

1 **Title:** Guiding Questions for Water Resources Systems Analysis Research

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3 Water Resources Systems Analysis (WRSA) combines quantitative and qualitative
4 methods informed by multiple scientific disciplines, serving many broad water-related societal
5 goals such as providing safe drinking water and mitigating floods and other disasters. Water
6 utilities, flood control districts, and government agencies have regulatory mandates to meet
7 these objectives. However, these entities face growing challenges including tradeoffs between
8 human and ecological needs, climate change, increasing population, aging infrastructure, and
9 pressures from interconnected sectors such as food and energy. The aim of WRSA research,
10 then, is to contribute new general methodologies for addressing these challenges and specific
11 solutions for pressing problems.

12 However, it is not always clear that knowledge developed in the WRSA field is
13 generalizable (across case studies and regulatory contexts) and actionable (both in real-world
14 systems and across academic fields). To this end, this editorial argues the need for systematic
15 guiding questions for WRSA research. Such questions should address the relative importance
16 of normative and positive analysis, the proper formulation of optimization problems, and the
17 fidelity of mathematical representations of water resources systems. After exploring these ideas,
18 we suggest pillars of guiding research questions for the field, to support the aim of increasing
19 generalizable and actionable knowledge within WRSA and improved water system
20 sustainability.

21 **Normative and Positive Analysis**

22 Place-based concerns hinder the ability for WRSA to have a single unifying structure.
23 Watersheds and aquifers have different hydrologic and climatic characteristics; they are also

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subject to different laws (across multiple levels of government, such as federal and state). Some water utilities, for example, manage their own supplies but do not own the land within watersheds where their runoff is generated. These case conditions set the fundamental structure of the analysis (i.e., modifying the format of models, objectives, and decisions) and thus research is situated in the regional context and may not be generalizable. In contrast, general knowledge for WRSA would extend beyond individual cases, yield scientific benefits, and improve management of multiple systems not previously studied.

Given the common dependence on a particular watershed, water utility, or case study, it is helpful to distinguish between positive and normative approaches within WRSA research. Positive analysis seeks to understand the way that things are (i.e., descriptive), an approach common in the natural sciences. Normative analysis, in contrast, suggests the way that things 'should be' (i.e., prescriptive). It has been argued that normative analysis is common in economics because the discipline was founded contemporaneously with the development of modern economies and nation states (Hausman 2018). Economic science was intimately linked to public policy, and the proliferation of WRSA research today could have a similar effect on current water policy decisions.

Normative economics is driven by fundamental assumptions about an overall objective (e.g., increasing welfare) and a mechanism for how that welfare should be realized (e.g., in a collective satisfaction of preferences). In generating, simulating, and evaluating alternative management solutions for water resources problems, WRSA assumes both an objective and that the current understanding of system processes is sufficient to identify reliable mechanisms to achieve that objective. This optimization framing is normative by construction, in that the philosophy of managing the system will be to maximize one or more objective functions as represented in a mathematical model.

There are cases, though, in which a positive analysis for WRSA can be helpful. In hydrologic science, a fundamental science basis to WRSA, positive inquiry focuses on process

understanding (e.g., runoff generation). Process understanding should also be emphasized in WRSA -- how multi-disciplinary water management processes interact (e.g., financial management, infrastructure operation). By using valuable input from social sciences, positive analysis within WRSA can aid in problem formulation and identify how management processes are carried out in the real world, and this increased understanding could foster better transfer of knowledge across cases and more realistic problem formulations for optimization analysis.

Problem Formulation and Model Fidelity

In 1960, Charles Hitch wrote of the search for objectives in systems studies and observed that there is not a “national objective” for the United States (e.g., protect national security, education, etc.) (Hitch 1960). Our current contested politics shows that this is even less true now. The provision of clean drinking water could be a primary WRSA goal, but contemporary water quality crises show that systems are not always organized around this goal (e.g., the Flint lead crisis, Butler et al. 2016). Moreover, the definition of objectives and specification of how to weigh tradeoffs are inherently value judgements. In fact, even the selection of the quantitative metrics used to directly compare alternatives is value laden. For example, is efficiency valued more than robustness? And what counts as a benefit or a cost, and for whom? Overall, the field has only recently begun systematically addressing questions of who participates in the definition of objectives and how different perspectives are reconciled or aggregated (Fletcher et al. 2022).

WRSA for policy-relevant questions requires a strong mathematical representation of the system. The modeler must understand the structure of the system at the level of dynamics that influence the problem and potential solutions at the relevant time scale(s). This applies to hydrological and water management processes as well as to the processes of decision making, policy change, and implementation. WRSA models commonly assume a social planner with perfect information and no barriers to action; however, this assumption may result in technically

optimal but practically unfeasible recommendations. For example, a social planner's optimal solution to water scarcity may identify long-term storage investments for which there is no political will to fund. Alternatively, a study may identify the creation of water markets as an efficient solution to an allocation problem, and this recommendation must be underpinned by an understanding of traders' behavior. These examples highlight the reliance on positive analyses that build understanding decision making and policy processes through empirical analysis (Griffin and Characklis 2002). Developing new approaches that can test whether our understanding of the system structure and processes is good enough could help discern whether study results are actionable.

Most mathematical models of water resources systems assume that system structures and objectives are constant and that processes only change in response to external or state variable changes. However, watersheds, technology, policy, and culture are always subject to change. In fact, the intensity of human activity has accelerated change in earth system and socio-economic processes (Steffen et al. 2015). Further, the water management alternatives assessed may themselves change the structure of the system. For instance, in the Colorado River, water allocations and reservoir construction have changed the natural hydrology and facilitated new spatial and temporal patterns of demand that would not have been otherwise possible. Moreover, the system is constrained by historical allocations and a regulatory structure that makes it difficult to fundamentally transform supply and demand dynamics. Therefore, guiding research questions in WRSA must continue to address change in system structure, processes, and even objectives.

Guiding Research Questions to Serve Society and Advance Science

Systematic categorization of research gaps, such as presented in Miles (2017), can be helpful for funding agencies, research groups, students, and others to contextualize different types of research activities. In the Miles taxonomy, the Practical Knowledge Gap suggests that

knowledge exists, but has not yet been applied to practical purposes. The Methodology Gap suggests that new methodologies can be developed, which are appropriate for decision support, for example. We are inspired by this research question taxonomy to suggest broad guiding questions for WRSA research, organized into pillars. Classifying specific research questions from WRSA into pillars could help researchers compare their studies and build knowledge across cases.

We propose three pillars of WRSA: problem solving, building understanding, and advancing methods (Figure 1). These three pillars align with three different research areas within WRSA and are interdependent, each serving as foundation and motivation for the others. Use of these pillars can demarcate which parts of the studies are generalizable versus being place-based.

Problem Solving

Problem solving is the primary motivation for WRSA and consists of identifying what set (or sets) of actions can achieve objectives. As previously mentioned, problem solving approaches must address disagreement and conflict in setting these objectives. Co-production (Dilling and Lemos 2011) advocates for collaborating directly with stakeholders and decision makers in defining objectives for individual systems instead of assuming them a priori. Often this collaboration leads to iteration between objectives and solutions, essentially bringing objectives into the design space (e.g. different perspectives on water demand and restrictions (Smith et al. 2017)). Problem formulations that have buy-in from stakeholders during the whole process have the promise to yield more effective selected alternatives. Improved problem solving in WRSA research would increase the transparency of tradeoffs (Hegwood et al. 2022) and clearly demonstrate the importance of objective setting. Critically, all problem solving efforts rely on a foundation of system understanding and accessible computational tools. To facilitate the

creation of generalizable knowledge while providing useful recommendations to specific problems, we posit the following guiding questions:

- **Who** set objectives and formulated the problem? Do competing problem formulations and hypotheses exist, and how do they compare? How can changes in objectives or problem formulation inform broader management goals in the system?
- Are the recommended solutions compatible with the current **governance** arrangements? If not, does the study recommend changes to these arrangements? What are the barriers for those changes to occur?
- Which **system characteristics** have the strongest influence on recommended solutions? How does this **compare** to other cases with similar objectives?

Building Understanding

Building system understanding requires synthesizing knowledge of hydrologic, economic, and policy processes, in addition to further disparate fields. We posit that WRSA-specific “process understanding” including regulatory and operational constraints would enable the identification of true opportunities, costs, and constraints. All WRSA applications inevitably simplify process representation due to the need to represent a wide range of processes (often computationally), with the question or problem driving the system boundary and level of abstraction. Mixed method analyses that synthesize across hydrological, socio-economic, and political data are a promising approach to build understanding in how disparate processes interact (Garcia et al. 2019). Structured cross-case comparison has great potential to develop general knowledge by either analyzing previous WRSA applications (Srinivasan et al. 2012) or selecting cases deliberately to test hypotheses (Deslatte et al. 2022). A complimentary strategy is to develop generic models that can be tuned to represent a range of systems. Testing such generic models against case data and with stakeholders enables hypothesis testing and model refinement (Garcia et al. 2020; Smith et al. 2017). To ensure robust findings in specific cases

while building WRSA process understanding we pose the following questions to WRSA researchers:

- Are the **process representations** in the model appropriate for the scope and time scale of the motivating problem? Do changes in process representation result in changes in conclusions? Can we apply process representations from one case study to similar WRSA case studies?
- Are recommendations or findings **robust** to severe uncertainties, and plausible changes in system structure or processes? If not, what kinds of system changes would alter the conclusions?

Advancing Methods

The application of WRSA relies on computational tools and methods to simulate the system efficiently and find decision variable values that optimize objective functions. Historically, WRSA formulations might have used limited process representation or lacked extensive sensitivity analysis due to limited computational resources. Emerging trends in the availability of exascale and larger computers reveal new challenges, such as making sure there is sufficient data and sustainable computer programs for larger and larger systems (Heldens et al. 2020). Increasingly popular, machine learning helps reveal (previously unknown) relationships between predictor variables and output variables (Sun and Scanlon 2019), benefiting both system understanding and problem solving. However, to have an impact beyond the academy, these tools must be accessible and interpretable to practitioners. Methodological advancement also furthers problem solving and system understanding when new methods change analysis outcomes (e.g., discover a more efficient or robust set of actions) or reduce the costs (e.g. computational, cognitive) of analysis and decision making. An important thrust for water resources systems analysis is to create tools that lower barriers to analysis and to share these tools in ways that increase the uptake (Sela and Housh 2019). Practitioners look to research to

learn about state of the art tools, but these studies are not always valued by universities and research labs. In fact, the push for newer and newer technologies in published research may disincentivize taking time to make methods accessible, and the proliferation of tools makes it more challenging for practitioners to follow the state of the art. To assess if methods advancement enhances the development of actionable and generalizable knowledge, we put forward the following guiding questions:

- How are tradeoffs between accessibility, search effectiveness, and computational efficiency balanced in the **selection** of computational tools and algorithms?
- Do new tools lead to new **policy recommendations**, provide clearer insights, decrease computational demands, or facilitate **cross-case learning**?

Conclusion

WRSA is motivated by important societal objectives, but insights are only as good as the foundation of system understanding and the methodological tools available. Moreover, these tools must be integrated into water resources practice, with the results therefore being comprehensible to the public and communities of decision makers. Although this challenge has existed for years (Rogers and Fiering 1986), it is exacerbated by quickening advancements in methodologies, the accelerating pace of water challenges, and political polarization. Critically, each of the pillars of WRSA are complementary and all are needed to advance WRSA. We therefore encourage researchers to continue pursuing diverse research questions, and to consider where their work fits in the pillars proposed in this paper. We argue that doing so will clarify study aims and limitations, better contextualize research studies, and build capacity for cross-case learning and a more robust WRSA community.

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