Water Resources Management: The Myth, the Wicked, and the Future

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> "The willingness to look ahead, . . . at low-, medium-, and high-level population densities reveals an awareness of the increasing importance of water in the future; and of the necessity for the present generation to plan for the water needs of the next" (Balchin 1960).

Current concerns about how change (climate, land-use, population, etc.) will strain our water resources systems could encourage the reader to dismiss Balchin's quote as an obvious cliché. Balchin's quote summarizes a U.S. Senate resolution passed nearly fifty years ago establishing a Select Committee on National Water Resources to carefully synthesize the state-of-knowledge for observing, predicting, and managing U.S. water resources from 1960 to 2000. This historical effort is far from a cliché and strongly parallels our field's current efforts to redefine the scientific basis by which we can promote sustainability, adaptivity, and reliability in our water resources systems while acknowledging their nonstationarity (Milly et al. 2008). As a new generation of water resources professionals confront these issues, it is worthwhile to explore the origins, legacies, and shortcomings of the problem-solving frameworks that have shaped the history and evolution of the water resources management field. We do not claim in this editorial to be original in recognizing the challenges to water management summarized below. Rather, we suggest here that our field needs to elucidate what water management science should be in the future, given that our past conveys recurrent discussions of key challenges, many of which remain underaddressed at present. In this vein, much can be learned from the historical criticism of the water resources planning and management field provided by Liebman (1976), which, by taking some creative license, can be summarized as follows:

1. *Optimality is a myth:* Classical single-criterion optimality has a very tenuous meaning for complex human-water systems decision making. Although the least-cost solution provides a mathematical bound for our analysis, it is nonetheless a narrowly defined and extreme view of any water system. Consequently, least-cost optimality very often has little merit or meaning for actionable decision making and/or design.
2. *Water is a wicked problem*: The optimality myth emerges from the ill-defined ("wicked") nature of water resources management problems because of their implicit uncertainties, their risks, and the diversity of perspectives that define the social value of water resources (Rittel and Webber 1973). Although these issues have been recognized for decades, only a tiny fraction of the water resources research literature blends social, technical, and scientific advances to more directly address the "wicked" nature of water management problems.
3. *The future requires transparency and constructive decision aiding*: Successful examples of consensus-based water management such as "shared-vision modeling" (Lund and Palmer 1997) represent the exception not the rule in the water resources research literature of the past several decades. A review of this *Journal*'s recent literature suggests that problem formulations are most often relegated to brief summaries in our methodologies. Defining our problems to be of use in real decision making is *the problem* in water resources management. Our problem-solving frameworks need to advance the collaborative "construction" of management models so that they can be evaluated rigorously from diverse perspectives for their transparency, their validity, and the equity of their impacts.

The Optimality Myth

For more than thirty years, we have recognized that the top-down "omnipotent" analyst approach to formulating and solving water management problems has severe limitations. Given the scale and magnitude of the challenges we are facing as water resources professionals, it is clearly still as relevant today as it was in 1976 when Liebman suggested we move beyond the assumptions of a omnipotent analyst with perfect system knowledge. Least-cost optimality assumes perfect problem formulations, perfect information and evaluation models that fully capture all states/consequences of the future. Since these assumptions have obvious flaws, the use of deterministic single-criterion optimality is not an appropriate focus for complex water resources systems problems. It can be argued that even a "simple" problem, such as calibrating a simulation model, cannot be adequately resolved using a single optimality criterion. This is directly evident in our national river forecasting centers, where manual calibration is still considered to be superior to single objective simulation-optimization.

Our systems frameworks' focus on single-criterion optimality originated with the emergence of operations research in World War II. The design challenges in World War II were for well-defined problems such as encryption and radar processing applications. Successes in these problems allowed operations research tools to evolve in several fields during the expansive intellectual advances of the 1950s and 1960s. Tsoukias (2008) provides a nice history of how these early advances in systems planning have shaped modern decision making and describes the potentially severe theoretical, cognitive, and computational limitations of too strict a focus on "the" singular optimal solution.

These limitations are reinforced by Climaco (2004) in his critique of using narrow mathematical definitions of optimality when balancing technological innovation and its concomitant societal risks. Managing climate and human-induced change requires a balance between the generation of wealth and its concomitant generation of technological risks, which cannot be easily defined using a single metric. Future water resources systems management paradigms must instead quantify wealth-risk trade-offs, their associated uncertainties, and the potential risks that may emerge from limitations in our observations and biases in our predictions. Given the complex trade-offs in public systems planning, we should avoid paradigms in which consequences, compromises, and hypotheses are hidden from stakeholders and decision makers. Moreover, decision making is fundamentally a human activity, and our use of models should avoid purposeful or inadvertent "numerical" decision making where decision-makers are only presented with "the" optimal alternative.

Our use of optimization highlights our strong concerns with avoiding locality (or myopia) in water systems' design spaces as defined by their formulations and evaluation models. The body of water management literature less commonly acknowledges that problem formulation, selection of a simulation, and the processes used for decision making have a far greater potential for myopia given the diversity of needs and perspectives implicit to water resources problems. Brill et al. (1990) clearly demonstrates the need for and value of using diverse problem representations to enhance decision making. Their study highlights that when water resources problems' evaluative criteria and/or quantitative objectives increase in number, optimal solutions found in lower dimensions are often considered inferior by decision makers. This work blends computer science, operations research, and psychology to clarify fruitful avenues for addressing the optimality myth. It acknowledges the fundamental challenges implicit to defining water resource problems, the limits in our understanding of causality in these systems, and the complexities associated with characterizing the emergence/equity of risks (often unintended) from the very acts of modeling or decision making.

Water: A Wicked Class of Problems

These challenges motivated Liebman (1976) to describe water resources planning and management as a "wicked" class of social value problems. The term "wicked" as used by Liebman actually originates from the work of Rittel and Webber (1973) in the policy sciences. Rittel and Webber (1973) provide what was, and still is, a direct criticism of using narrow definitions of optimality in solution frameworks for social value problems. They contend that water resources planning and management is a class of wicked social value problems that: (1) lack definitive formulations (the optimal utopia is different for everyone), (2) are not true or false (i.e., judgments can only be subjective not objective), (3) are unique and nondecomposable, (4) possess decisions that are often irreversible, and (5) yield a range of consequences that are highly uncertain if not completely unknown.

It is worthwhile to consider what role or impact each of these problem properties could have on modern water resources management, especially as we seek to evolve the tools and principles of our field. The structure of our management models is an important and underappreciated source of uncertainty. The structural choices of objectives, constraints, evaluative models, and planning horizons are not objective (i.e., true or false). Generating and judging water resources management alternatives is in reality subjective down to the individual and a legitimate scaling challenge when seeking consensus at institutional, regional, or national levels. The "uniqueness of place" (Beven 2000) is clearly a challenge when modeling or managing any water resources system. We should also carefully consider the risks and consequences of the traditional problem decompositions that are artifacts of our education, research, and practice traditions (e.g., separating the fields of surface water, groundwater, urban water, etc.). A worthwhile question to consider is, do these traditions limit our ability to understand the implications of coupling and feedbacks in the water cycle across the built, natural, and social systems that define them? Clearly, our emerging understanding of the water cycle has broad implications on how local water resources management decisions impact other watershed systems locally, regionally, and even globally (e.g., see Gordon et al. 2005; Maxwell and Kollet 2008).

Water science and engineering has predominantly supported problem decompositions and analysis frameworks that treat water-cycle science, engineered water, and policy sciences as being separate. Consequently, we are left with little agreement on how to provide internally coherent and consistent projections of change in engineering problems that bridge these disciplines. More than 30 years ago Liebman (1976) warned of the risks of the convenient but artificial separation of "engineering," "science," and "policy." In reality, any optimization-simulation framework used to address or effect change is a hypothesis unto itself with structural biases and uncertainties. Rarely do we discuss how these factors ultimately shape our ability to judge the equity and causality assumptions of proposed policy or management alternatives. As a concrete example, spatially distributed regulatory decisions in the Chesapeake Bay watershed are currently informed by operational use of a lumped stream-reach-based terrestrial model with more than 100,000 parameters and that neglects groundwater processes (Chesapeake Bay Program 2009). Although the model has had a very positive impact on policy in the Chesapeake Bay, it also exemplifies the challenges and questions that still remain in how to formulate, parameterize, and use our models in a manner that does not invalidate our ability to falsify important hypotheses. Moreover, we should be careful that structural biases in accepted operational models do not directly degrade the validity and/or the equity of our decisions (Where/when/why are we wrong? Who is impacted? Are the resulting policies capricious?). The frequency of use for a model must not be confused with the appropriateness of its use. Rigorous model evaluations from social, technical, and scientific perspectives are vital for future water management frameworks.

The Future Requires Constructive Modeling

Although many of the real-world complexities and challenges highlighted in the prior sections have been discussed repeatedly and eloquently in the historical literature of our field, some may be struck by how little progress has been made over the past fifty years. This lack of progress is indeed a legitimate point of concern, as noted by Lettenmaier (2008) in this *Journal*. Building on Lettenmaier (2008), the purpose of this editorial is to frame the contention that beyond research funding for water management, there are strong methodological limitations in the traditional ways many water management problems are classified, decomposed, and solved. For example, are water management and water-cycle science separate fields? Although some may contend otherwise, it is quite challenging to incorporate state-of-the-art water-cycle science into real-world operational water management applications (or vice versa). This breach between theory and practice is growing when we consider our emerging knowledge of coupling and feedbacks in surface, subsurface, and atmospheric systems, particularly in the context of drought (Maxwell and Kollet 2008).

Addressing the knowledge gap between water management and water-cycle science is vital if we hope to assess our modeling frameworks for their transparency, their ability to inform causality in real-world contexts, and judge the equity of their impacts. We must avoid artificial assumptions that the built, natural, and social systems that define our watersheds are independent. Recent innovations in information processing, optimization, simulation, and management should be used to provide as broad a range of plausible water futures as possible to better diversify our knowledge and decision-making (Brill et al. 1990; Liebman 1976). *The problem* when seeking to manage the impacts from population, climate, or land-use change is defining appropriate problem conceptualizations.

Formally, to improve our problem conceptualizations, we should consider the tools and literature that have emerged over the past 40 years to yield the field Bernard Roy (1999) has termed "constructive decision-aiding science." Constructive decision aiding can be viewed as a process of collaborative learning and negotiation that can exploit diversity in evaluative perspectives and objectives to identify alternatives that capture a broad suite of system behaviors relevant to both modeled and unmodeled objectives. Although optimization may have an important role, there is no a priori assumption that a singular solution or tool is appropriate. Fundamentally, constructive decision aiding is a formalized mechanism for discovering system dependencies and/or trade-offs so that this information can be exploited in the adaptive management of complex water resources systems. Our models must provide a diversity of hypotheses and convey knowledge as broadly as possible to stakeholders, decision makers, scientists, and engineers.

Gleick (2002) contended that "soft water paths" should be the focus of future water management strategies, and this assertion advocates the need for future research to more rigorously evaluate our modeling frameworks (conceptual versus physical, deterministic versus stochastic, normative versus constructive) to better understand the spatial, temporal, and social contexts where they are most appropriate. Returning to Balchin's quote from the beginning of this editorial, it has always been true that change represents a defining challenge and opportunity for the water resources field. Consequently, we must bridge the growing gap between water management and water-cycle science by coupling our observations and predictions to their social contexts and by collaboratively constructing a diverse range of sustainable management alternatives to aid water resources decision making in the future.

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