

## A Bayesian Hierarchical Modeling Approach to Predicting Flow in Ungauged Basins

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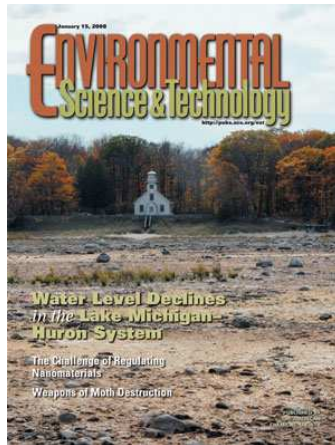
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# Outline

- 1 Introduction
- 2 Methodology
- 3 Conclusions







## POLICYFORUM

## CLIMATE CHANGE

Stationarity Is Dead:  
Whither Water Management?P. C. D. Milly,<sup>1</sup>\* Julie Beven<sup>2</sup>, Melia Falkenmark,<sup>3</sup> Robert M. Hirsch,<sup>4</sup> Zhiyuan W. Kundzewicz,<sup>5</sup> Dennis P. Lettenmaier,<sup>6</sup> Ronald J. Stedler<sup>7</sup>

**S**ystems 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 historical 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 ocean and ice sheets (2, 3). Planners have tried to adjust their analyses for known human disturbances within river basins, and justifiably so, but 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 default assumption in water-resource risk assessment and planning. Finding a variable successor is critical 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 gains and losses 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 news (indeed). Nevertheless, scintillating objections to discarding stationarity have been raised. For a time, hydrologic had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operational 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 mean changes are bolstered by the recently demonstrated predictive skill of climate models. The global pattern of observed annual streamflow trends is unlikely to have arisen from unforced variability and is consistent with model responses 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). Practical changes in runoff during the multidecadal lifetime of major water infrastructure projects began now are large enough to peak hydroclimate beyond the range of historical experience (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<sub>2</sub> and the thermal inertia of the Earth system (4, 20).

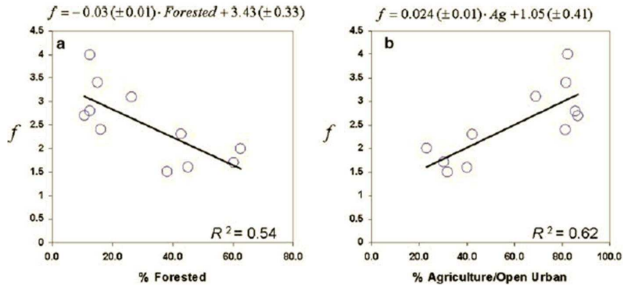
It is necessary. We must find ways to identify anomalous probabilistic models of relevant environmental variables and to use those models to optimize water systems. The challenge is daunting. Patterns of change are complex; uncertainties are large; and the knowledge base changes rapidly.

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

How can we propagate uncertainty and variability  
into hydrological models  
*and*  
reflect them in a meaningful way in ecosystem forecasts  
and management decisions?

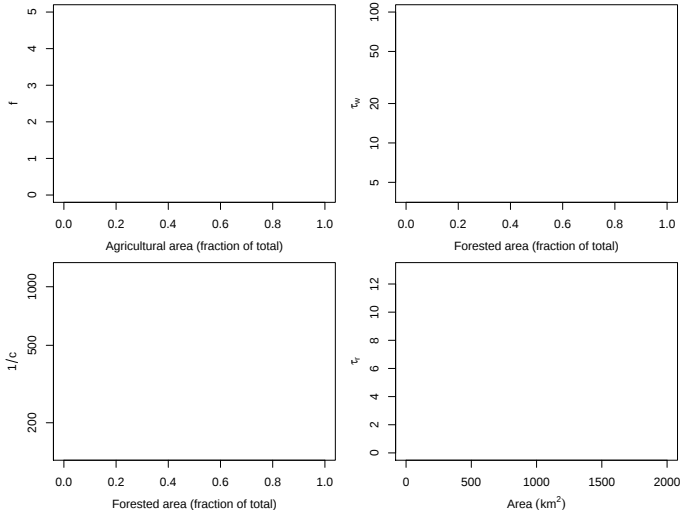
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# Parameter estimation: regression-based approach

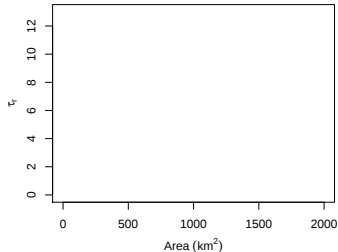
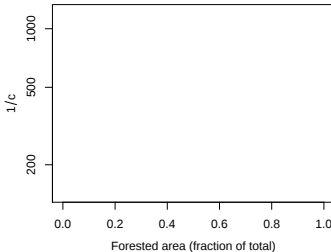
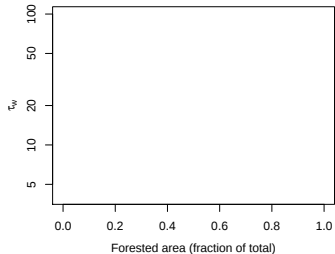
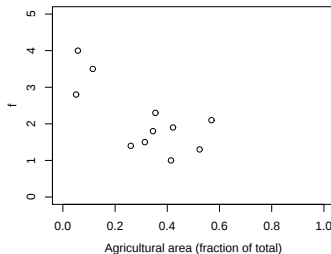


R. M. Anderson, B. J. Hobbs, J. F. Koonce. *Ecosystems*. 2006. **9**(5): 725–739.

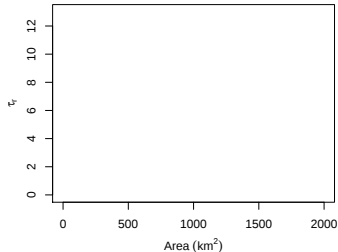
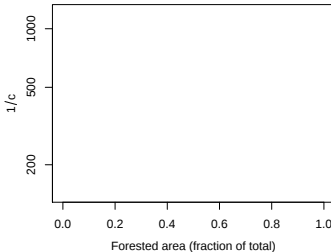
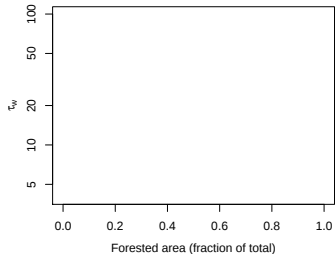
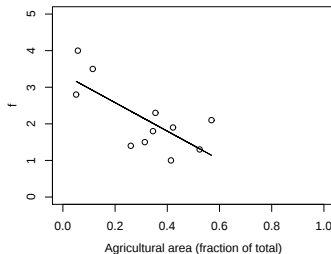
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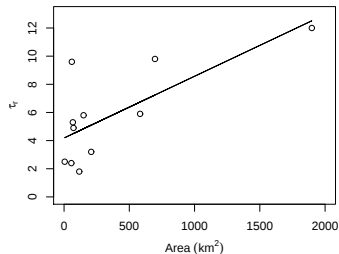
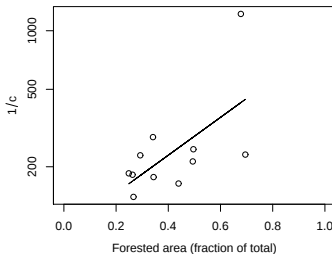
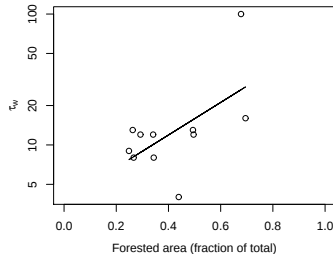
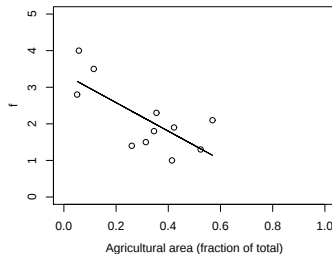
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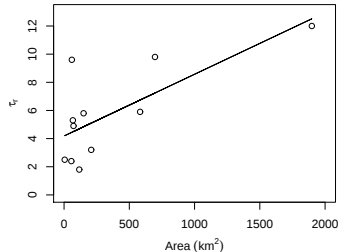
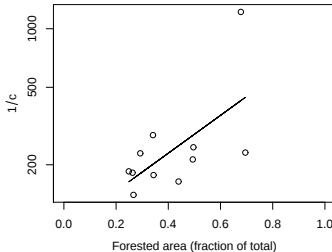
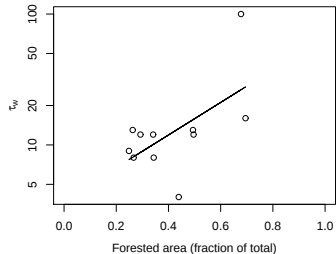
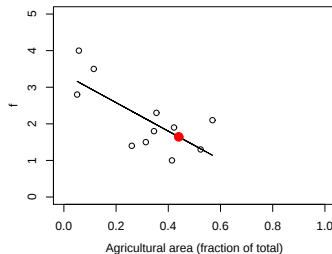
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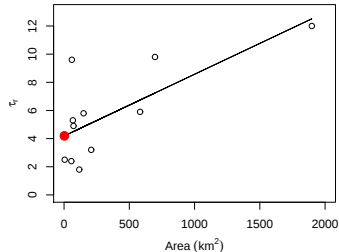
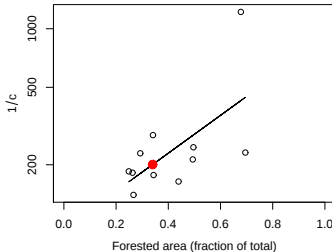
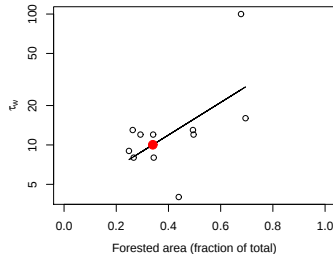
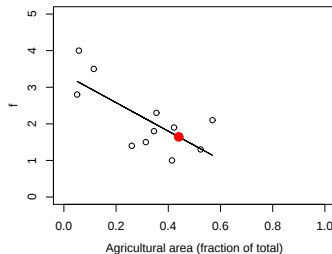
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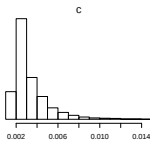
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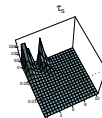
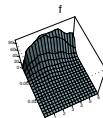
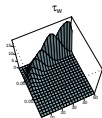
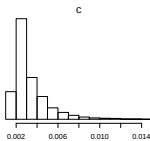
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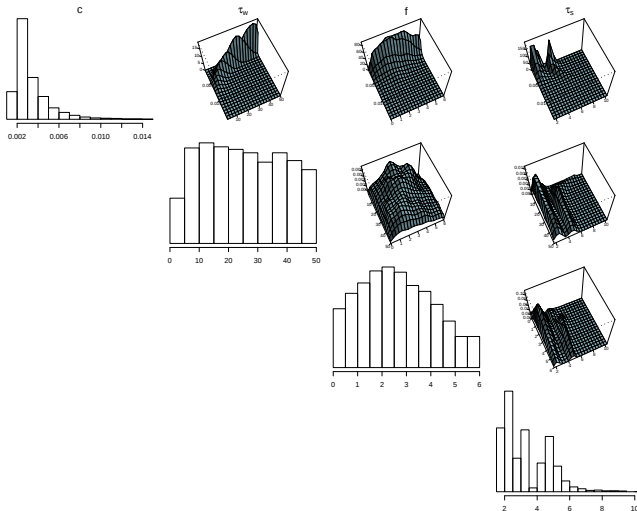
# Parameter estimation: Bayesian approach



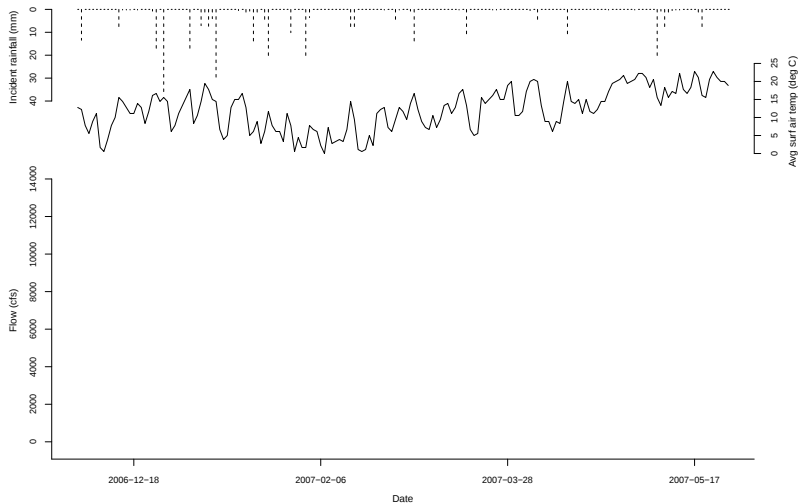
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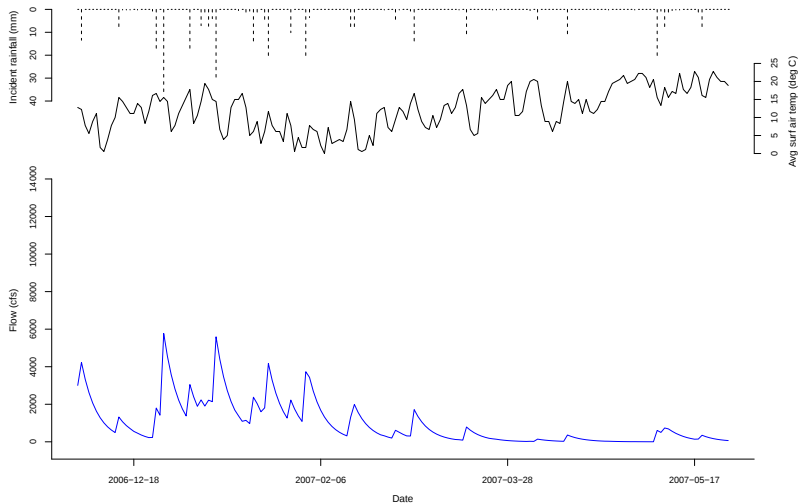
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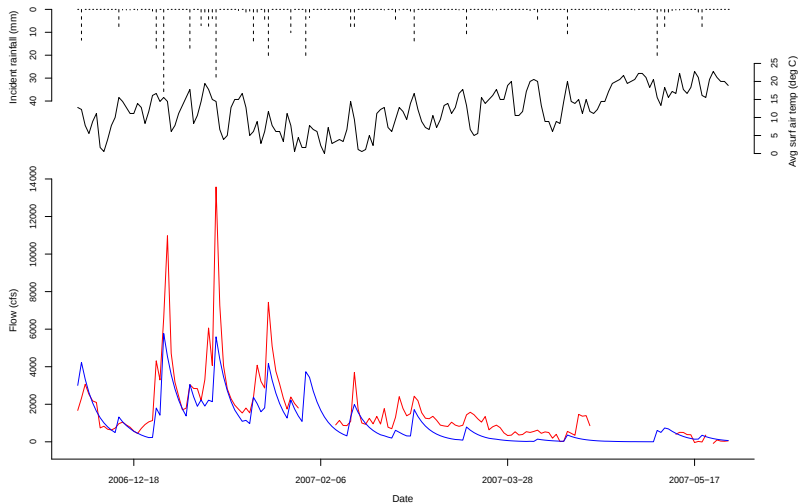
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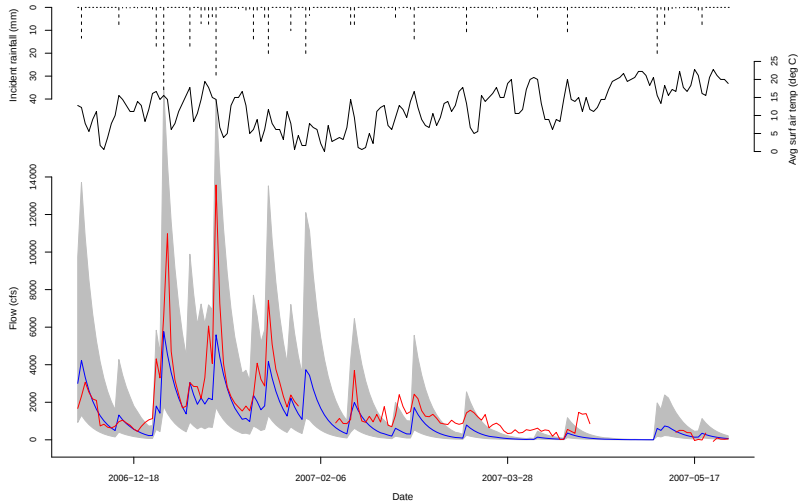
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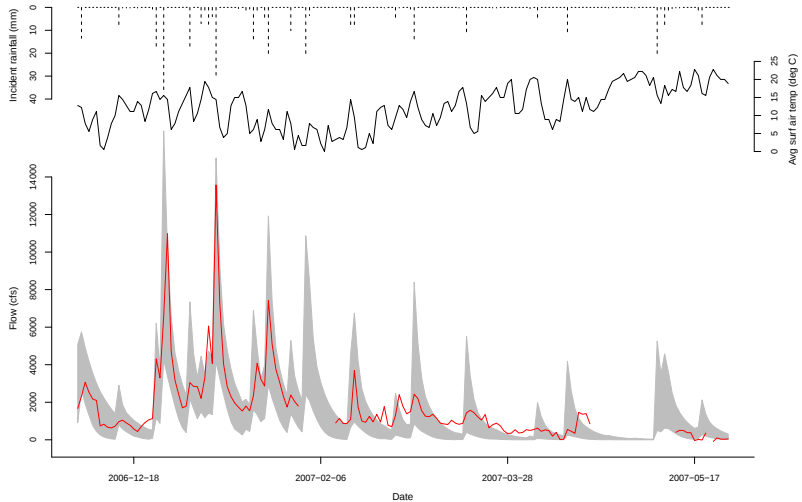
# Model verification: regression-based approach



# Model verification: regression-based approach



# Model verification: Bayesian approach



# Conclusions

- Current approaches to predicting flows are inefficient
- Intrinsic uncertainty exceeds impacts of land use change
- Regionalized approach could benefit large-scale planning

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## A Bayesian Hierarchical Modeling Approach to Predicting Flow in Ungauged Basins

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