Reflections on Water Resources in a Changing World

Robert M. Hirsch
U.S. Geological Survey
10 September, 2016
Stationarity Is Dead: Whither Water Management?

P. C. D. Milly,1 Julie Betencourt,1 Malin Falkenmark,2 Robert M. Hirsch,1 Zbigniew W. Kundzewicz,1 Dennis P. Lettenmaie,1 Ronald J. Stouffer1

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 palaeohydrologic 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.$550 billion (7).

The stationarity assumption has long been compromised by human disturbances in river basins. Floods, water supplies, and water quality are affected by water infrastructure, channel modifications, drainage works, and land-conversion 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 low damping of the oceans and ice sheets (2, 3). Planters have tools to adjust their analyses for known human disturbances within river basins, and justifiably so; others have considered natural change and variability to be sufficiently small to allow stationarity-based design.

In view of the magnitude and ubiquity of the hydroclimatic change apparently now underway, 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, while 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 supplies (10) is not a new finding. Nevertheless, sensible objections to discounting stationarity have been raised. For example, hydroclimate has not dramatically exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (11, 12). Accounting for the substantial uncertainties of climate 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 run-off 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 modelled response to climate forcing (15). Palaeohydrologic 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 multidecadal lifetime of major water infrastructure projects are now 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 CO2 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...
The challenge is how to build a bridge from the observed past to an uncertain future?
Why should we do trend studies?

• To provide the basis for design and operations decisions

• To evaluate deterministic trend models

• To evaluate progress & identify emerging issues
“Data without models are chaos, But models without data are fantasy”

The study of change needs BOTH statistical inference AND process-based modeling.

There is room for diverse approaches to tease out the meaningful signals from the noisy data.
Trend in daily precipitation volume for the 1% daily frequency, between 1958 and 2012. That’s the event that is exceeded about 3 days per year. (reported in National Climate Assessment).

- Can climate models produce patterns like this?
- Do streamflow statistics show trends that are consistent with this?
- What are the implications for flood hazards?
Little Androscoggin River, near South Paris, Maine
190 km² watershed
Can the models create patterns like this?

Little Androscoggin River near South Paris, Maine

How to describe it?
Everyone tells me “Hydrologic variability has been increasing” - so what’s your metric? Mine is the 21-year moving standard deviation of the log daily discharge. What’s your definition of variability? Can we document that it is increasing?
Flow Duration Curves for 3 segments of the record.

Little Androscoggin River near South Paris, Maine
Frequency Distribution of Discharge for 3 Periods

The 1% point on the flow duration curve

Discharge in cms

Daily Exceedance Probability
Look at all events above 24.2 m$^3$/s. A level such that from 1940-1969 there were an average of 2 events per year. Are these events getting more frequent, lasting longer, having a larger volume, or a higher peak day?
Little Androscoggin River near South Paris, Maine
Daily discharge above a threshold of 24.2 Cubic Meters per Second
Using the Mann-Kendall test for trend: the two-sided p-value is 0.005. Frequency has gone from an average of 2 per year in the base period to an average of 3.3 per year since 1990.
Using the Mann-Kendall test for trend: the two-sided p-value is 0.7 (a non-significant decrease)
Using the Mann-Kendall test for trend: the two-sided p-value is 0.6 (a non-significant decrease)
using the Mann-Kendall test for trend: the two-sided p-value is 0.5 (a non-significant decrease)
Three watersheds in New England

- Little Androscoggin River
- Ammonoosuc River
- Bunnell Brook
Using the Mann-Kendall test for trend: the two-sided p-value is 0.5. Frequency has gone from an average of 2 per year in the base period to an average of 2.2 per year since 1990.
Using the Mann-Kendall test for trend: the two-sided p-value is 0.002. Frequency has gone from an average of 2 per year in the base period to an average of 4.1 per year since 1990.
Diversity of flood behaviors: Tau values of trends

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>Duration</th>
<th>Volume</th>
<th>Peak Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Androscoggin</td>
<td>+0.22**</td>
<td>-0.03</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>Ammonoosuc</td>
<td>+0.05</td>
<td>-0.05</td>
<td>-0.05</td>
<td>-0.05</td>
</tr>
<tr>
<td>Bunnell Brook</td>
<td>+0.25**</td>
<td>-0.03</td>
<td>+0.097*</td>
<td>+0.14**</td>
</tr>
</tbody>
</table>

Can atmospheric and hydrologic models result in similar outcomes?
Can we explain the differences among watersheds?
Changing Streamflow

- Do we have up-to-date characterizations of streamflow for design and management purposes (low flow, high flow, seasonal, ...)?

- Are we using the data to test deterministic models of change (using model hindcasts)?

- Are we using the data to inform us of widespread changes and their possible causes?

- Are we operating observation networks that will help us characterize change into the future?
Now we will shift gears

Moving from

• changes in streamflow
• to changes in surface water quality
Chesapeake Bay Nontidal Monitoring Network

- 117 stations
- About 20 samples per year (calendar and event based) for N, P, and SS
- Daily discharge at all sites
- Looking for trends in load
Data analysis issues

• The data can be highly variable
• Highly related to streamflow and season
• Highly skewed
• Sometimes censored

• Assessments of progress can be easily obscured by the random, but persistent, pattern of wet and dry years ("The thrill of victory, the agony of defeat")
Potomac River at Washington, DC  Total Phosphorus
Water Year
Annual Flux Estimates

The thrill of victory
Look at the discharge record

Potomac River at Washington, DC
Water Year mean daily

Four dry years

Discharge in $10^3$ ft$^3$/s

The agony of defeat
It's all about the flow!

Potomac River at Washington, DC
Water Year mean daily

Discharge in $10^3\text{ft}^3\text{/s}$


It’s all about the flow!

USGS
What’s my point here?

- This history of loadings is very useful to the ecologist trying to understand the drivers of the receiving water body.

- But, it is not useful for assessing progress because it is overwhelmed by random year-to-year variation in streamflow.

- We are smarter than Homer! We can deal with the influence of flow.
Analysis method

- Use Weighted Regressions on Time, Discharge and Season (WRTDS)
- WRTDS bootstrap test for uncertainty analysis
Choptank River, 293 km² watershed

WRTDS Example
Choptank River Near Greensboro, MD
Dissolved Orthophosphate, as P
Concentration versus Time

Concentration in mg/l as P

USGS
WRTDS characterizes the evolving relationship of concentration to season and discharge.

Choptank River Near Greensboro, MD  Dissolved Orthophosphate, as P
Estimated Concentration Surface in Color

Discharge in m$^3$/s


mg/L

0.14  0.12  0.10  0.08  0.06  0.04  0.02  0.00
• Provides a detailed description of change.
• But managers want answers to 2 simple questions:
  • Is it getting better or worse?
  • What is the rate of change?
• Integrate this surface over the seasonal frequency distribution of discharge to get “Flow-Normalized Annual Flux”.
Change from 2005 to 2014
3800 kg/yr to 5700 kg/yr
Measures of uncertainty

Trend magnitude in Dissolved Orthophosphate, as P Flow Normalized Flux 2005 to 2015
Choptank River Near Greensboro, MD Water Year

Best estimate: a 54% increase
Chesapeake Bay TMDL story

- The official model for the TMDL showed Orthophosphorus declining. This WRTDS analysis has helped show how flawed that is.

- This empirical result is a wake-up call about an emerging problem in the region
Another story: Chloride trends for the Hockanum River near East Hartford, CT
Nutrient, organic carbon, and chloride concentrations and loads in selected Long Island Sound tributaries—Four decades of change following the passage of the Federal Clean Water Act, by John Mullaney
Weighted Regressions on Time, Discharge, and Season (WRTDS)

HOCKANUM RIVER NEAR EAST HARTFORD, CT. Chloride Estimated Concentration Surface in Color

Discharge in m³/s

1995 2000 2005 2010

mg/L

0 20 40 60 80 100 120
HOCKANUM RIVER NEAR EAST HARTFORD, CT. Chloride
Season Consisting of Dec Jan Feb Mar
Mean Concentration (dots) & Flow Normalized Concentration (line)

Note: this time we are tracking concentration
Black is Dec-Jan-Feb-Mar
Red is July-Aug-Sept-Oct

Concentration in mg/l

0 10 20 30 40 50 60 70 80 90 100

1995 2000 2005 2010
Why all this complexity?

Different products for different purposes

• Concentration versus flux

• Actual history versus flow-normalized history

• Seasonal versus annual trends
An aside about software

Most of the analysis and visuals in this talk were produced with the USGS open source R-software packages:

- `dataRetrieval`
- `EGRET` (Exploration and Graphics for RivEr Trends)
- `EGRETci` (confidence intervals)

All available from CRAN
Stationarity Is Dead: Whither Water Management?

P. C. D. Milly, Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, Ronald J. Stouffer

“In a nonstationary world, continuity of observations is critical”
Mauna Loa Observatory
Funding sources for C.D. Keeling CO$_2$ measurements 1956-2005

(amounts adjusted to 2007 dollars)

Mauna Loa Observatory, Hawaii
Monthly Average Carbon Dioxide Concentration

CO$_2$ Concentration (ppm)

Annual Support

$1,000,000$

$2,000,000$


NASA
Calif. Space Inst.
NBS
UNEP-WMO
EPRI
DOE
ESSA/NOAA
NSF
IGY
IGY
USWB
Temperature trends for Amherst, MA

Long-Term Trends in Temperature

Annual Mean Temperature (1837-2011)

Mean Temperature
Linear Trend

Mean Temperature (°F)

From poster presentation by Arcusa, Bradley, and Rawlins, U. of MA, Amherst
Connecticut River at Thompsonville, CT
Water Year

- **Maximum Day**
  - Discharge ($10^3 m^3/s$)
  - Data from 1920 to 2020

- **Mean Daily**
  - Discharge ($10^3 m^3/s$)
  - Data from 1920 to 2020

- **7-Day Minimum**
  - Discharge ($10^3 m^3/s$)
  - Data from 1920 to 2020

- **Standard Deviation of log(Q)**
  - Dimensionless
  - Data from 1920 to 2020

USGS
The only way to figure out what is happening to our planet is to measure it, and this means tracking changes decade after decade and poring over the records.

Ralph Keeling, 2008, Recording Earth’s vital signs, Science, p1771-1772
How to build the bridge

Collect the data over decades, be persistent
Pore over the data for signals, describe them
Use the data to test the models
Use decision frameworks that recognize deep uncertainty
How to build the bridge

Avoid arrogance and avoid paralysis
Build resilient plans and operations – the future may be well outside our envelope of experience
Use diverse portfolios and be adaptive (which demands observations and repeated analysis)