Stationarity Is Dead: Whither Water Management?

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CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

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Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global investment in water infrastructure exceeds U.S.$500 billion (*1*).

The stationarity assumption has long been compromised by human disturbances in river basins. Flood risk, water supply, and water quality are affected by water infrastructure, channel modifications, drainage works, and land-cover and land-use change. Two other (sometimes indistinguishable) challenges to stationarity have been externally forced, natural climate changes and low-frequency, internal variability (e.g., the Atlantic multidecadal oscillation) enhanced by the slow dynamics of the oceans and ice sheets (*2*, *3*). Planners have tools to adjust their analyses for known human disturbances within river basins, and justifiably or not, they generally have considered natural change and variability to be sufficiently small to allow stationarity-based design.

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An uncertain future challenges water planners.

In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Finding a suitable successor is crucial for human adaptation to changing climate.

How did stationarity die? Stationarity is dead because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (*4*, *5*) (see figure, above). Warming augments atmospheric humidity and water transport. This increases precipitation, and possibly flood risk, where prevailing atmospheric water-vapor fluxes converge (*6*). Rising sea level induces gradually heightened risk of contamination of coastal freshwater supplies. Glacial meltwater temporarily enhances water availability, but glacier and snow-pack losses diminish natural seasonal and interannual storage (*7*).

Anthropogenic climate warming appears to be driving a poleward expansion of the subtropical dry zone (*8*), thereby reducing runoff in some regions. Together, circulatory and thermodynamic responses largely explain the picture of regional gainers and losers of sustainable freshwater availability that has emerged from climate models (see figure, p. 574).

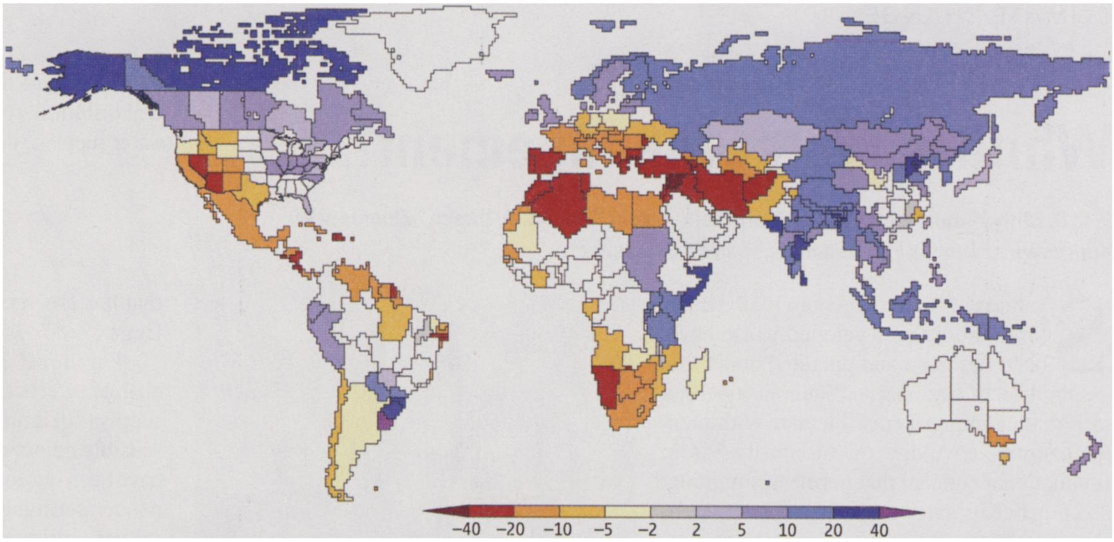
Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (*12*, *14*).

Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the recently demonstrated retrodictive skill of climate models. The global pattern of observed annual streamflow trends is unlikely to have arisen from unforced variability and is consistent with modeled response to climate forcing (*15*). Paleohydrologic studies suggest that small changes in mean climate might produce large changes in extremes (*16*), although attempts to detect a recent change in global flood frequency have been equivocal (*17*, *18*). Projected changes in runoff during the multidecade lifetime of major water infrastructure projects begun now are large enough to push hydroclimate beyond the range of historical behaviors (*19*). Some regions have little infrastructure to buffer the impacts of change.

Stationarity cannot be revived. Even with aggressive mitigation, continued warming is very likely, given the residence time of atmospheric CO_2 and the thermal inertia of the Earth system (*4*, *20*).

A successor. We need to find ways to identify nonstationary probabilistic models of relevant environmental variables and to use those models to optimize water systems. The challenge is daunting. Patterns of change are complex; uncertainties are large; and the knowledge base changes rapidly.

Under the rational planning framework advanced by the Harvard Water Program (*21*, *22*), the assumption of stationarity was



Human influences. Dramatic changes in runoff volume from ice-free land are projected in many parts of the world by the middle of the 21st century (relative to historical conditions from the 1900 to 1970 period). Color denotes percentage change (median value from 12 climate models). Where a country or smaller political unit is colored, 8 or more of 12 models agreed on the direction (increase versus decrease) of runoff change under the Intergovernmental Panel on Climate Change's "SRES A1B" emissions scenario.

combined with operations research, statistics, and welfare economics to formulate design problems as trade-offs of costs, risks, and benefits dependent on variables such as reservoir volume. These trade-offs were evaluated by optimizations or simulations using either long historical streamflow time series or stochastic simulations of streamflow based on properties of the historical time series.

This framework can be adapted to changing climate. Nonstationary hydrologic variables can be modeled stochastically to describe the temporal evolution of their pdfs, with estimates of uncertainty. Methods for estimating model parameters can be developed to combine historical and paleohydrologic measurements with projections of multiple climate models, driven by multiple climate-forcing scenarios.

Rapid flow of such climate-change information from the scientific realm to water managers will be critical for planning, because the information base is likely to change rapidly as climate science advances during the coming decades. Optimal use of available climate information will require extensive training of (both current and future) hydrologists, engineers, and managers in nonstationarity and uncertainty. Reinvigorated development of methodology may require focused, interdisciplinary efforts in the spirit of the Harvard Water Program.

A stable institutional platform for climate predictions and climate-information delivery may help (*23*). Higher-resolution simulations of the physics of the global land-atmosphere system that focus on the next 25 to 50 years are crucial. Water managers who are developing plans for their local communities to adapt to climate change will not be best served by a model whose horizontal grid has divisions measured in hundreds of kilometers. To facilitate information transfer in both directions between climate science and water management, the climate models need to include more explicit and faithful representation of surface- and ground-water processes, water infrastructure, and water users, including the agricultural and energy sectors. Treatments of land-cover change and land-use management should be routinely included in climate models. Virtual construction of dams, irrigation of crops, and harvesting of forests within the framework of climate models can be explored in a collaboration between climate scientists and resource scientists and managers.

Modeling should be used to synthesize observations; it can never replace them. Assuming climatic stationarity, hydrologists have periodically relocated stream gages (*24*) so that they could acquire more perspectives on what was thought to be a fairly constant picture. In a nonstationary world, continuity of observations is critical.

The world today faces the enormous, dual challenges of renewing its decaying water infrastructure (*25*) and building new water infrastructure (*26*). Now is an opportune moment to update the analytic strategies used for planning such grand investments under an uncertain and changing climate.

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