The End of Reliability

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Recent attention has focused on the declaration of the death of stationarity and the associated implications for water management (Milly et al. 2008; Lettenmaier 2008). A recent panel convened by the EPA on the subject of water infrastructure planning in the context of climate change was notable for a lack of consensus and need for guidance expressed by water managers. Here I argue that the major implication of the end of stationarity is the end of the static design paradigm, exemplified by the concept of reliability, as the underlying design principle for water resource systems.

Here reliability is defined in a general way, as "the probability of failure." To define failure it is useful to consider two archetypical water resources challenges that water engineers face. The first is planning for excess water, which normally involves a flood control system design. In this case the overtopping of a dike is an example of a failure. The second is deficient water for a water supply system, as a result of drought. In this case failure would occur when the water supply system is unable to deliver the water that is demanded by its customers. Reliability is the probability that these failures do not occur.

In each of these cases, static assumptions about long-term probabilities, such as reliability, are a primary design consideration. The water system is designed to be reliable up to a given probability. Typically, the marginal cost of increases in reliability are low up to a point of high reliability where the marginal cost then increases rapidly for each incremental increase in reliability. The decision to build the infrastructure for a specified reliability reflects the decision-makers' choice on the tradeoff between cost and reliability and is typically taken by the engineer as a fixed design variable. Flood control systems may be designed to withstand all floods up to, say, the flood, which is the flood that is estimated to have a 1% chance of being equaled or exceeded in a given year and consequently have a reliability of 99% and a probability of failure of 1% in any given year. This is a simplification of an actual design process but serves to illustrate the underlying principle. A water supply system could be designed to withstand a drought of some design duration with a return period and again have a reliability of 99% in a given year. The traditional design of infrastructure where greater reliability is achieved through more storage volume and greater dike heights, which equal greater cost, means that there is a tradeoff between reliability and cost, including the cost of failure of the system. These decisions are dependent on our ability to accurately estimate reliability.

An estimate of reliability depends on the assumption that it is possible to estimate the probability of a rare hydrologic event. As currently practiced, it relies on an assumption of stationarity. Reliability can also be calculated on a dynamic basis but is rarely done so in practice. Systems are designed to be reliable to a degree that is based on statistics of the historical record and thus the estimated reliability is dependent on unchanging statistics. The death of stationarity means that those statistics are changing and therefore our estimated reliability is not what we expect it to be. More generally, the traditional approach to water supply design depends on precise estimates of the probabilities of events that are difficult to estimate, involve linked physical and societal processes that are difficult or impossible to model and have only recently been considered worthy of research, and due to secular changes in climate, land use, etc., are becoming even more uncertain. This presents the water manager and the larger water resources research community with a dilemma.

The Traditional Design Approach in the Face of Nonstationarity

The first choice that seems to dominate current discussions and research funding is the attempt to reduce the uncertainty that nonstationarity implies while giving little regard to the design of the system. That is, can we develop better methods to improve our ability to estimate the probabilities associated with hydrologic risk and update our designs while retaining the static design paradigm? Although popular, this approach is presently unsatisfying because it inevitably leads to attempts to ascertain future design variables and reliability from deterministic models of coupled physical-social systems we don't understand well enough. The dominant example involves attempting to develop design or planning guidance from the output from a GCM. Unfortunately, the typical wide range of GCM projections, the coarse spatial resolution of GCM output, the employment of downscaling techniques that rely on their own assumptions of stationarity, the lack of skill that GCMs have in reproducing variability and the use of emissions scenarios that do not have probability assigned to them severely limit the utility of GCM output for the purposes of water resources planning and management. For example, the IPCC states that climate change projections are most skillful at the *continental scale,* hardly applicable to the problem of design of a particular water resource system (Solomon et al. 2007). Downscaling increases the resolution of this output but cannot reduce the range of GCM projections or produce agreement among the GCM input if they disagree. Furthermore, it is inadvisable to attempt to select a single GCM that performs best for a particular analysis (Gleckler et al. 2008). The use of paleoclimatology is useful to better estimate the range of historical variability but its usefulness for future planning is again dependent on a stationarity assumption.

These issues apply only to the climate change issue. Human alteration of the hydrologic cycle is another important source of nonstationarity. If the nascent field of hydromorphology is supported and flourishes, in the future we may be able to predict the direction and implications of human action on the hydrologic cycle; but at this point it is largely unknown. All of these issues make it unlikely that we can produce better estimates of reliability in the near term. This topic was entertainingly explored by Klemes (2002), and Fiering and Matalas (1990) visited it as well, stating, “we can spend megabucks on climate research ... and still not answer the questions” regarding water planning and management under climate change.

The End of Reliability—A New Paradigm for Water Resources Design

An alternative to the dominant approach that is advocated here is accepting the end of reliability and the static design paradigm for water resource systems. Our current understanding of change in the statistics of hydrologic variables in the anthropocene is so limited that it is fruitless to attempt to reduce the uncertainty of reliability estimates in the practice of water resources design. Note that I’m not arguing against attempts in the research community to reduce this uncertainty—clearly improvement in GCM and advances in hydromorphology are needed; but they are either not imminent or likely to produce marginal improvements. What is advocated is a new research direction that focuses on the design of the water system to create innovations in water resources planning and management that enable water systems to respond dynamically to a changing world.

There is good reason to rethink the static design paradigm for water systems even without the death of stationarity. The traditional mindset is to design a system to “not fail” up to some reliability and then give little regard to what happens when an exceeding event does occur. However, when an engineer designs a system to be reliable up to a 1 in 100 event, she is leaving the job 99% done. Given enough time and space, inevitably we’ll be inundated in 1 in 100 events and the associated negative consequences—that is, failure—and we are! That may be acceptable in some fields, but when that 1% event entails the human suffering of Katrina or the mayhem in Atlanta during the drought of 2007, it cannot be deemed acceptable in this field. Instead, there is a need to replace the binary straitjacket of reliability (fail or not fail) with a continuous vision. We need to design for all events, not just a design event (Green et al. 2000; Barros and Evans 1997).

Some would argue that water resources engineers have always dealt with uncertainty and the historical paradigm continues to be adequate. Certainly there is much to be learned from the manner in which water engineers have addressed uncertainty in the past (Burges 1979). Many of these lessons are still relevant. However, the nature of the current problem is different. We currently recognize not just uncertainty due to short records, but also temporal structure in climate variability and change that contributes to the uncertainty (such as interannual and multidecadal variability, as well as secular trends due to anthropogenic climate change). Much else has changed since the development of the static design paradigm. From a planning standpoint, we’ve moved from an era where optimality and economic efficiency were accepted objectives to a time where common objectives are difficult to specify amid multiple and competing interests and the new objective is to find “politically feasible solutions.” In addition, the realization of the importance of flows for the sustenance of ecosystems has reduced the operational space for meeting other objectives. On the positive side, technological advances in remote sensing, information and communication technology, and computation provide us with a cornucopia of information about the environment that enables real time monitoring and in some cases skillful forecasts. The management of water resources requires updating not just to address nonstationarity but also to better reflect our values, and perhaps most important, to realize the potential benefit of the observational and information technology resources that are now available. We need a water resources management paradigm that is commensurate with these innovations.

Implications of the End of Reliability for Water Resources Management

What does the end of reliability mean for water resources planning and management? A useful thought exercise is to consider what one would do if there were no historical hydrologic data and therefore it was impossible to estimate the probabilities or return periods of hydrologic events of interest. I offer it as a koan to my colleagues in the profession, a question to reflect on as an exercise toward enlightenment. My answer has three parts.

1. First, I would want to know as much as possible about what the future holds. I would want a forecast of my water supplies on an operational basis and the operational rules that enable forecast use (disregarding the historical data that might be needed to do so in the spirit of the exercise). Thus I would want real-time observation of my system and utilize forecasts of supply and demand at daily, weekly, seasonal, and annual timescales that are now possible due to our extensive monitoring of the earth system. However, even a perfect forecast will produce no benefits unless the operational rules are designed to allow adaptive decision making based on forecast information. Therefore, I would design my operational system with the ability to adjust dynamically in accordance with the available forecasts. Here, reliability can be used as a dynamic measure conditional on a current forecast, for example.
2. Second, since I would have no sense for the overall reliability of my system I would assume that sooner or later my design value will be wrong; thus, I would design the system to manage the consequences of this “failure.” To paraphrase Fiering and Matalas (1990), the focus would be on having good results rather than being “right.” I would design a system that didn’t fail when the design variable was exceeded and a single component failed because it would consist of multiple components that performed in a continuous fashion. Some would call this robust. Furthermore, since I would suspect that some components of this system design might not be needed often (or ever) I would incorporate them in such a way that they were only called upon only when needed—“on demand infrastructure,” to borrow a phrase from computing.
3. Third, to achieve safe fail design or on demand infrastructure, I would consider providing the services of water infrastructure by means that go beyond traditional structural systems. This would entail the integration of structural and nonstructural systems (White 1968, cited in Burgess 1979; Gleick 2003) during design to create water systems designed for all floods and drought, not just the design event. Incorporating innovations in communications, information technology (IT), and the application of economic mechanisms are examples that may prove fruitful for enhancing water system performance.

These are components of a water resources paradigm that promotes dynamic response to changing conditions at all timescales. The death of stationarity implies that the future will hold surprises, whether in short-term supply expectations or long-term demand projections, and our water resources systems must be prepared to react to them. A summary of these new principles might be called the three “F’s”: forecasts, flexibility, and fields (as in, multidisciplinary). Forecasts (daily, weekly, seasonal, longer) of both supply and demand represent the best estimate of the future that we have, inaccuracies and uncertainties and all. This includes using unconditional climatology when there isn't a strong climate signal. Where they have skill they allow us to enact anticipatory actions that mitigate the effects of hydrologic extremes. Their utility presupposes that anticipatory actions are possible and that we have back-up plans for when an anticipatory action might be mistaken (i.e., when a forecast is "wrong," the issue of whether a probabilistic forecast can be wrong notwithstanding). At present it is often difficult to employ forecasts beneficially in systems that were designed to function without them. Flexibility enables the system to adapt to changing and unexpected conditions and to call upon resources that might be needed only rarely and would be prohibitive to provide continuously. Examples would include economic mechanisms such as temporary water transfers and controlled flooding of designated areas to relieve flood risk (Characklis et al. 2006; Kundzewicz and Takeuchi 1999). Multidisciplinary fields allows a focus on water resources management that is not limited by the single field and its prevailing assumptions that may have dominated the subject in the past; or that allows the field to evolve beyond the traditional borders of departments and disciplines.

Many of the ideas cited here are not new. However, they will remain as good ideas with only anecdotal support while the static paradigm persists. The end of reliability presents an opportunity for a scientific initiative to develop the new paradigm for water resources planning and management. For that to happen, the subject of water resources research calls for an approach that is consistent with the concept of sustainability science, a new field and section of the Proceedings of the National Academy of Sciences which "transcends the concerns of its foundational disciplines and focuses instead on understanding the complex dynamics that arise from interactions between human and environmental systems" (Clark 2007). Particularly relevant to water resources research is the idea that sustainability science "serves the quest for advancing both useful knowledge and informed action by creating a dynamic bridge between the two" (Clark 2007). In our field, there is a need for strong linkage between practitioners and theorists to ensure science benefits society and a perhaps stronger need for practitioners to advocate for the science that will yield innovations in practice.

This essay has called for a new paradigm for water resources planning and management and presented a list of possible principles that reflect the challenges and opportunities of the current era. Unfortunately, the resources for testing and expanding these principles are limited due to a lack of research funding for water resource management initiatives within the field of water resources research (Lettenmaier 2008). Certainly water is a fundamental aspect of sustainability and may even be considered a bellweather of sustainability. Now we need support for the science that will produce the innovations in water resources planning and management that are sorely needed to replace the static design paradigm in this era of nonstationarity.

References

Barros, A. P., and Evans, J. (1997). "Designing for climate variability." *J. Prof. Issues Eng. Educ. Pract.*, 123(2), 62–65.

Burges, S. J. (1979). "Water resources systems planning in U.S.A.: 1776–1976." *J. Water Resour. Plng. and Mgmt. Div.*, 105(1), 91–111.

Characklis, G. W., Kirsch, B. R., Ramsey, J., Dillard, K. E. M., and Kelley, C. T. (2006). "Developing portfolios of water supply transfers." *Water Resour. Res.*, 42, W05403.

Clark, W. C. (2007). "Sustainability science: A room of its own." *Proc. Natl. Acad. Sci. U.S.A.*, 104(6), 1737–1738.

Fiering, M. B., and Matalas, N. C. (1990). "Decision-making under uncertainty." *Climate Change and U.S. Water Resources*, P. E. Waggoner, ed., Wiley, New York.

Gleckler, P. J., Taylor, K. E., and Doutriaux, C. (2008). "Performance metrics for climate models." *J. Geophys. Res.*, 113, D06104

Gleick, P. H. (2003). "Global freshwater resources: Soft-path solutions for the 21st century." *Science*, 302(5650), 1524–1528.

Green, C. H., Parker, D. J., and Tunstall, S. M. (2000). "Assessment of flood control and management options." *World Commission on Dams Thematic Review Options Assessment IV*.

Klemes. (2002). "Risk analysis: The unbearable cleverness of bluffing." *Risk, reliability, uncertainty, and robustness of water resources systems*, J. Bogardi and Z. Kundzewicz, eds., Cambridge University Press, Cambridge, U.K., and New York.

Kundzewicz, Z., and Takeuchi, K. (1999). "Flood protection and management: Quo vadimus?" *Hydrol. Sci. J.*, 44(3), 417–432.

Lettenmaier, D. P. (2008). "Have we dropped the ball on water resources research?" *J. Water Resour. Plann. Manage.*, 134(6), 491–492.

Milly, P. C. D., et al. (2008). "Stationarity is dead: Whither water management?" *Science*, 319(5863), 573–574.

Solomon, S., et al., eds. (2007). "Climate change 2007: The physical science basis." *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, U.K., and New York.

White, G. F. (1968). *Strategies of American water management*, University of Michigan Press, Ann Arbor, Mich., 155.