“The only way to figure out what is happening to our planet…”

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From Ralph Keeling

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.

Keeling, 2008, Recording Earth’s vital signs, Science, p1771-1772
• To manage the future, we must understand the past
• Mankind is conducting several unplanned experiments.
• Learn from them!
• We need new tools for this purpose.

Two issues

For streamflow: how do we move beyond the stationary paradigm?

For water quality, we have long accepted the idea of non-stationarity, but we need tools to describe the changes and not be fooled by the influence of random streamflow variations.
Nutrient enrichment: the Des Moines River

A 36,000 km² watershed in the US corn belt
• From 1940 – 2008, average concentrations of nitrate increased from about 0.2 mg/L to about 5.7 mg/L
• Flux of nitrate increased, about 1300%
• Many areas of US and Europe have increases of 200% to 1000% above pristine conditions
Can we decompose this data set and learn what is happening?
Use the data and a simple, highly-flexible smoothing model to decompose the data into 4 components.

1) Time trend
2) Discharge
3) Seasonal cycle
4) Random component

**Weighted Regressions on Time, Discharge and Season (WRTDS)**

Can we use statistical smoothing principles to describe the history of concentration as a function of time, streamflow and season?
This is a “map” of the difference between the years 1985 and 2011
From 1995 – 2011
Concentration increased 22%
Flux increased 12%
Sediment plume from the Susquehanna River into Chesapeake Bay, Tropical Storm Lee, September, 2011

Photo credit: NASA MODIS, Sept. 13, 2011

Susquehanna River at Conowingo, MD, Total Phosphorus

Conowingo Dam
Black is before 2000
Red is 2000 to present

Susquehanna River at Conowingo, MD
Total Phosphorus
Concentration versus Discharge

Susquehanna River at Conowingo, MD
Total Phosphorus
Estimated Concentration Surface in Color
Black lines are 5 and 95 flow percentiles
Since 1995
Concentration is up 10%
Flux is up 55%
Conclusions - Nutrients

- What’s the question? Concentration or Flux
- What’s the solution? Focus on high flow sources (overland flow, reservoir scour) or Focus on low flow sources (point sources, groundwater)
- Need the right software tools

A Montana water quality example, the Powder River, downstream of coal and coal-bed methane development
Describe the change 1950 to 2010
### Concentration History

**Powder River near Locate MT**

**Dissolved Sodium**

**Estimated Concentration Versus Discharge Relationship at 2 specific dates**

- **1952-09-01**
- **2008-09-01**

**Discharge in ft³/s**

**Concentration in mg/L**

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**Concentration History**

**Powder River near Locate MT**

**Dissolved Sodium**

**Water Year**

**Mean Concentration (dots) & Flow Normalized Concentration (line)**

**Concentration in mg/L**

Flux History

WRTDS estimates of changes in Dissolved Sodium Powder River near Locate, MT

<table>
<thead>
<tr>
<th>Period</th>
<th>Change in flow-normalized concentration</th>
<th>Change in flow-normalized flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>1951 - 2011</td>
<td>+72%</td>
<td>+52%</td>
</tr>
<tr>
<td>2000 - 2011</td>
<td>+26%</td>
<td>+17%</td>
</tr>
</tbody>
</table>
Changing streamflow?

Missouri River at Fort Benton, USGS streamgage, since October 1890

44,570 days

Streamflow change: why do we care?

• Flood adaptation
• Water supply for cities, industry, energy, and agriculture
• Water for aquatic habitat
• Water for navigation
• Water for recreation
Potential change drivers:

• Urbanization
• Agricultural land drainage systems
• Irrigation
• Groundwater depletion
• Exports and consumptive use
• Reservoir regulation
• Quasi-periodic climatic oscillations
• Enhanced greenhouse forcing
Quasi-periodic oscillations:

- ENSO
140 years of ENSO

Quasi-periodic oscillations:
- ENSO
- PDO
- AMO
Chaotic behavior, not predictable (as yet) and important to water resources

Quasi-periodic oscillations:
- ENSO
- PDO
- AMO
- ??O
- Ice Ages

Can we avoid confusing these with human-driven change, and why should we care?
Mississippi R. at Keokuk, Iowa
308,000 km² watershed
Annual Peak Discharges

Increase 1940-2011:
49%
Increase 1880-2011: 2%
Let’s search for the greenhouse signal in streamflow data

- Places with long records
- Places where human activity on the landscape is minimal
- Places where snow is a big part of the hydrologic story
Let's go west to a very pristine basin high in the Sierra Nevada.
What if we look at the coldest months of the year?

Relationship of streamflow & greenhouse forcing

Approaches to the issue:

1) Use climate models to drive hydrologic models and simulate future hydrologic change.

2) Use the past century as an unplanned global experiment. Streamflow records in many watersheds are “experimental subjects.”

3) Use climate models in hindcast mode to create multiple realizations of the past century. Then ask: Do the actual hydrologic records fall within the envelope of the climate model hindcasts?
An example of approach 2

Hirsch and Ryberg, 2011, Hydrologic Sciences Journal

Picked 200 very long streamflow records with limited human intervention.

Regress log(annual peak discharge) on global mean CO₂ for that year and take the regression slope as a measure of “effect” without regard to “statistical significance”

What’s the pattern, nationally, regionally, by drainage area?

National results: 200 streamgage records

Units are % change per 10 ppm change in CO₂ (current increase is about 10 ppm every 5 years)
CARBON DIOXIDE REGRESSION RESULTS

Median Slope 1.6 0.9 -0.6 -4.0

p 0.14 0.40 0.57 0.002
Take away messages:

• The only region with strong statistical evidence of an association between floods & global CO$_2$ is in the southwest, and the relationship there is negative.

• All approaches to understanding the streamflow/greenhouse gas connection have flaws. But we need to look at the data regularly and with diverse approaches to see what might be emerging.

Approach 3 (hindcast studies)

• Use multiple climate simulations, forced with historical greenhouse and other forcings

• Explore the climate-model derived runoff for large regions

• Explore the actual historic runoff for large watersheds in those regions

• Do the observed trends behave anything like the range of hindcasted trends?

Plotting all those pairs of model trends versus streamgage trends.

Results are “statistically significant” but $R^2 = 12\%$
Milly, et al. (2005, Nature)

Estimated percentage change in runoff for 1971-98 vs. 1900-1970 due to global atmospheric forcing, ensemble of GCM model runs

The map shows Montana as an area of small change: something like -5% to +2%

- The Yellowstone River at Billings, comparing 1929 – 1970 versus 1970 – 1998 showed an increase of 12%

- The Missouri River at Ft. Benton, comparing 1900 – 1970 versus 1970 – 1998 showed an increase of 8%
We generally don’t see a “greenhouse signal” in hydrologic records. Why not?

• Models might be wrong (feedbacks)
• Signal is small compared to noise
• Long-term persistence is too strong
• There are thresholds
• Modifications of watersheds overwhelm the climate signal

Don’t forget the non-climate drivers!

• Let’s take a short, hydrologic tour, ending in Montana
Groundwater development of alluvial aquifer
Spokane River at Spokane, Washington
11,111 km² watershed

1900 – 1950
-0.8 % / year

1950 – 2010
-0.5 % / year
Regulation, diversion, and climate change
Colorado River at Lees Ferry, Arizona
290,000 km² watershed
iEMSs keynote

Hirsch

July 2012

1946 mean = 342

2009 mean = 331

Max day down 77%

Mean day down 37%

7-day min up 176%

0.9 to 0.3
But first, let's look at a river about 750 miles East of here

Red River of the North (North Dakota and Minnesota)

Change
1935-2011

435%

482%

650%

Be glad you don’t have their planning problem!
Clarks Fork Yellowstone R. nr Belfry MT
Water Year

Jan-Feb
Clarks Fork Yellowstone R. nr Belfry MT
Season Consisting of Jan Feb
Take away messages

• Keep the uncertainty bands wide.
• Test the models against the unplanned experiments. Be a skeptic.
• Trends (in water quality or streamflow) are never simple – they can be very different for highs versus lows or in different seasons.
• Management insights depend on getting the description of change correct.
When all is said and done:
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.