines and scales and adaptive to evolving team membership. For example, coauthors reported that knowing that models could be iterated on over time allowed space for team members to participate at different stages according to their changing capacities. The fact that the facilitators were knowledgeable of and experienced with inclusive practices in academic settings also facilitated the effective use of self-reflection, structured sharing activities, and discussion of participants' relationship to the research across modeling activities to break down power structures within the research team and make the process more collaborative and inclusive (Hattery et al. 2022). One outcome of prioritizing inclusion was the development of the related Fuzzy SETS framework, which allowed different views about social, ecological, and technological system elements to coexist without violating the principles of others (Lin et al. 2025).

Inclusion across academic settings was also sought in the initial recruitment to the mid-scale workshop. The workshop was broadly advertised through email listservs subscribed to by researchers interested in water resources at the University of New Mexico and through the Intermountain West Transformation Network, a collaborative research network described elsewhere in this Special Feature (see Morgan et al. 2025). However, we note that initial recruitment and participation strongly influenced team membership and modeling elements explored thereafter, and therefore functioned as a bottleneck to intellectual diversity included in the first iteration of the framework. To test the bridging of additional disciplinary and epistemological divides, the team's composition could have been evaluated and revised at an earlier date.

Adding novel disciplinary and epistemological perspectives was further encouraged by the adaptive design of the CAMS framework through its embedded revision process. For example, evaluating uncertainty in the coarse-scale structural analysis was novel to this study and effectively highlighted important gaps in expertise in the research team around the role of traditional knowledges in watershed management. In addition, discussing existing models provides a point of entry that may be appropriate and accessible for new collaborators and prompts formulation of new coarse- and fine-scale models (Fig. 1*b*–*c*). As an example, one of our initial mid-scale models suggested that trust between community members and local news media organizations is a key factor influencing the effective uptake of information from public water education campaigns (Append. 1*A*). This hypothesis could be explored by discussing it with community members and including them in the process of developing a fine-scale model using techniques from the Group Model Building literature (Richardson and Andersen 1995, Vennix 1996, Rouwette 2016). Such hypotheses can also be explored by seeking new collaborators with data or data-gathering methods appropriate for parameterizing models (Fig. 1*c* (Step 1)).

To allow for even broader collaboration, community members and other researchers can be engaged in future work in the formulation of new questions, elements, or models at any scale without any engagement with prior versions. These elements can replace existing elements in the framework entirely, be integrated into existing models through the revision process, or be used to reflect on the influence of the participants' disciplinary and epistemological perspectives. Together, these revision approaches provide a continuum of possible collaboration—from simple outreach to true co-creation of research—so that the CAMS framework can be applied appropriately to various contexts and stages of community partnership (Carson et al. 2022). However, ongoing use will push the framework's capacity to remain inclusive and integrative of diverse perspectives beyond what could be evaluated in the present study.

As adaptive revision processes occur, additional and larger epistemological divides will challenge the framework's adaptability. For example, more accessible approaches are needed to effectively integrate complex social dynamics like trust in quantitative systems dynamics models (Luna-Reyes and Anderson 2003, Gunda et al. 2018). Our fine-scale modeling teams found this challenging, and as a result, their system dynamics models tended to favor readily quantifiable elements such as reservoir levels. Further still, ontological divides—different ways of perceiving reality—may become apparent. For example, the coarse-scale modeling team identified traditional knowledges as a potential input to the system. This revealed that the team was unable to understand such knowledge as intrinsic to the living whole of a water resource system, as some Indigenous perspectives might describe it (Chief et al. 2016, Muller et al. 2019). Bridging such divides may be essential to conducting truly innovative convergence research (Morgan et al. 2025). To address this challenge and realize it as an opportunity, the CAMS framework must incorporate emerging "fourth wave" approaches in systems thinking that move beyond rational analysis to embrace experiential, presentational, and practical ways of knowing (Midgley and Rajagopalan 2021).

With more epistemological, ontological, and methodological diversity, creating an inclusive environment within research teams will become more challenging and more important. Convergence-minded research techniques, such as systems thinking, are tools to create inclusive research teams because they remove some technical barriers between participants to facilitate collaboration. However, we assert that inclusivity is not only a prerequisite for convergence research but is its very foundation. Effective inclusivity extends beyond simply amplifying marginalized voices; it shapes our approach to convergence research, ensuring that pursuit of novel insights is rooted in ethical practices that transcend transactional or extractive models of research. Thus, it is crucial for facilitators to know the audience and be trained in inclusive practices for that audience, or, better yet, share the identities and perspectives of marginalized members of the research team (Hattery et al. 2022). Still, those representing larger epistemological and ontological divides might want to keep their knowledge separate from modeling activities even if "fourth wave" systems thinking ideas and inclusivity are achieved (Muller et al. 2019). As such, more research is needed on how the CAMS framework can be used alongside diverse ways of knowing as a complementary tool rather than a means to integrate it with other knowledge.

Continuing use of the CAMS framework should further consider how inclusion and equity influence team evolution and how this influences models. In the present application, some members of the mid-scale modeling team opted out over time, particularly in the transition from an intensive workshop to more protracted methods of coarse- and fine-scale modeling. We do not know if this reflected a lack of a sense of belonging (an inclusivity issue), a lack of bandwidth (an equity issue), or simply a lack of interest. We do know that it impacted the coarse-scale model, as demonstrated by uncertainty about traditional knowledge's role in watershed management (Fig. B5, B7 in Append. 1*B*). Future work should evaluate in more depth how the makeup and consistency of evolving research teams impact model development, especially as more non-academic participants become involved. Such work could explicitly compare what is prioritized by different research teams and use the results to reflect on how participant identities and relationships to the research impact results. Future work should also provide financial incentives when possible to reduce team turnover and address equity barriers for early career researchers and non-academics. Despite these uncertainties, we note that the CAMS framework adeptly allowed modeling to progress as the team evolved, which is essential to promoting its long-term use and its responsiveness to new information and collaborative opportunities.

CONCLUSION

Convergence research, driven by deep integration and co-production of knowledge within diverse teams, is needed to better anticipate and plan for a challenging future for water resource management. We developed and applied a new framework to build a convergence research team around the task of characterizing the Santa Fe Watershed as a complex system and hypothesizing water management dynamics there. The CAMS framework successfully engaged and integrated the knowledge and interests of an intellectually diverse research team and modeled water resource management in the Santa Fe Watershed across spatial and temporal scales. The insights gained from this case study, such as the potential importance of trust and traditional knowledges in watershed management, can inform more effective and sustainable water management strategies.

Beyond its innovations toward adaptively characterizing complex, multi-scale systems, applying the CAMS framework highlighted the essential role of inclusivity in convergence research on water resources. Water resource systems are replete with multifaceted stakeholder perspectives and management dynamics that require diverse research teams to characterize. Inclusivity in convergence research goes beyond mere representation; it creates a culture of belonging to ensure that participants from different perspectives feel valued and heard. Inclusive environments encourage open communication, collaboration, and the co-creation of knowledge, facilitating a deeper integration of ideas. Ultimately, inclusion in convergence research not only enhances the quality and depth of insights but also contributes to the ethical and equitable advancement of knowledge. This lays the foundation for more effective solutions to the complex issue of water resource management. For the CAMS framework to be used to identify strategic interventions in water management, inclusivity must be a core consideration.

Author Contributions:

AJW and YCL coordinated the development, conceptualization, design, and analysis of the study, and share co-first authorship for this article; AJW wrote the original draft of the manuscript and led the revision process. CS additionally contributed to the analysis. Author names are listed according to the degree of significant contribution (first three authors), then listed alphabetically to indicate equal contribution in discussion of concepts in the original workshop (six sessions, January–February 2022) and monthly follow-up meetings through 2022. MCS is placed as the senior last author position to signify unique contributions to project oversight, mentorship, and funding acquisition. All authors also participated in revising and editing the manuscript, and all authors approved the final manuscript.

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Data Availability:

The data and code that support the findings of this study are available at https://github.com/ajwebster2/CAMS-SDM and archived at https://doi.org/10.5281/zenodo.14927689. Ethical approval for this research study was not required.

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APPENDIX: Facilitating convergence research on water resource management with a collaborative, adaptive, and multi-scale systems thinking framework

APPENDIX CONTENTS:

APPENDIX A: WORKSHOP DETAILS

To illustrate the Collaborative, Adaptive, and Multi-Scale (CAMS) system thinking framework in action, we initiated the process at the mid-scale with a six-part workshop series in January 2022 using techniques from the Group Model Building literature (Richardson and Andersen 1995, Vennix 1996, Rouwette al. 2016). The Group Model Building literature describes a series of group facilitation techniques linked to computer models developed with a group in a meeting setting. Our workshop brought together researchers from a wide range of disciplines and levels of expertise to learn about systems dynamics modeling, hypothesize dynamics in a case study watershed (the Santa Fe Watershed, New Mexico (see Box 1)), and model those dynamics. All workshop meetings were conducted online to allow for remote participation and uncertainty around in-person meetings during the COVID-19 pandemic.

Before the workshop, the facilitators did a literature review, including of the gray literature, local news media, and preliminary results from a recent stakeholder assessment (Henderson et al. 2022), to describe 12 broad themes related to water sustainability concerns in the Santa Fe Watershed. These were: (1) water quality; (2) water quantity; (3) ecological and hydrological restoration; (4) public water education; (5) water planning – cooperation and transparency; (6) water planning – innovation and resilience; (7) forest management for wildfire; (8) outdoor recreation and access; (9) building cultural competencies to better enable the incorporation of Indigenous perspectives on water; (10) sustainable development and planning; (11) recognition of Pueblo and acequia water rights; and (12) stormwater management. We first presented these themes in an informational meeting in December 2021 that invited people to participate in the workshop. The workshop was broadly advertised through email listservs subscribed to by researchers interested in sustainable water management at the University of New Mexico and through a collaborative research network (the Intermountain West Transformation Network, described elsewhere in this issue (e.g., Morgan et al. *this issue*)). The purpose of presenting the themes was to provide potential workshop participants that were not directly familiar with the Santa Fe Watershed context to identify how their expertise could be relevant. The one hour informational meeting also described the goals of the workshop series, the time commitment, and specific anticipated outcomes. At the end of the informational meeting, participants indicated their interest and commitment to participating in the workshop. Interested parties filled out a survey describing their interests and expertise, which we used to select and target activities in the remaining workshop.

Workshop Day 1: Taking ownership

On the first day of the workshop, we discussed systems dynamics modeling and did three exercises designed to understand who the participants were and support participants in taking ownership of the workshop. In the first exercise, participants self-identify on a stakeholder biplot. This involved participants opening a shared virtual plot and placing a dot on the plot according to how they perceive that they personally affect dynamics in the Santa Fe Watershed in comparison to how they are influenced by dynamics in the watershed (Figure A1). The exercise provided a point of reflection for individuals, and also quantified participant positionality (Dhirasasna and Sahin 2019). The reflexive nature of this exercise intended to set the stage for participants to discuss how their own and others' positionality impacted their perspective on the watershed throughout the workshop. Participants primarily identified as moderately to not influenced or affected by dynamics in the Santa Fe Watershed (Figure A1). This was expected given the target audience of academic researchers located at universities nearby but outside the watershed. It was important to identify one researcher who owned land inside the watershed and who had relationships with water managers there, and thus identified as more affected and influential.

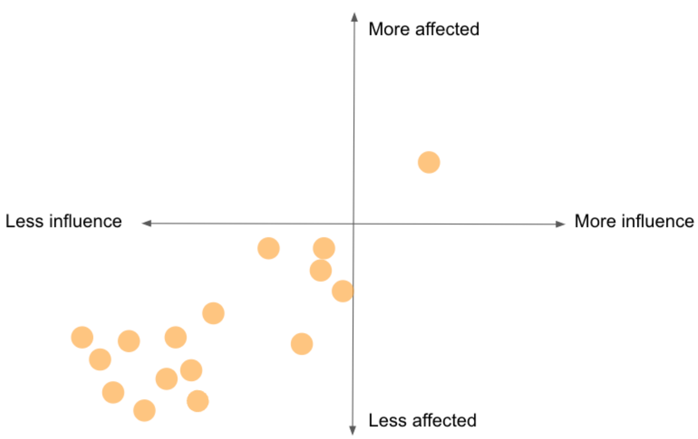


Figure A1: *Results of biplot exercise. Each orange dot was placed by a workshop participant to indicate the extent they believed they were able to influence dynamics in the Santa Fe Watershed (x axis) and the extent they believed they were affected by dynamics in the Watershed (y axis).*

The second exercise was to discuss and revise the 12 themes introduced in the informational session to reflect a shared understanding. Revisions included rewording (1) "water planning – cooperation and transparency" to "cooperation and conflict in water planning, management, and governance" and (2) "water planning – innovation and resilience" to "innovations in water planning, management, and governance". Discussing and revising the themes required talking across disciplines to begin to build a shared vocabulary and set the stage for hypothesizing what may drive the behavior of the system. Finally, participants identified which themes they had expertise in, interest in, or which were entirely unfamiliar with. This exercise provided a point of reflection as in the biplot exercise, but now in the context of mapping themselves onto the revised themes.

Workshop Day 2: Discover and define variables influencing the watershed

Two fundamental concepts in systems thinking are an openness to complexity and a dynamic perspective. In other words, in complex systems, many factors interact and those factors change all the time (Anderson and Johnson 1997). To emphasize these concepts, we did two connected exercises on the second day of the workshop. First, participants freely brainstormed variables across the theme categories discussed on the previous day. We defined variables as elements or parts of the system that are in some way quantifiable and can change over time. Variables perceived outside the themes were allowed. A total of 196 unique variables were identified. Second, participants broke out into groups of 3-5, selected variables of shared interest from the brainstormed list, and collaborated to draw conceptual graphs of how they expected those variables to have changed or will change over time in the Santa Fe Watershed. This "graphs over time" exercise guided participants to think about variables dynamically (Figure A2, Hovmand et al. 2012). We ended the day with a whole-group discussion and found that participants improved their ability to identify and define a variable that is appropriate for use in systems dynamics modeling.

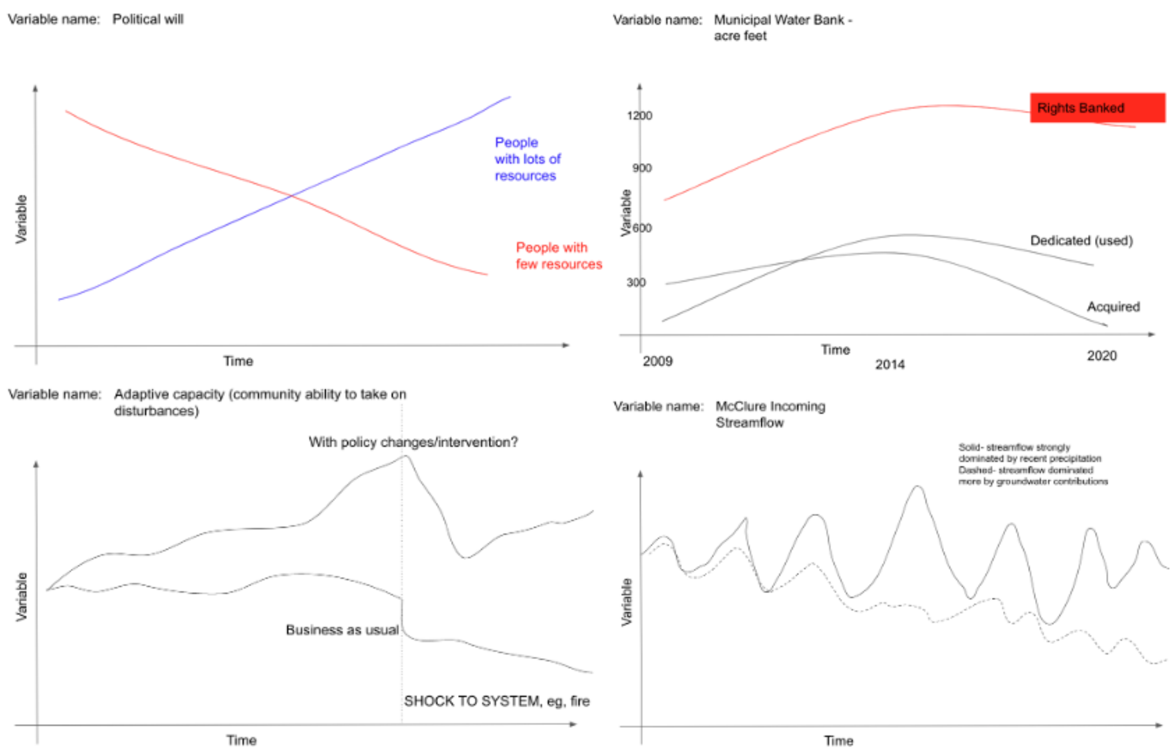


Figure A2: *Example results of group "graph over time" exercise.*

Workshop Day 3: Produce research questions

The third day of the workshop focused on co-producing research questions. Participants broke out into new teams of 3-5, assembled the "graph over time" cards they found interesting, and attempted to connect the graphs with arrows to conceptualize how variables might influence each other. The groups then articulated a research question related to the connections between variables and uncertainties among them. This exercise intended to guide participants to co-produce novel questions based on their shared knowledge, interests, and knowledge gaps, rather than using pre-formed research questions from their disciplinary specialties. The resulting questions included:

- What are the connections between trust and adaptive capacity in the Santa Fe Watershed?

- Under what conditions does information/education increase water conservation or attitudes about water conservation in the Santa Fe Watershed?
- What are the natural controls on water that's available for natural systems, human populations (agriculture, urban, periurban, rural) given climate change?
- How is policy change efficacy impacted by disconnects between information, knowledge, and behavior resulting from the failure to integrate the Indigenous perspective, deprioritization of relationship and trust building, and the resulting inadequacy of information and holistic/inclusive knowledge development in the Santa Fe Watershed?

Workshop Day 4: Model subsystems to address research questions

Participants moved from conceptualization to building systems dynamics model diagrams on day four. The day started with a presentation on stock and flow modeling, in which stocks, inflows, outflows, intermediate variables, and system boundaries were defined with generic shapes and diagrams to create a shared "visual vocabulary". Participants were also provided examples on how stocks and flows control dynamics in familiar systems (e.g., water in a bathtub, money in a bank account, CO_2 in the atmosphere). Participants then self-selected into teams to work on a research question identified in the previous workshop day, and used a virtual set of stock, flow, and variable shapes to create a stock and flow diagram relevant to the question. Participants were encouraged to discuss and indicate their uncertainty about elements and relationships within their diagrams with numeric values (4 for very certain to 1 for very uncertain) or in notes associated with the diagram.

Workshop Day 5: Refine subsystem models and make connections across subsystems

The fifth day of the workshop was spent refining subsystem models in a system dynamics software, then identifying connections across subsystems through storytelling. We had participants work within Insight Maker (Fortmann-Roe 2014), which is a free, web-based, general-purpose simulation and modeling tool that allows collaborative model-building. Insight Maker guided participants to refine their models to fit systems dynamics conventions. Insight Maker also provides a tool to identify feedback loops and provides a list of these loops, which were used to identify interesting and potentially counterintuitive interactions and dynamics. After working in the software for much of the day, teams spent time identifying and articulating a story about a feedback that had emerged from their refined models to the larger group. For example, the team addressing the influence of information and education on water conservation described a hypothesized feedback they identified, in which public information impacts water use policy through how it first shapes water use behavior. They also identified trust as an influence on this feedback through how it may impact the uptake and loss of public information and knowledge. Through these discussions, we identified trust as a key stock shared by three out of the four models, and municipal water storage as a stock shared by all four models.

Workshop Day 6: Review results and work on next steps

The final day of the workshop was spent reviewing the results of the workshop and discussing next steps. Much of this discussion centered on challenges around defining scope and scale in system dynamics models to accurately represent hypotheses and research questions. It was concluded that important next steps should include a) synthesizing the four models created in the workshop into one broader model, and b) creating opportunities to refine parts of the four models into more detailed, finer-scale models.

To these ends, the facilitators proposed leading development of one broader model using methods from the *la prospective* literature (e.g., Godet 1986) and solicited interest from participants to continue work together on that next step. Facilitators also proposed leading development of finer-scale models with graduate student researchers through the development and teaching of a class on environmental modeling, and solicited students in the workshop and affiliated with the participants to enroll in the class. The workshop ended with a survey designed to capture the successes and limitations of the workshop in facilitating transdisciplinary collaboration.

After the Workshop: Revising Workshop Products into Mid-scale Models in GoldSim Software

Transitioning the workshop models into *GoldSim* initially began as purely transferring components of conceptual models (i.e., stocks, flows, converters, and links) into the visual *GoldSim* modeling space. Within this environment, components of the system had to be defined as discrete elements of various types. Within this software, elements are defined using appropriate data and/or formulas, then linked to other elements that have direct influence. System inputs are typically modeled using data elements, outputs are shown using result elements, and stock and function elements lie in between to model relationships between inputs. Some components of the conceptual model are more clearly implementable between conceptual space and a quantitative modeling, i.e., *GoldSim*, space. For example, with quantitative system components like streamflow, data can be directly transferred to an appropriate input element in *GoldSim.* For qualitative elements like trust – which was a major theme of the workshop – the quantitative representation of those dynamic relationships requires additional consideration and calibration. We note that while there are no "absolute" values associated with these types of intangible variables, the focus of modeling qualitative variables is important for understanding their relative values and dynamic behaviors.

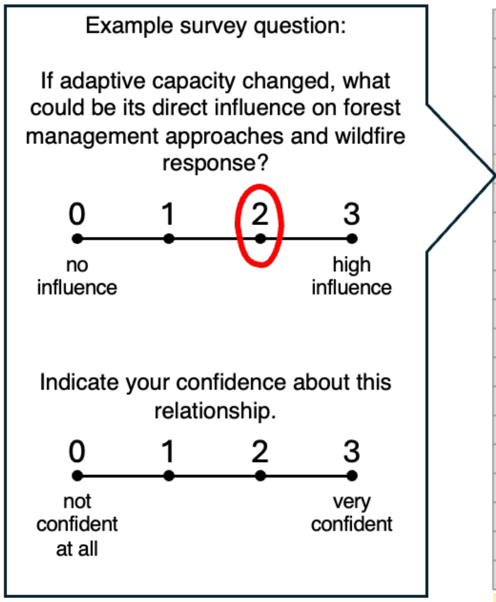
APPENDIX B: CROSS-IMPACT MATRIX MULTIPLICATION ANALYSIS (MICMAC) DETAILS

Background on the MICMAC method and its application in the CAMS framework

Cross-impact matrix multiplication applied to classification (matrice d'impacts croisés multiplication appliquée á un classment (MICMAC)) is a structural analysis method used to study or hypothesize relationships among variables representing a complex system. The method was developed by Jean-Claude Duperrin and Michel Godet starting in 1973 (Duperrin and Godet 1973) and has been refined over time through application and software development (Godet 1986, Arcade et al. 1999, Ahmad et al. 2019, Dhirasasna and Sahin 2019, Bashir et al. 2020). MICMAC classification is based on a combination of expert opinion and systems theory and is meant to reveal the role of each element in guiding the behavior and outcomes of the whole system.

We wish to recognize that the spelling of the acronym 'MICMAC' is the same as a common but incorrect, colonially-imposed spelling of the name of the Mi'kamaq First Nations people. This similarity is an unintentional outcome of the original French name for this method. We have retained use of the acronym to maintain its connection to previous work on the structural analysis method, but reinforce here that it has no intended relation to the Mi'kamaq First Nations people.

Element selection can be done through surveys, literature reviews, or working groups of stakeholders, experts, or other interested groups. Elements are components of the system and are often also referred to as variables in the literature. Here, an initial list of elements was brainstormed in a workshop of interested researchers, revised throughout the workshop, then aggregated and reduced through a series of smaller working groups (see Table B1 and Lin et al. *this issue*). Once elements were selected, participants scored the direct influence of each element on each other element in a survey. Specifically, participants received a survey for each element x asking "If [element x] changed, what could be its direct influence on [element y]?" for every possible element y. Participants answered on a scale of 0 (no influence) to 3 (high influence), and also indicated their confidence about the relationships on a scale of 0 (not confident at all) to 3 (very confident). This resulted in 20 surveys of 19 questions each, which participants completed based on their interest and expertise in each element. A glossary defining each element was available during the survey. Survey responses resulted in a matrix of influences and dependencies from each response (Figure B1).



	ad_cap	ag_h2o	biodiv	eco_serv	disturb	for_mgmt	gov_pol	trad_know	inf_gov	infra	lulc	city_h2o	ws_edu	soc_cap	soil	tech_inn	h2o	ws_econ	wtr_clm	fire
ad_cap	0	3	3	3	3	3	3	3	2	2	3	2	2	3	2	3	3	3	3	3
ag_h2o	2	0	2	2	2	2	3	2	2	2	3	2	1	2	2	3	3	3	3	2
biodiv	2	2	0	2	3	3	2	2	2	2	3	2	1	1	3	2	3	2	3	3
eco_serv	2	2	3	0	3	3	2	2	2	2	3	2	1	1	3	2	3	1	3	3
disturb	2	2	2	2	0	2	2	2	1	2	2	1	1	2	2	2	2	1	3	2
for_mgmt	2	1	2	2	2	0	3	3	2	2	2	2	2	2	2	2	3	2	3	3
gov_pol	2	2	2	2	2	2	0	2	2	2	2	2	2	3	1	2	3	3	2	2
trad_know	2	2	1	2	2	2	2	0	2	1	2	1	2	3	1	2	2	2	1	2
inf_gov	2	2	1	2	2	2	3	3	0	2	2	2	2	3	1	2	2	3	2	2
infra	2	2	1	2	2	2	3	2	1	0	2	2	1	2	1	2	2	3	2	2
lulc	2	3	2	2	3	3	3	3	2	2	0	2	1	2	3	2	3	2	3	3
city_h2o	2	3	1	2	2	2	3	2	2	3	3	0	3	2	2	3	3	3	2	2
ws_edu	2	2	2	2	2	2	2	3	2	2	1	2	0	2	1	2	2	2	2	3
soc_cap	3	2	1	2	2	2	2	3	3	3	2	2	3	0	1	2	2	2	2	2
soil	2	3	3	2	3	2	1	2	1	2	3	2	1	1	0	2	3	1	3	3
tech_inn	2	2	1	2	2	2	2	2	2	2	2	2	2	2	1	0	3	3	2	2
h2o	2	3	2	3	3	3	3	2	2	3	3	3	2	2	3	3	0	3	3	3
ws_econ	2	3	1	3	2	2	2	2	2	3	3	3	2	2	1	2	3	0	2	2
wtr_clm	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	0	1
fire	2	1	2	2	3	3	2	2	2	2	3	1	1	2	2	2	2	1	3	0

Figure B1: *Example matrix resulting from survey responses from one respondent, and example survey question from which the matrix value was derived. We also show the related survey question about confidence but do not show the resulting matrix of confidence values. See Table B1 for the long names and definitions of element abbreviations shown.*

The resulting matrices and networks of influences are inevitably complex and require a structural analysis to summarize. Responses are summarized into mean influences and dependencies, while response variation is summarized by the standard deviation of responses. Here, we additionally asked about respondents' confidence in their answer and this was summarized into a mean confidence and standard deviation for each element's influence. Each element's total influence is the sum of mean influences (the sum of matrix columns). Each element's total dependence is the sum of mean dependencies (the sum of matrix rows).

Each element's relative influence and dependence is used to classify its role in the system. MICMAC categorizes elements into four main groups and eight subgroups (see Table B2, summarized from Arcade et al. 1999). MICMAC also identifies indirect relationships and highlights any cases in which a variable has a higher influence through indirect relationships compared to direct relationships. Variable classification and indirect influence analysis aim to stimulate reflection about sometimes counterintuitive results. Here, response variability and certainty were additionally used to interpret results (Arcade et al. 1999).

MICMAC results are often used to inform development of causal loop diagrams and other types of systems models. Here we introduce a novel application of MICMAC results to create a broadly-scoped conceptual model. We first interpreted the MICMAC element types into a conceptual model template that highlights exogenous versus endogenous versus "core" endogenous variables and their interrelationships. "Core" endogenous variables are those most central to the internal dynamics of the system. We then mapped our MICMAC results onto this template (Figure 3 in main text).

Table B1: Elements considered in the MICMAC analsyis with element names, abbreviated element names referenced in subsequent figures, definitions, and citation for definitions included where applicable.

Element name [abbreviated name]	**Definition**
Adaptive capacity [ad_cap]	A component of resilience that reflects the learning aspect of system behavior in response to disturbance. Systems with high adaptive capacity are more able to re-configure without significant changes in crucial functions or declines in ecosystem services (i.e., they have more resilience). Adaptive capacity in ecological systems is related to genetic diversity, biological diversity, and the heterogeneity of landscape mosaics. In social systems, the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups play an important role in adaptive capacity. Definition adapted from: Carpenter et al. 2001, Folke et al. 2002.
Agricultural water use [ag_h2o]	The total amount of water withdrawn or diverted from its source to be used for growing, harvesting, or packing of crops and rearing of animals for food and fiber. Definition adapted from: Reig 2013, CDC 2016, "Agriculture" 2023.
Biodiversity [biodiv]	The diversity of genes, populations, species, communities, and ecosystems across scales, including alpha, beta, and gamma diversity at different scales. Alpha diversity refers to the diversity within a particular area or ecosystem, and is often expressed by the number of species (i.e., species richness) in that ecosystem. If we examine the change in species diversity between several areas or ecosystems, we are measuring the beta diversity. Gamma diversity is a measure of the overall diversity for the different areas or ecosystems within a region. Definition adapted from: Bynum 2022; Mace et al. 2005.
Ecosystem services [eco_serv]	Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth. Definition adapted from: Millennium Ecosystem Assessment 2005.
Environmental disturbance regimes (ecological, climactic, pollution-caused) not including fire [disturb]	The type, size, frequency, severity, and timing (i.e., the regime) of events or series of events that disrupt ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment. Disturbances can be press forcings, meaning they cause cumulative disruption gradually, or pulse forcings, meaning they are relatively discrete. Definition adapted from: Collins et al. 2011, Pickett and White 1985.
Forest management approaches and wildfire response [for_mgmt]	The combined scientific, technical, administrative, legal, economic, and social activities and planning processes that are applied to forest ecosystems by humans to achieve a desired set of ecosystem services. We include in this how wildfires are responded to and managed as discrete events and series of events. Definition adapted from: FAO 2020.
Formal (legal) governance, policy, and policy innovations [gov_pol]	The "written" rules, regulatory processes, mechanisms, and organizations through which political actors influence actions and outcomes and innovate. Contrast to informal governance. Definition adapted from: Chaffin et al. 2014, Steelman 2022.
Incorporation of traditional watershed knowledges into broader understanding and approaches [trad_know]	The extent to which the knowledge, histories, innovations, and practices of indigenous and local communities are incorporated into shared public understanding about a watershed, as well as systems of formal and informal governance, policy, management, and other activities in a watershed. Definition adapted from: ANSC 2023, *Traditional Knowledge* 2023.
Informal governance	A set of "unwritten" rules, practices, and social networks that develop and are

[inf_gov]	maintained outside of formal legal rules, practices, organizations/institutions through which political actors (individuals, groups, and entities with political influence) influence actions and outcomes. Definition adapted from the following references to make more specific to informal forms: Chaffin et al. 2014, Steelman 2022.
Infrastructure [infra]	The physical systems involved in the production, storage, and/or transportation/distribution of public goods. Can include human-made and non-human made components that are interconnected. Definition adapted from: EPA 2023, Investopedia 2023.
Land use land cover [lulc]	Structural heterogeneity of the land surface, including the physical attributes of vegetation, surfaces, and structures on the landscape, as well as attributes that reflect human decisions about how land is used. Definition adapted from: Cadenasso et al. 2007.
Municipal water use [city_h2o]	The total amount of water withdrawn or diverted from its source to be used in the public water supply system, which may include domestic use, industrial use, and municipal landscaping, among others. Definition adapted from: Kohli et al. 2010, Reig 2013.
Public watershed education approaches and knowledge [ws_edu]	Interdisciplinary place-based education both inside and outside of schools, aimed at the public broadly, that is integrated by its relevance to how a particular watershed functions, and the knowledge accumulated by the public through this process. Definition adapted from: "Public Education" 2023, Stapp 2000.
Social capital [soc_cap]	The benefits derived from being social, including the store of solidarity, goodwill, and trustworthiness between people and groups of people, the nature of these social connections, the norms and shared understandings that influence our action and interaction. Definition adapted from: Claridge 2020, 2014.
Soil structure and function [soil]	The organization of soil's abiotic and biotic components and how this determines its stability, its ability to support life, and how it exchanges nutrients, energy, and water with connected environments. Definition adapted from: Ponge 2015.
Technical innovations [tech_inn]	A new idea, method, or device that improves application of scientific knowledge to fulfill practical human needs. Definition adapted from: "Innovation" 2023, "Technology" 2023.
Water quantity, quality, and availability [h2o]	The extent to which water is present, available, and suitable for a particular use based on its spatial, temporal, physical, chemical, and biological characteristics. Definition adapted from: Cordy 2001.
Watershed economics [ws_econ]	The production, distribution, and consumption of wealth within a watershed. Definition adapted from: Blaug 2023.
Weather and climate regimes [wtr_clm]	The combination of air pressure, temperature, humidity, wind speed and direction, precipitation, solar radiation and other events in our atmosphere over the short and long term and how these manifest into forcings of different types, sizes, frequencies, severities, and timings. Definition adapted from: NOAA NCEI 2018.
Wildfire regime [fire]	The type, size, frequency, severity, and timing (i.e., the regime) of wildfire events. Definition adapted from: Pickett and White 1985.

Table B2: Types of elements based on the influence and dependence plot as per the MICMAC structural analysis method. Summarized from Arcade et al. (1999).

Element category	**Element sub-category**	**Definition**
Influent		Very influential with little dependence. Can act strongly on the system. Can be considered input variables.

	Environmental	Conditions the system and cannot be controlled
	Determinant	Some dependence. Key factors influencing the system
Relay		Very influential and very dependent. They have a consequence on other variables if they are impacted
	Stake	The 'potential breakpoint of the system' due to their strong simultaneous influence and dependence. Can have a strong influence on the system as a whole.
	Target	More dependent than influential, resulting from the system's evolution. Can strongly influence the system if guided through strong action.
Dependent		Little influence and very dependent, sensitive to changes of influent and relay variables
	Exit	The outcomes or results of system dynamics
Excluded		Relatively disconnected from system dynamics
	Disconnected	Mostly autonomous; may be in system but do not strongly guide or result from its dynamics
	Secondary levers	More influential than dependent. Can serve as secondary leverage points to change system outcomes
	Regulating	May weakly act as secondary levers, targets, stakes, or determinants

MICMAC Results and Discussion

Survey responses by variable

Members of the research team received a survey for each element x asking "If [element x] changed, what could be its direct influence on [element y]?" for every possible element y. This resulted in 20 surveys of 19 questions each for a total of 380 possible questions. Participants completed surveys based on their interests and abilities. Response rates varied by element x (Figure B2). The most responses (9 out of 12 possible) were received for questions asking about the influence of biodiversity, municipal water use, and weather and climate regimes. The least responses (5 out of 12 possible) were received for questions about the influence of land use/land cover and watershed economics.

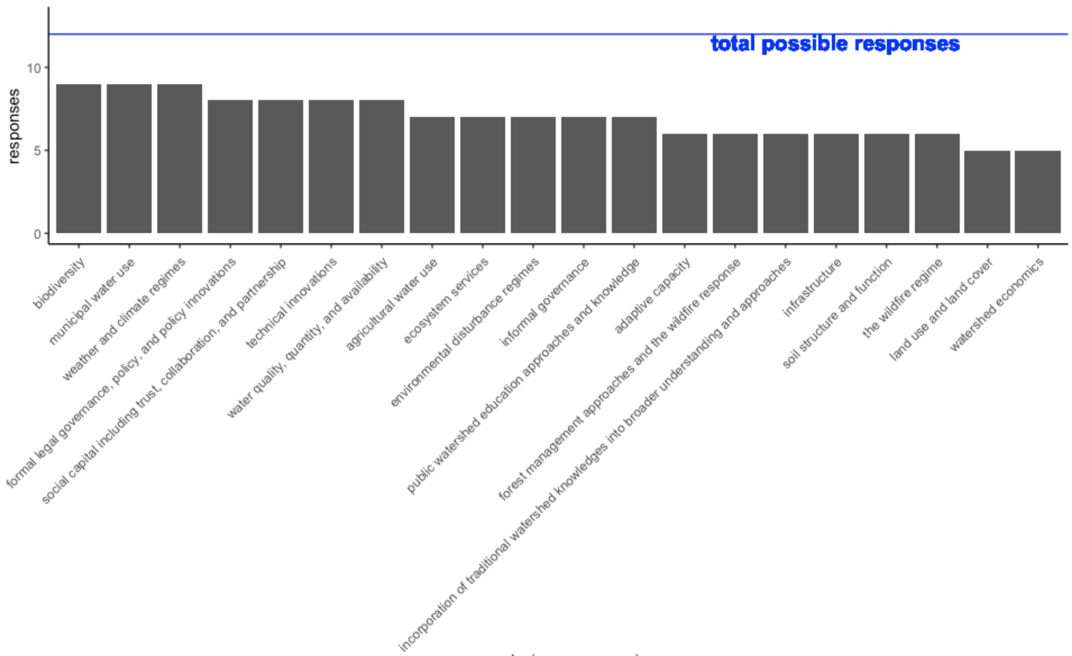


Figure B2: *Number of unique survey responses by element, sorted by highest to lowest number of responses.*

Direct Influence and Dependence

The below matrix heat maps are challenging to interpret by themselves, but are useful for questions about specific relationships when viewing results that are aggregated, such as in the Influence-dependence Plot (Figure B7). A few general insights are apparent:

- A majority of elements have strong to intermediate direct influences and dependencies (Figure B3), indicating that this is a highly connected and complex network of relationships. Two exceptions are soil structure and function which has relatively low influence, and weather and climate regimes which are strongly influential but relatively low dependency (see blue vertical column in Figure B3). These relative influences and dependencies are better summarized in Figure B7.
- Variation in responses among survey-takers was low for most relationships (Figure B4). In fact, many relationships had zero variation in responses. Among these, the elements with the most zero-variation responses were about the influence of environmental disturbance regimes, land use/land cover, forest management and the wildfire response, social capital, and weather and climate regimes. Nevertheless, some elements had high variation in responses, such as the influence of soil on other elements.
- Confidence reported by survey participants was mostly near the middle of the range (Figure B5). A few notable exceptions with high confidence were the influence of weather and climate regimes on wildfire regimes, weather and climate regimes on water availability, social capital on informal governance, and water availability on biodiversity.
- Variation in confidence was variable (Figure B6). One notable exception was the influence of adaptive capacity on other elements, which had generally high variability in confidence among survey-takers.

Direct influences and dependencies, including variation and confidence, are summarized in the Influence-dependence Plot (Figure B7). This plot allows classification of elements into the categories in Table B2. In general, the system has many relay elements, which indicate an unpredictable and unstable system (see Figure B8). In the words of Arcade et al 1999: “These variables.. are by nature factors of instability since any action on them has consequences on the other variables in case certain conditions on other influent variables are met. But these consequences can have a boomerang effect which either amplifies or forestalls the initial impulse”. In other words, these elements are involved in feedbacks that maintain system behavior and control outcomes.

Stake elements are relay elements with a particularly acute mix of dependency and influence, and are thus considered possible fracture points in the system. Unsurprisingly for a semi-arid watershed, water quality, quantity, and availability is one of these fracture points. Survey participants were also on average very confident about the influence and dependence of this element. The other clear stake element was formal governance, policy, and policy innovations. Interestingly, survey participants were very confident about the influence of this element but not as confident about its dependence. What influences formal governance, policy, and policy innovations and whether it is indeed a fracture point in the system may therefore be a good subject for future research.

Contributing to the unstable effect more is the fact that we identified no determinant elements, which are those that can act as key influenceable controls. In other words, determinant elements are relatively easy-to-access leverage points in the system. In contrast, weather and climate regimes strongly condition the system but cannot be controlled, and thus make for poor leverage points. We also identified many depending elements. These elements are products of the system’s internal dynamics and are difficult to change without changing the whole system. Depending elements therefore also make for poor leverage points because they are hard to access. The closest element to the determinant element range was “incorporation of traditional watershed knowledges into broader understanding and approaches”. However, this element also had the lowest mean confidence of responses. This may make it a good subject for future research.

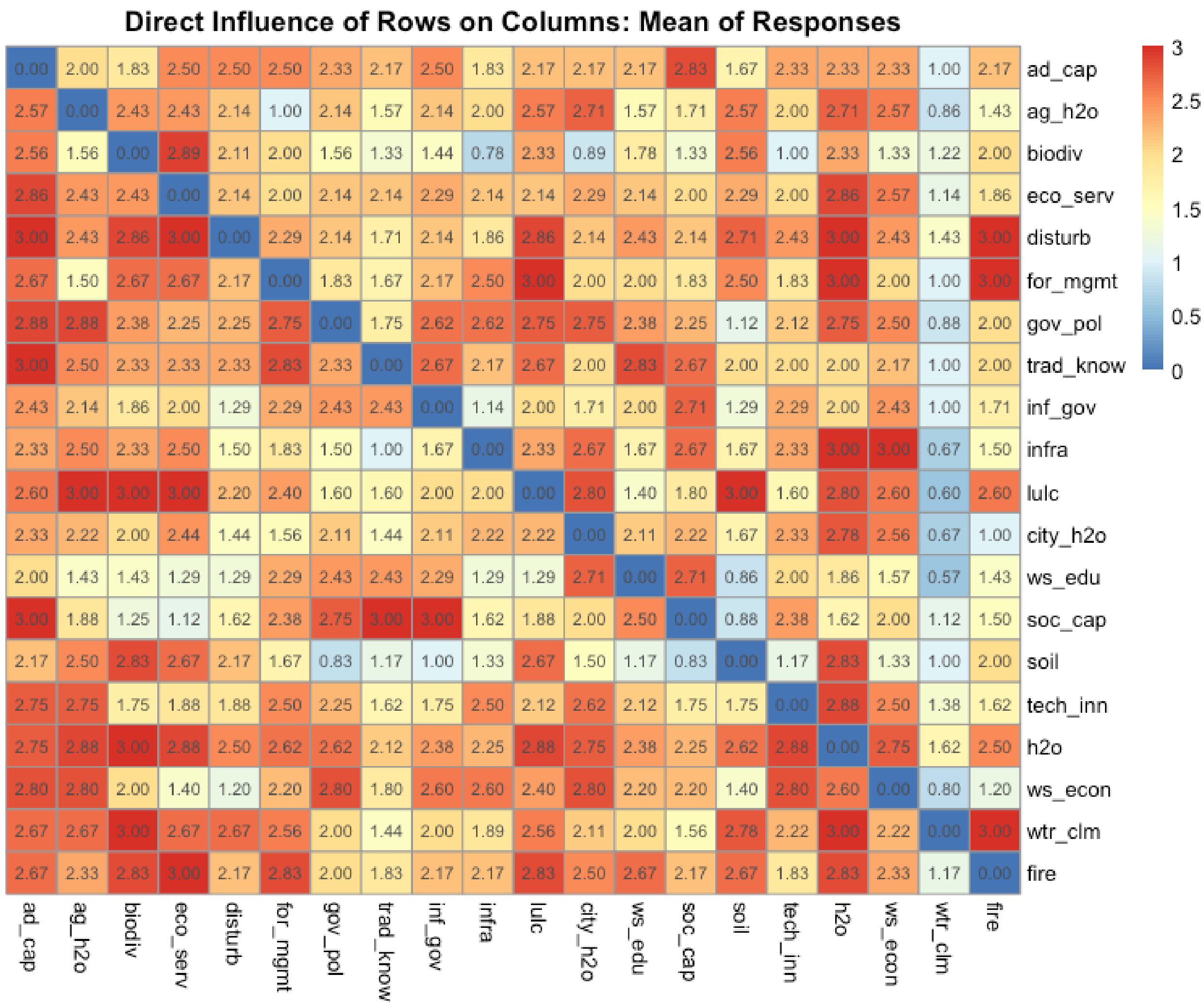


Figure B3: *Mean direct influence/dependence matrix, colored by high (red) to low (blue) influence of elements in rows on elements in columns. For example, the direct influence of adaptive capacity (ad_cap) on agricultural water use (ag_h2o) is 2.00.*

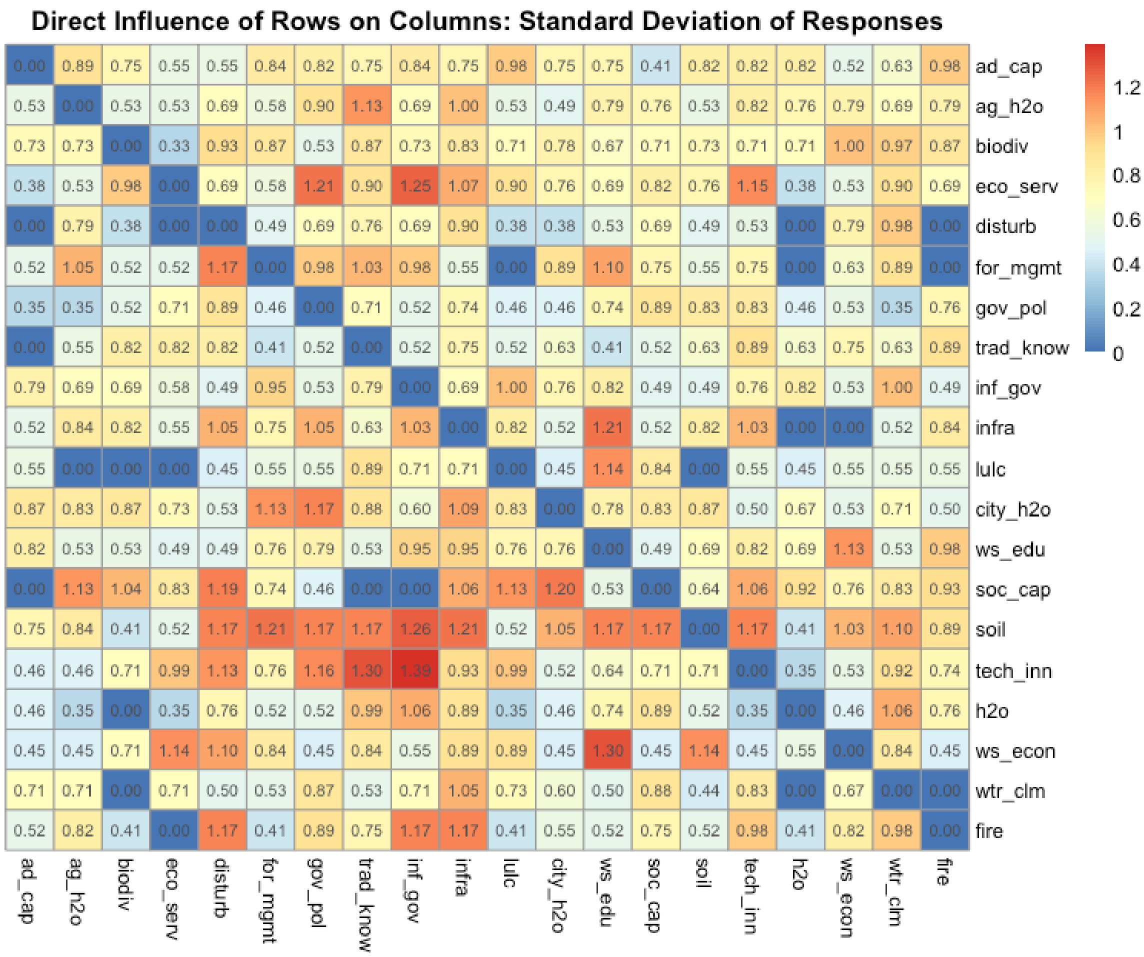


Figure B4: *Standard deviation of responses for direct influence/dependence matrix, colored by high (red) to low (blue) standard deviation of responses about the influence of elements in rows on elements in columns. For example, the standard deviation in responses about the direct influence of adaptive capacity (ad_cap) on agricultural water use (ag_h2o) is 0.89.*

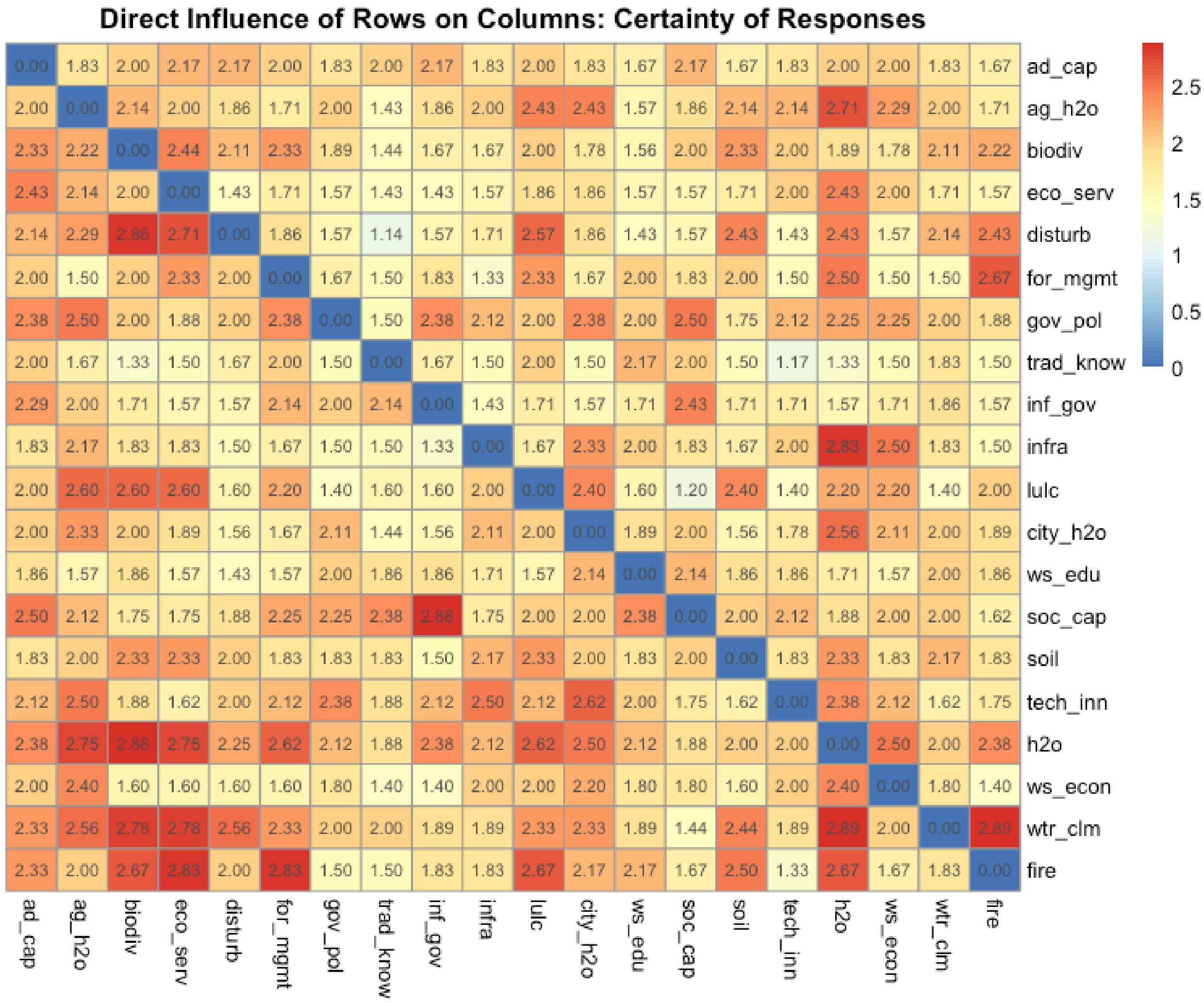


Figure B5: *Mean confidence of responses for direct influence/dependence matrix, colored by high (red) to low (blue) certainty among respondents about the influence of elements in rows on elements in columns. For example, the mean confidence in responses about the direct influence of adaptive capacity (ad_cap) on agricultural water use (ag_h2o) is 1.83.*

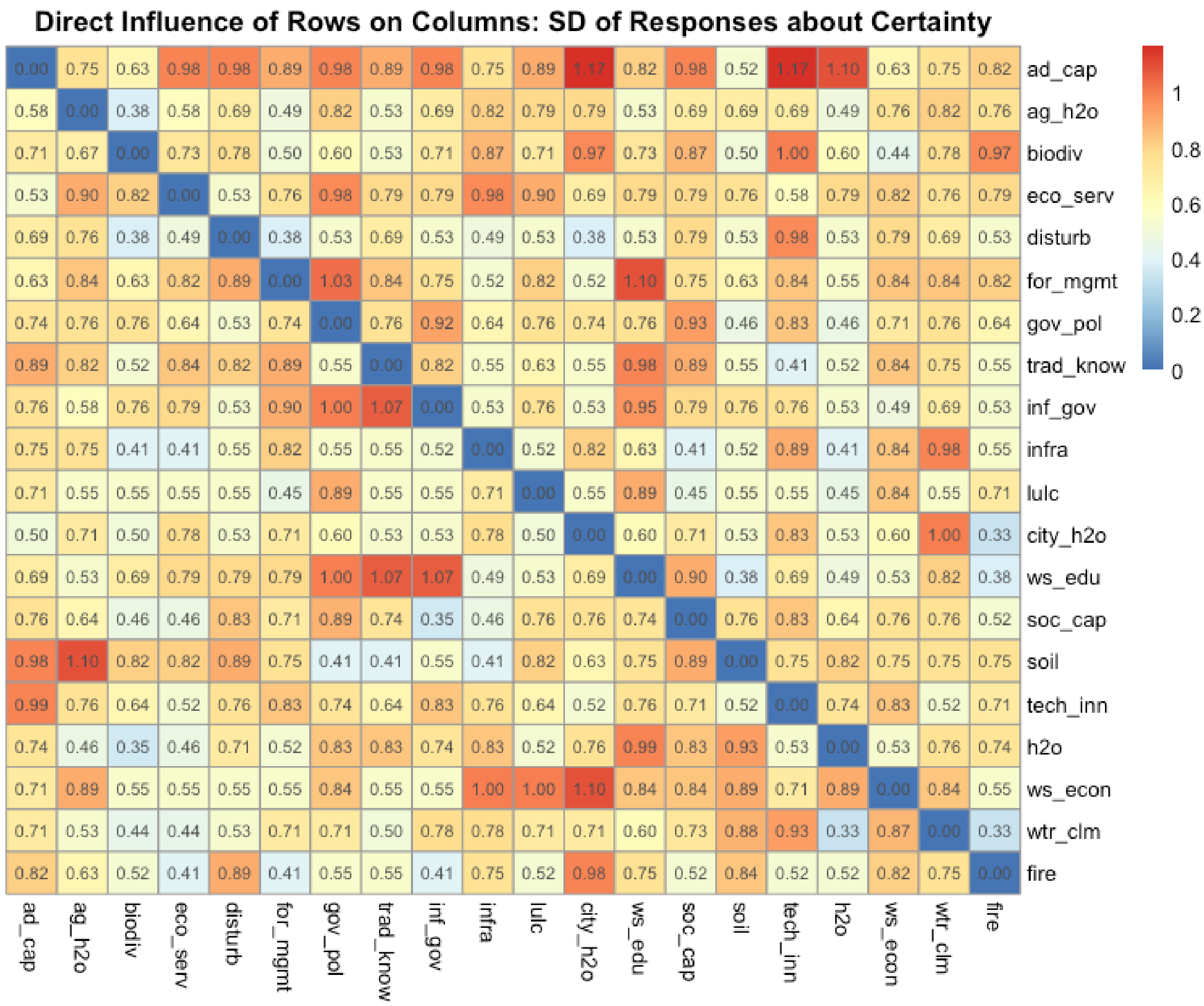


Figure B6: *Standard deviation of responses about confidence, colored by high (red) to low (blue) standard deviation of confidence about the influence of elements in rows on elements in columns. For example, the standard deviation of confidence in responses about the direct influence of adaptive capacity (ad_cap) on agricultural water use (ag_h2o) is 0.75.*

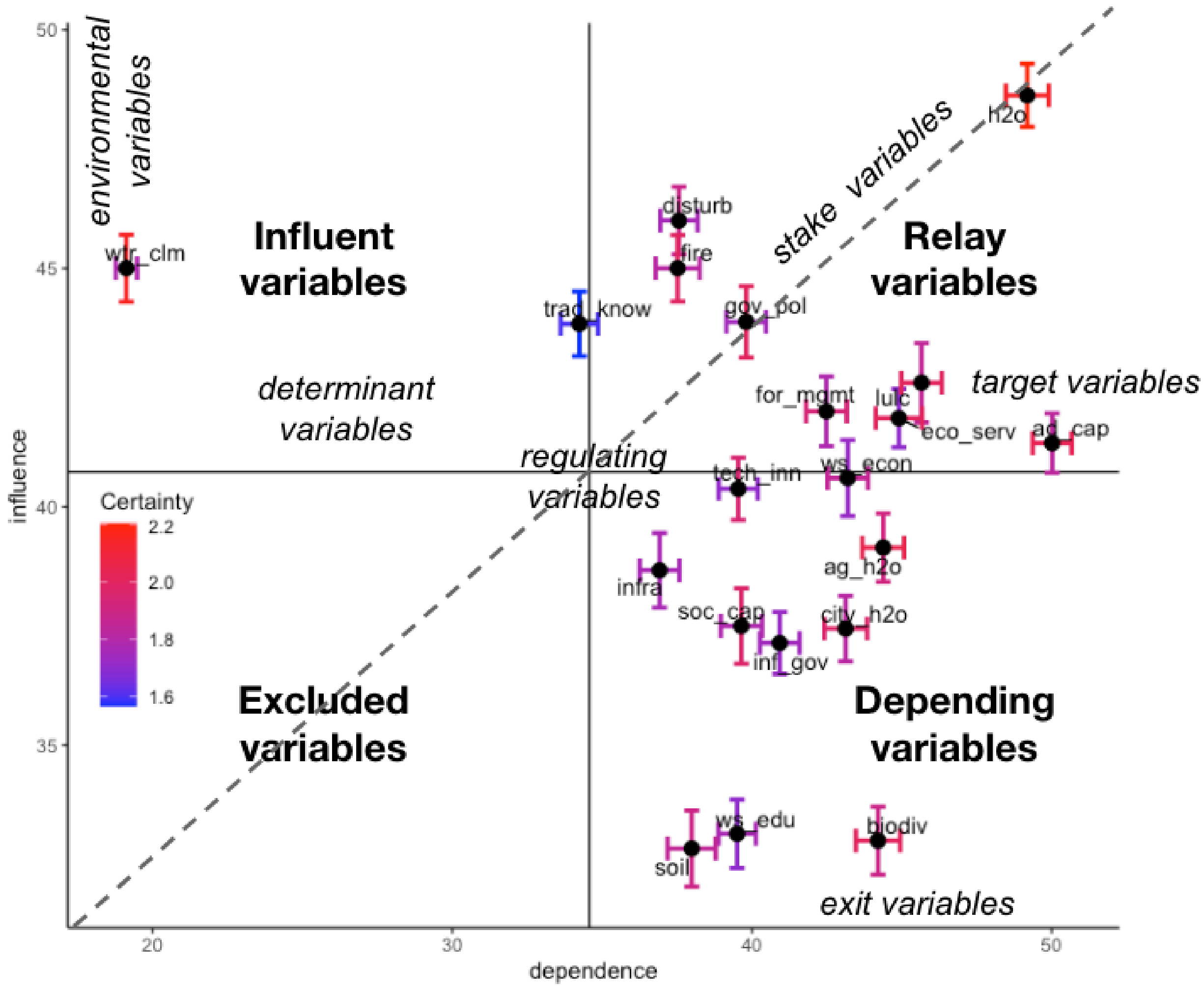


Figure B7: *Influence-dependence plot in which elements are ranked by their total mean influence and total mean dependence. Error bars are standard deviations from the mean indicating variation in responses from survey-takers. Error bar colors are the mean confidence of variable influence (vertical) and dependence (horizontal) as reported by survey-takers, where red is high confidence and blue is low confidence on a scale of 0 to 3. Quadrants are delineated by the midpoints of total mean influence and dependence and delineate element types (see Table B2 for details).*

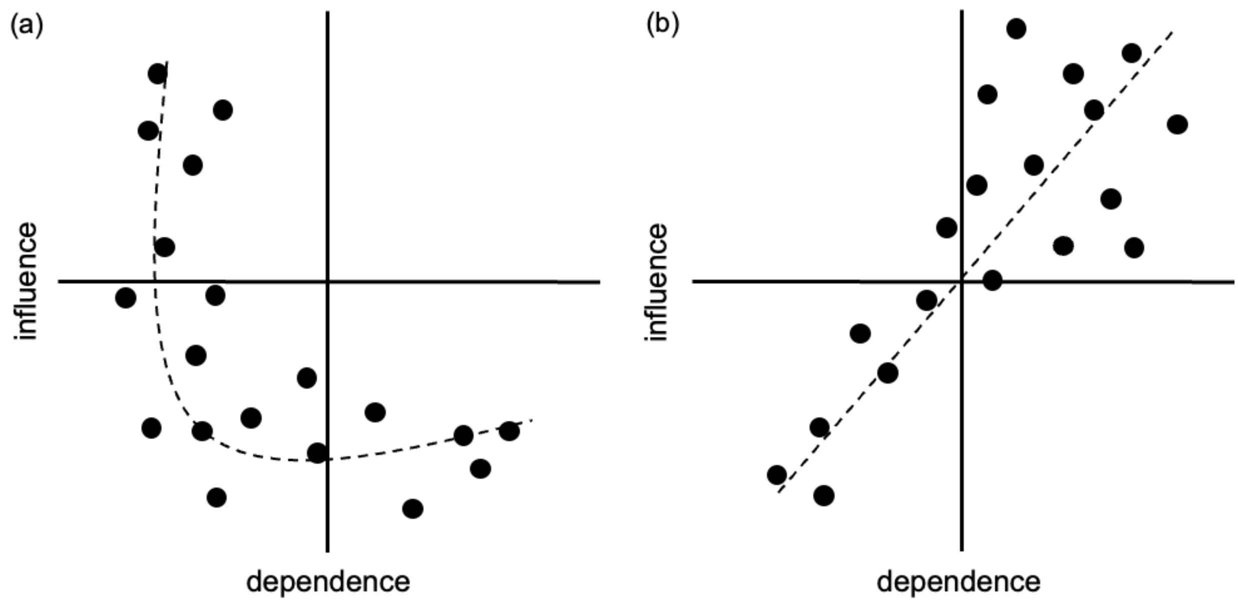


Figure B8: Adapted from Arcade et al. (1999). The shape of the system in the influence-dependence plot can be interpreted as indicating a more stable or unstable system. (a) The more the cloud of points spreads along the axes to create an L shape, the more one can expect the system's response to change in response to determining elements, making for a stable system. (b) When the cloud spreads along the bisecting line and/or many elements are in the top right quadrant, the system is characterized by strong influence and dependence with more uncertain outcomes when elements change, making for an unstable system.

Indirect Influence and Dependence

To calculate indirect relationships among variables, the influence-dependence matrix is multiplied by itself repeatedly until a stabilized matrix is obtained. Stability is achieved when the rank of indirect influences no longer changes. We tested 2 to 10 iterations and achieved stability after 2 iterations (Figure B9).

Matrix multiplication results in a matrix of indirect influences through a linear transformation. A linear transformation is a function from one vector space to another that respects the underlying (linear) structure of each vector space. This transformation corresponds to paths through the interaction network, and would correspond to the input versus output of a fully built system dynamics model. Matrix multiplication thus represents a trip through the interaction network. We did several iterations to compute the influences and dependencies as realized through all possible paths.

Indirect relationships were very similar to direct relationships (Figures B10 and B11). This may be because a highly connected network like this already has most possible paths realized. Two exceptions where elements had higher relative indirect compared to direct influences were technical innovations and biodiversity (Figure B11). However, these shifts were quantitatively small (Figure B10). Closer examination revealed that the higher rank of technical innovation's indirect influence is due to it having strong indirect influences on biodiversity, ecosystem services, and land use/land cover. Closer examination revealed that the higher rank of biodiversity's indirect influence is due to it having strong indirect influences on municipal and agricultural water use. In both cases, the intermediate variable appears to be the influence of each variable on water quantity, quality, and availability, though a fuller examination of the indirect paths is needed.

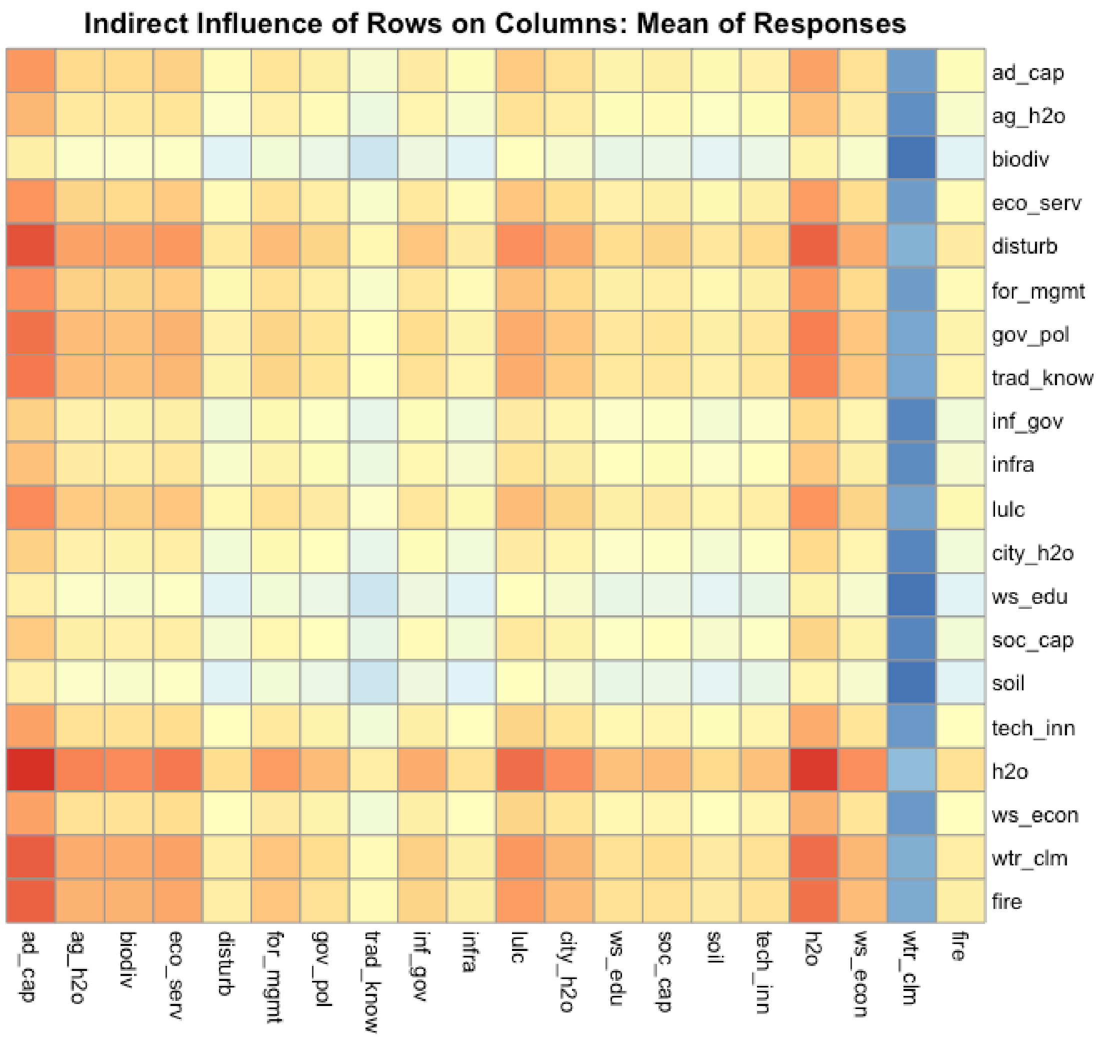


Figure B9: *Mean indirect influence/dependence matrix, colored by high (red) to low (blue) indirect influence of elements in rows on elements in columns. Values are large and so are not shown.*

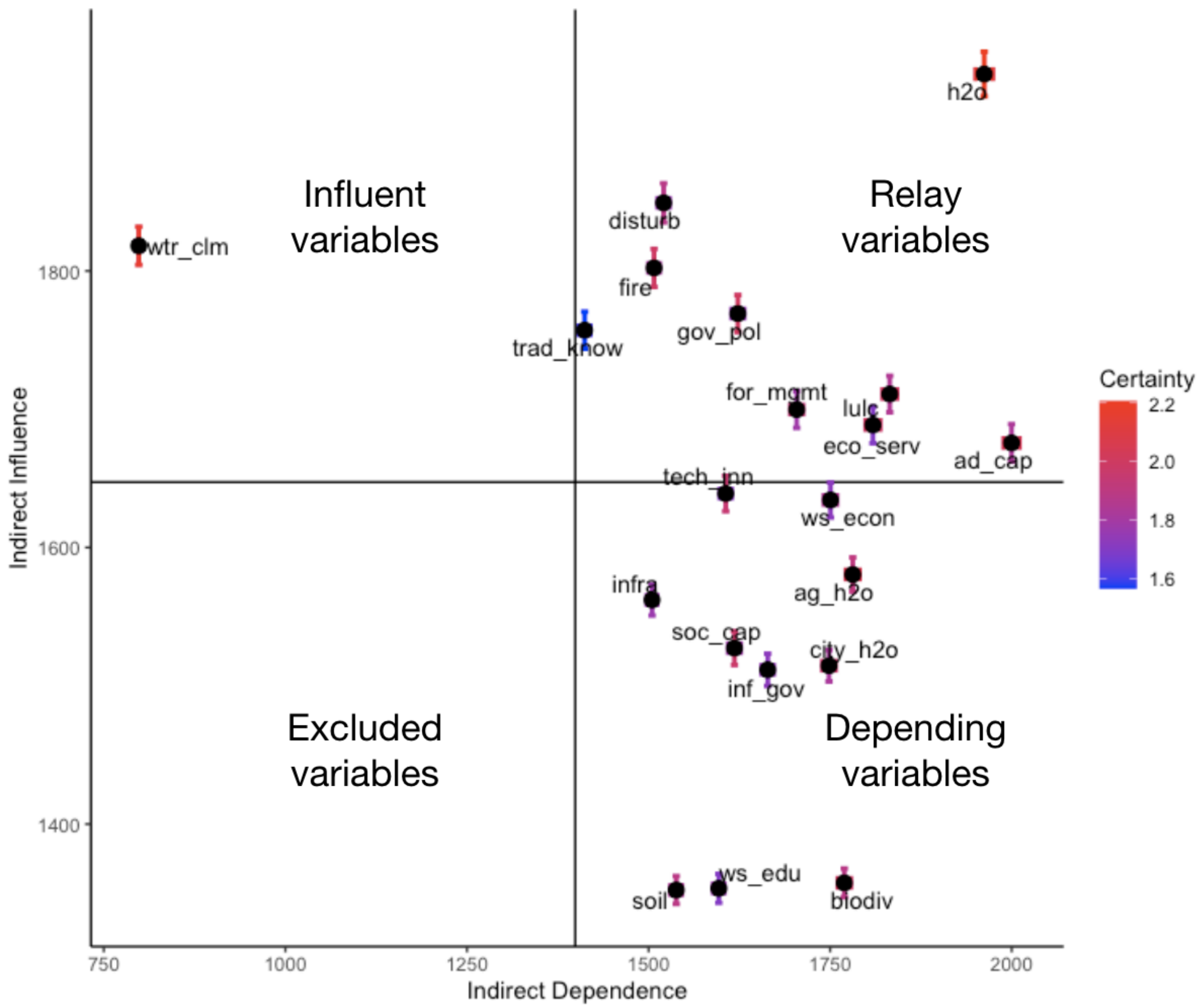


Figure B10: *Indirect influence-dependence plot in which elements are ranked by their total mean indirect influence and dependence. Error bars are standard deviations from the mean indicating variation in the results of matrix multiplication. Error bar colors are mean confidence of element influence (vertical) and dependence (horizontal) as reported by survey-takers, where red is high confidence and blue is low confidence on a scale of 0 to 3; values shown here are the same as in the direct influence-dependence plot. Quadrants are delineated by the midpoints of total mean indirect influence and dependence and delineate influent, relay, excluded, and depending variables (see Table B2 for details).*

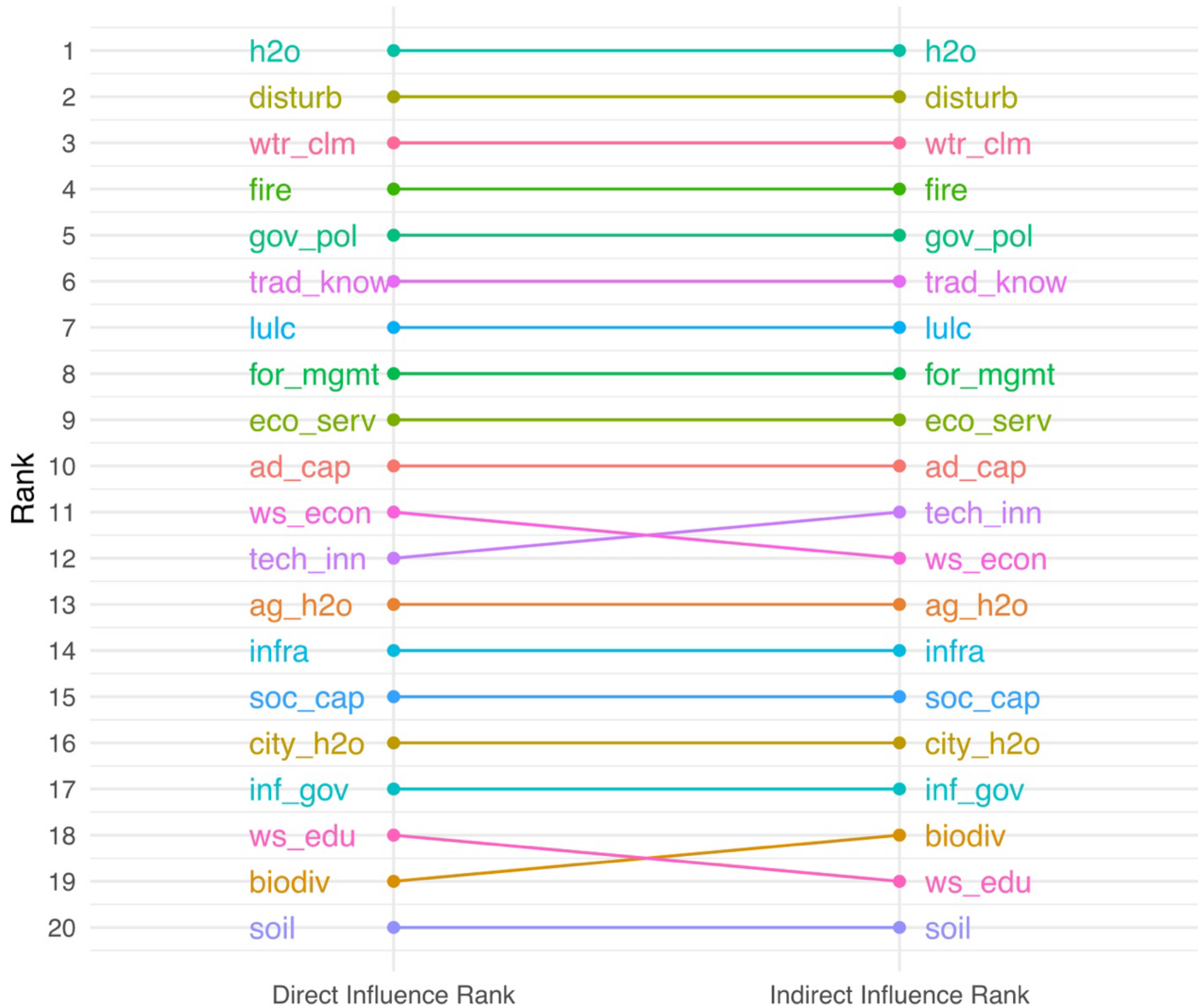


Figure B11: *Elements ranked by total direct and indirect influence, with paths showing elements that change rank when indirect influence was calculated. Note that fire and wtr_clm had the same total direct influence value and rank but are shown here with different ranks to highlight how other elements changed rank from direct to indirect influence.*

APPENDIX C: ENVIRONMENTAL SYSTEMS MODELING CLASS DETAILS

Revising Mid-scale Models into Fine-scale Models through an academic course

We share one example of revising mid-scale models into fine-scale models, based on a graduate student course at the University of New Mexico: GEOG 523 Environmental Systems Modeling. This course-based project started at the mid-level models and is arranged in three stages. In Stage 1, individual students start with an element chosen from a pre-identified list of elements and build expertise in that specific element. This list is a product of a previous workshop on modeling the Santa Fe Watershed (January 2022) and was comprised of researchers from the TN and UNM Water Resources Grand Challenge. In Stage 2 of the project, students connected those elements in subsystems along disciplinary lines (social, ecological, technological). Students worked in groups of 3-4 with other students in their shared subsystem. This moved the model into the bottom-tier, where the models are narrow in scope but high in detail. In the final, Stage 3 of the project, students moved back to the mid-tier level and came up with revised research questions across the whole social-ecological-technological system (SETS). Students again worked in groups of 3-4 students, but this time they were cross-pollinated such that each student brought expertise from a particular subsystem in order to find connections across the whole SETS. The project was designed with the jigsaw method of teaching (Sanchez-Muñoz et al. 2020), where each of student established expertise in a "home" domain of knowledge, and then shared and furthered that knowledge through the convergent course project.

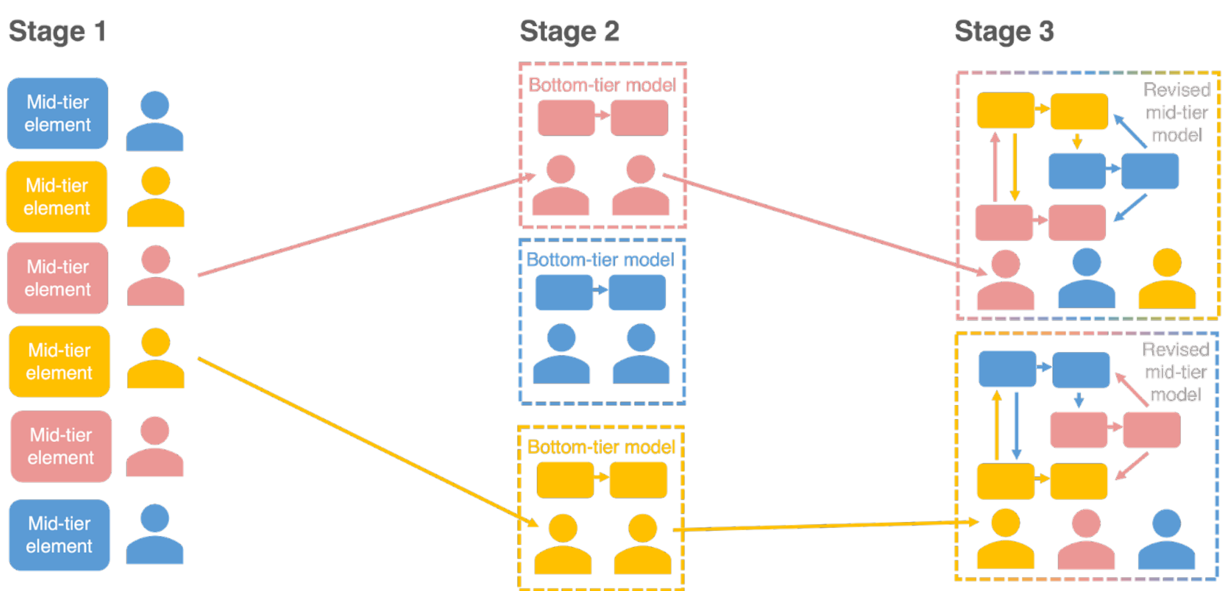


Figure C1: *Overview of the 3 project stages, designed with the jigsaw method for teaching (see section on pedagogy below). Different colors represent different subsystem types (socal, ecological, or technological).*

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