Water and Hazards: Hydrologic Extremes and Risk Assessment under Non-stationarity

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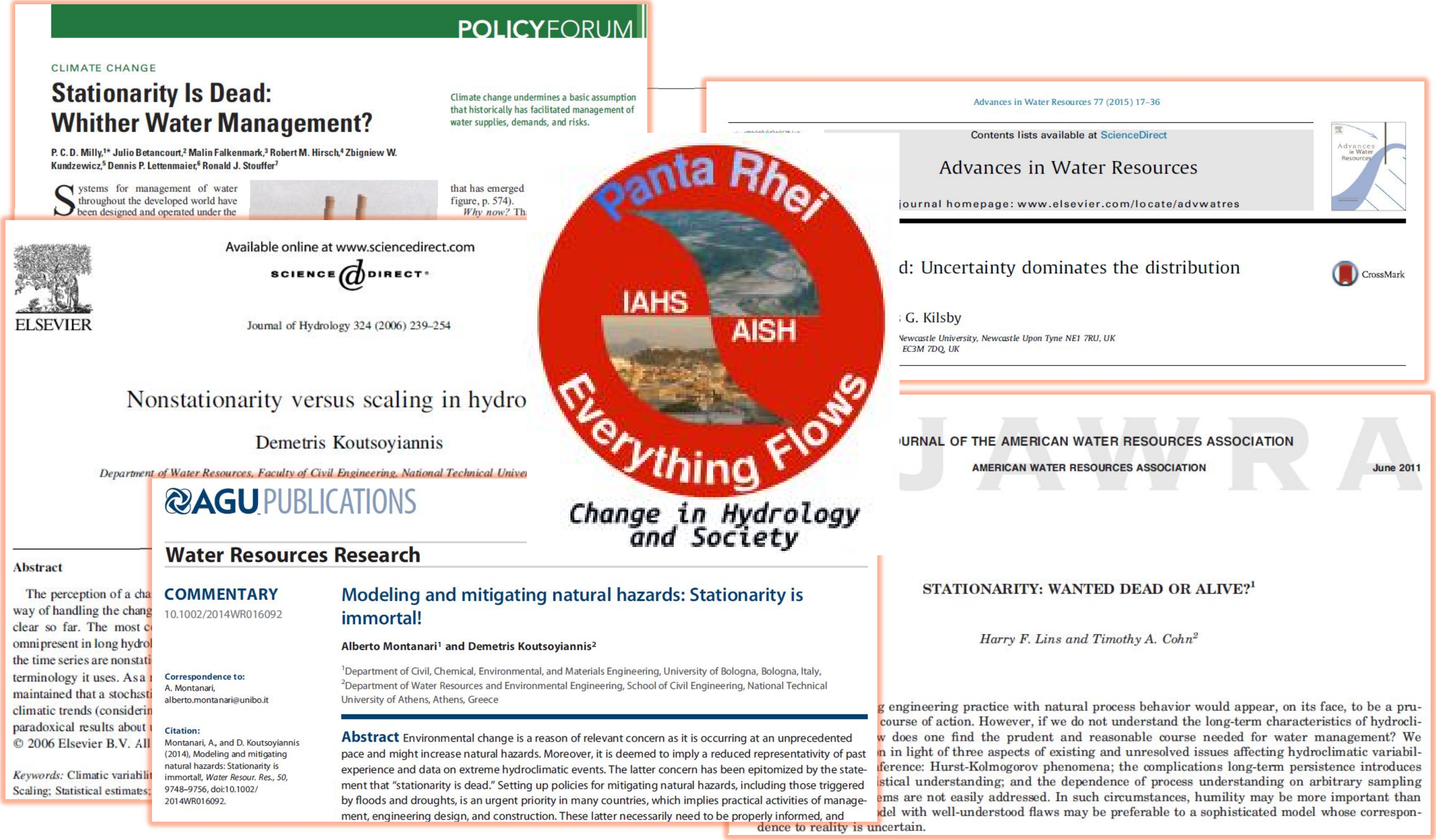
Acknowledgment: **P P Mujumdar**, IISc Bangalore.

Non-stationarity: why is it important?



POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

P. C. D. Milly,[1*] Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

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

Systems for management of water throughout the developed world have been designed and operated under the

that has emerged figure, p. 574). *Why now?* Th

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Nonstationarity versus scaling in hydro

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Abstract

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terminology it uses. As a
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Keywords: Climatic variabilit
Scaling; Statistical estimates;

AGU PUBLICATIONS

Water Resources Research

COMMENTARY

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Modeling and mitigating natural hazards: Stationarity is immortal!

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Montanari, A., and D. Koutsoyiannis (2014), Modeling and mitigating natural hazards: Stationarity is immortal!, *Water Resour. Res., 50,* 9748–9756, doi:10.1002/2014WR016092.

Abstract Environmental change is a reason of relevant concern as it is occurring at an unprecedented pace and might increase natural hazards. Moreover, it is deemed to imply a reduced representativity of past experience and data on extreme hydroclimatic events. The latter concern has been epitomized by the statement that "stationarity is dead." Setting up policies for mitigating natural hazards, including those triggered by floods and droughts, is an urgent priority in many countries, which implies practical activities of management, engineering design, and construction. These latter necessarily need to be properly informed, and

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Everything Flows

Change in Hydrology and Society

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d: Uncertainty dominates the distribution

CrossMark

G. Kilsby

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June 2011

STATIONARITY: WANTED DEAD OR ALIVE?[1]

Harry F. Lins and Timothy A. Cohn[2]

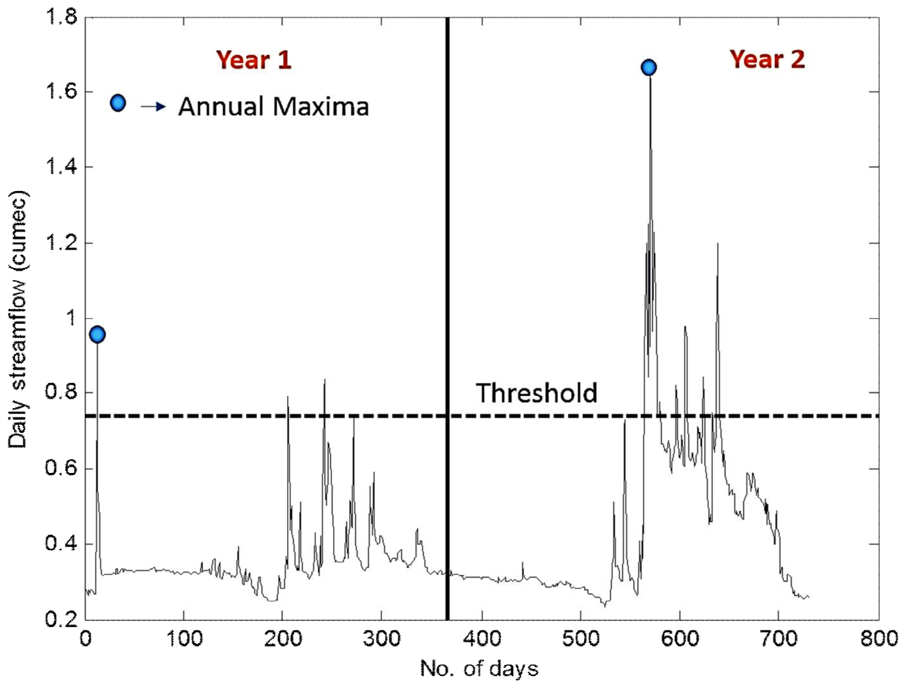
g engineering practice with natural process behavior would appear, on its face, to be a prudent course of action. However, if we do not understand the long-term characteristics of hydroclimate, w does one find the prudent and reasonable course needed for water management? We n in light of three aspects of existing and unresolved issues affecting hydroclimatic variabil- ference: Hurst-Kolmogorov phenomena; the complications long-term persistence introduces istical understanding; and the dependence of process understanding on arbitrary sampling ems are not easily addressed. In such circumstances, humility may be more important than del with well-understood flaws may be preferable to a sophisticated model whose correspondence to reality is uncertain.

The context of hydrologic extremes – floods and droughts

Some challenges in the Indian context

- The seasonality of the Indian Summer Monsoon Rainfall
- **Droughts**: rainfall variability, cheap electricity, over exploitation of water resources, climate change.
- **Floods**: rapid growth and urbanization, encroachment of flood plains, non-adherence to standards for water quality, climate change.
- Lack of good quality data for a comprehensive analysis

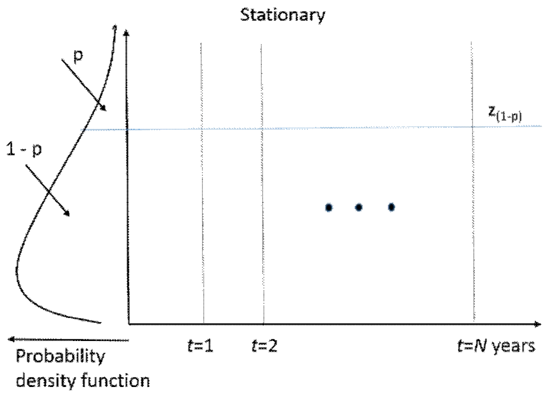
Approaches to define extremes



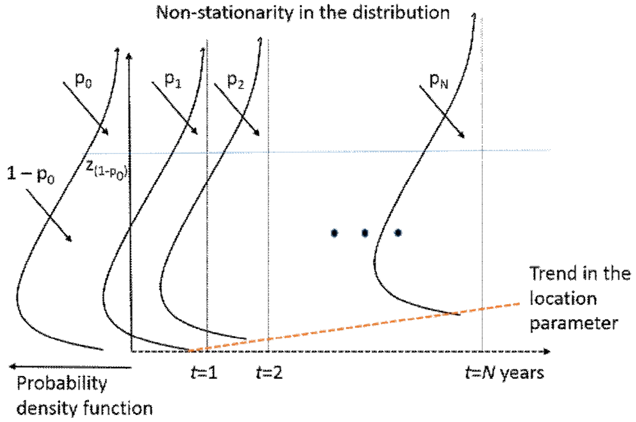
- Block Maxima Approach
  - The maxima M_n of a sequence of random variables follow the Generalized Extreme Value (GEV) distribution
- Threshold Exceedance (peak-over-threshold) Approach
  - The excesses above a high threshold follow the Generalized Pareto (GP) distribution
- Point Process Approach
  - The excesses above a threshold and their frequencies modeled simultaneously using a non-homogeneous Poisson process

Non-stationarity in hydrologic extremes

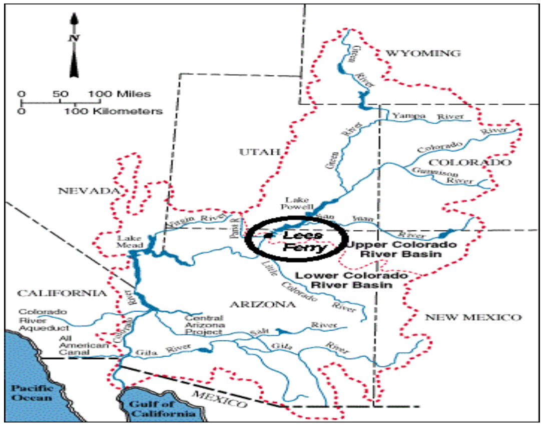
- Historically derived tail quantiles of floods and droughts such as the *N*-year return level (for example, ‘100-year flood’) and the associated uncertainties based on *stationarity.*
- *Whether* and *when,* the future return levels are likely to be significantly different from the *observed* return levels, taking into account the associated uncertainties?
- Block maxima approach for floods.
- Peak-over-threshold approach for droughts.
- Parameters $\mu(t)$, $\sigma(t)$ and $\xi(t)$ vary with time t.

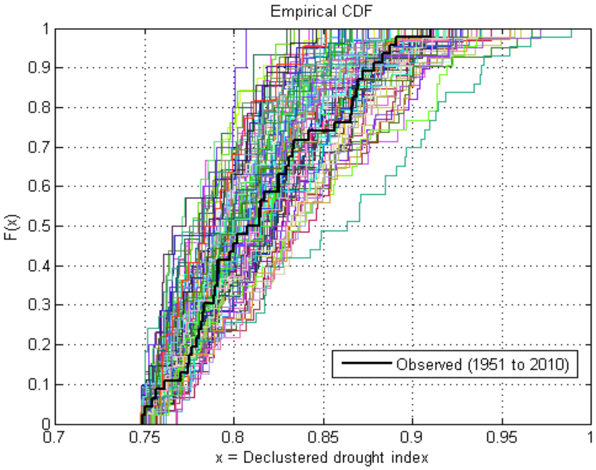


$Q_p = F^{-1}(1-p)$, where $p = 1/T$, T = return period of the flood of magnitude



Droughts in the Colorado River at Lees Ferry





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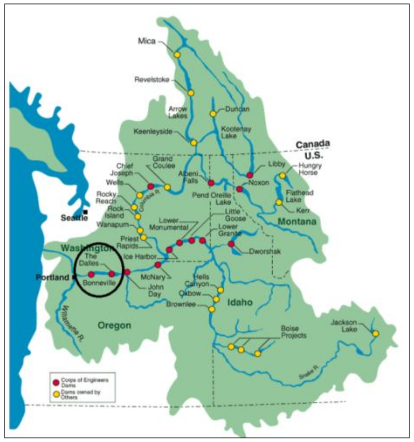
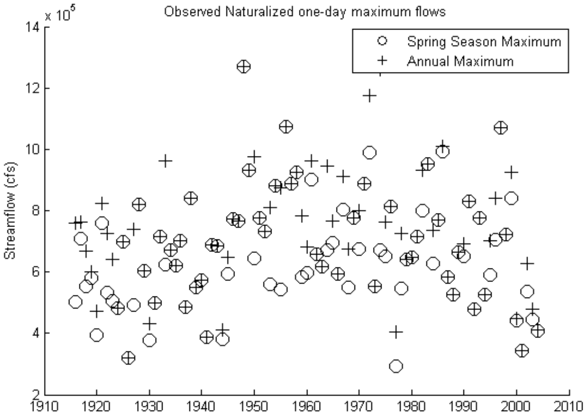
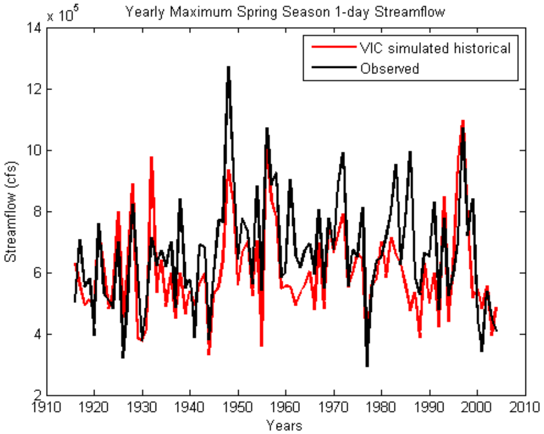
- Observed monthly naturalized streamflows in the Colorado River at Lees Ferry used for the period 1907-2010
- The statistically downscaled T and P as input to VIC run at 1/8° x 1/8° grid (similar to Das *et al*, 2013; Cayan *et al*, 2013)
- 112 projections from 16 GCMs and the 3 IPCC scenarios - A1B, A2 and B1 (Reclamation, 2011)
- Monthly streamflows are converted to a standardized drought index (Ben-Zvi, 1987; Modarres, 2007; Nalbantis, 2008)

$$D_3 = \frac{(R_3 - R_3^{clim})}{\sigma_{R_3^{clim}}}, \qquad R_3 = \sum_{i=1}^{3} R_i$$

Floods in the Columbia River at the Dalles







Mondal and Mujumdar, J Hydrol. Eng., in press.

- Warmer climate -> earlier snow melt -> increase in spring peak flows
- Mean runoff projected to increase by 1.2 to 3.7% (Reclamation, 2011)
- Model-simulated historical and future flow projections obtained from the Climate Impacts Group, University of Washinton (Hamlet *et al*, 2013)
- The hydrologic model (VIC) run at 1/16th degree grid (Hamlet and Lettenmaier, 2005) with statistically downscaled meteorologic variables
- IPCC A1B and B1 scenarios for 1950-2097

Time of detection

- Likelihood ratio test for suitability of the non-stationary model

- The observed *N*-year return level z_o and its associated variance $\sigma_{z_o}^2$ is constant (stationary). The projected *N*-year return level z_f and its associated variance $\sigma_{z_f}^2$ can be constant (stationary) or transient (non-stationary).

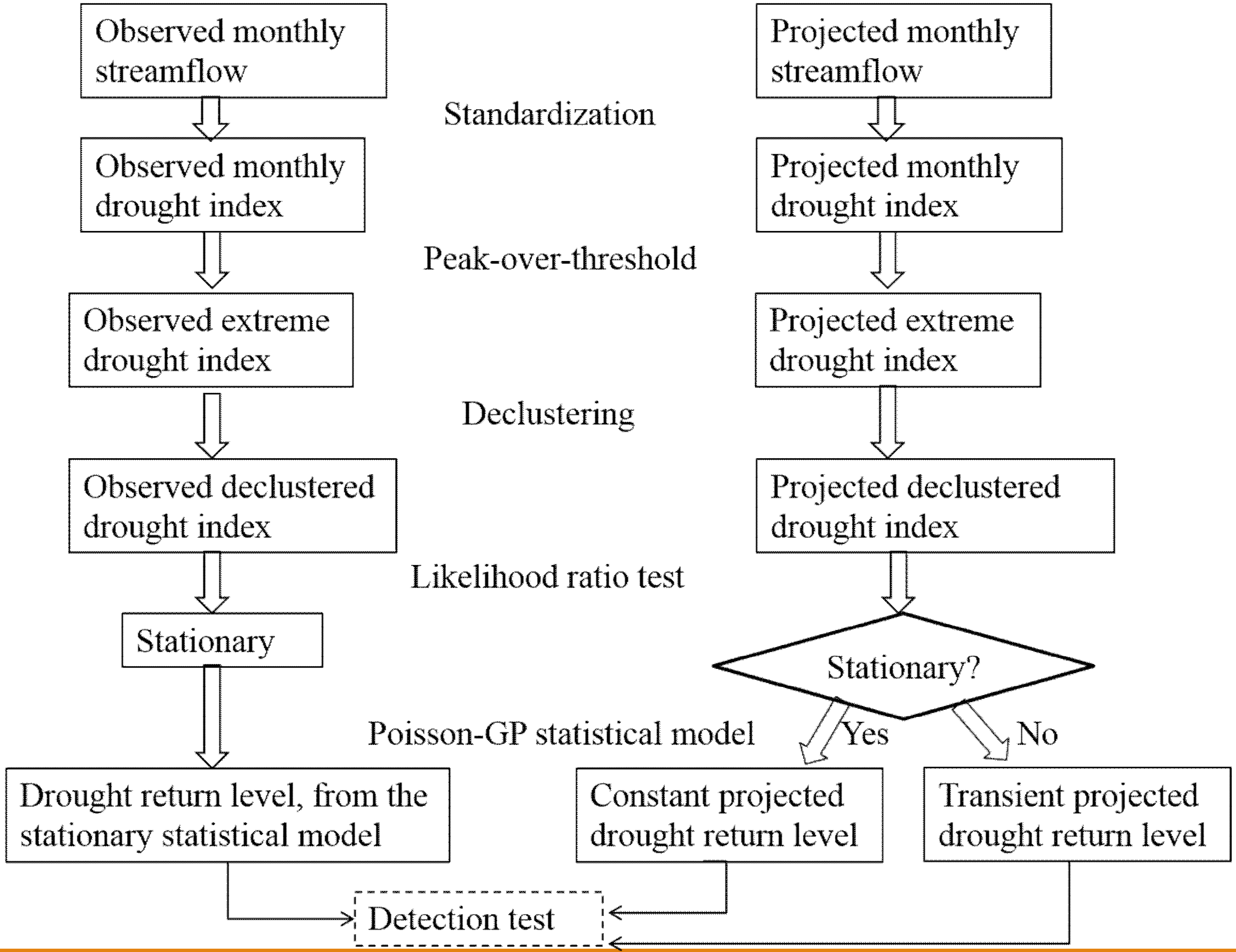
- Detection occurs at a future time step *f* if $D_f = \frac{z_f - z_o}{\sqrt{\sigma_{z_f}^2 + \sigma_{z_o}^2}} \geq Z_{critical}$

- $Z_{critical}$ is the standard normal variate corresponding to the $(1-\alpha)^{th}$ quantile, where α denotes the chosen level of significance.

Mondal and Mujumdar, AWR, 2015

Detection of change in return levels of droughts

Mondal and Mujumdar, AWR, 2015



Observed monthly streamflow

Standardization

Projected monthly streamflow

Observed monthly drought index

Projected monthly drought index

Peak-over-threshold

Observed extreme drought index

Projected extreme drought index

Declustering

Observed declustered drought index

Projected declustered drought index

Likelihood ratio test

Stationary

Stationary?

Yes

No

Poisson-GP statistical model

Drought return level, from the stationary statistical model

Constant projected drought return level

Transient projected drought return level

Detection test

Time of detection – droughts in the Colorado River

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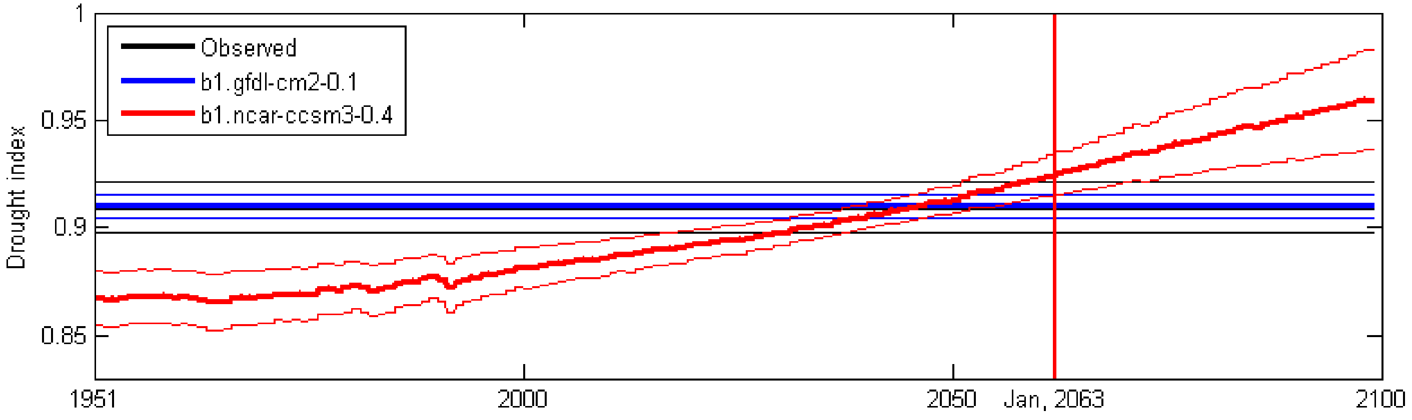
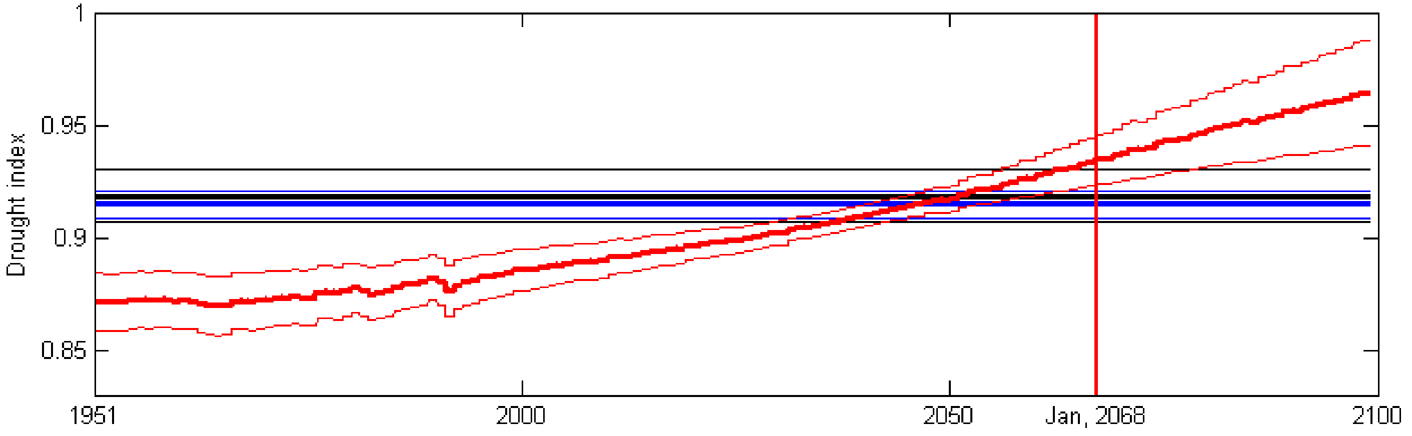
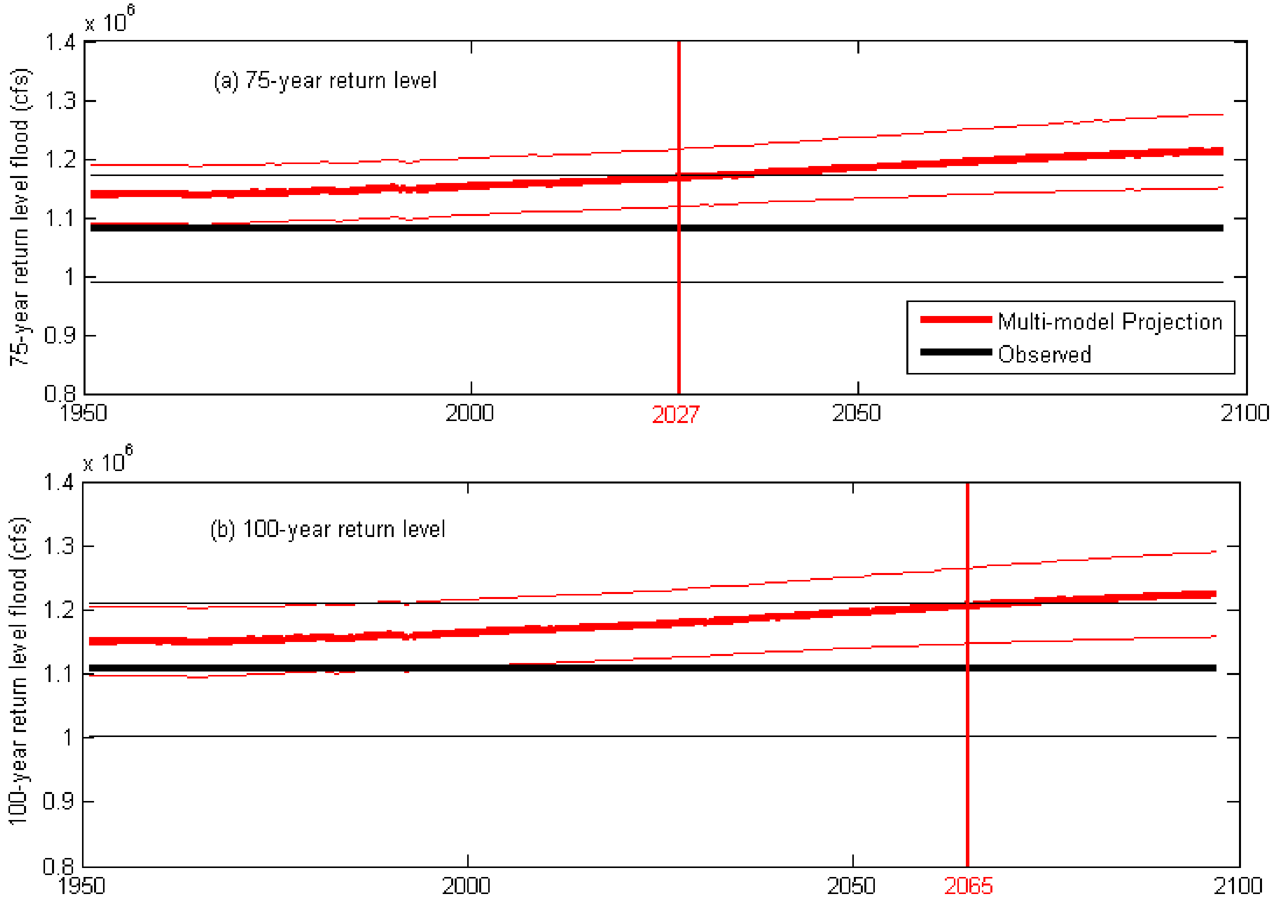

(a) 50-year return level


(b) 100-year return level

Time of detection – floods in the Columbia River

Mondal and Mujumdar, J Hydrol. Eng., in press



Definition of return period under non-stationarity

Find the level for which the expected waiting time for exceedance of this level is *m* years (Cooley, 2013; Salas and Obeysekara, 2013)

$$
\begin{aligned}
P(T=t) &= P(M_1 \le r)P(M_2 \le r)\dots P(M_{t-1} \le r)P(M_t > r) \\
&= \prod_{y=1}^{t-1} F_y(r)(1-F_t(r)) \\
\Rightarrow E[T] &= \sum_{t=1}^{\infty} t \prod_{y=1}^{t-1} F_y(r)(1-F_t(r)) \\
&= 1 + \sum_{i=1}^{\infty} \prod_{y=1}^{i} F_y(r),
\end{aligned}
$$

Equate with m and solve for *r*. Not straightforward!

This interpretation was first presented by Olsen et al. (1998)

The expected number of events in *m* years is 1 (Cooley, 2013). This interpretation was first proposed by Parey et al. (2007)

$$
\begin{aligned}
N &= \sum_{y=1}^{m} I\left(M_y > r\right) \\
\Rightarrow E[N] &= \sum_{y=1}^{m} E[I\left(M_y > r\right)] \\
&= \sum_{y=1}^{m} P(M_y > r) \\
&= \sum_{y=1}^{m} (1 - F_y(r)).
\end{aligned}
$$

Equate with 1 and solve for *r*.

Not used in hydrology so far. Fixes the design life as well as the probability of failure.

Alternate definitions of risk under non-stationarity

- The return period T can be misleading. Assumption: observations are iid! For example, T = 1/p does not hold in the non-stationary case.
- At “each year”, the probability of getting the event is p. T is only a derived quantity.
- A perhaps viable alternative is the *risk* of failure. In the iid case (Chow et al., 1988)

$$p_M := 1 - \prod_{j=1}^{M} (1 - p_j) = 1 - (1 - p)^M = 1 - (F(x_d))^M. = 1 - \left(1 - \frac{1}{T}\right)^M.$$

- More generally,

$$\begin{aligned} p_M &= 1 - \mathbb{P}[X_1 \leq x_d \cap X_2 \leq x_d \cap \ldots \cap X_M \leq x_d] \\ &= 1 - H_M(X_1 \leq x_d, X_2 \leq x_d, \ldots, X_M \leq x_d) \\ &= 1 - C_M(F_1(x_d), F_2(x_d), \ldots, F_M(x_d)), \end{aligned}$$

The design life level

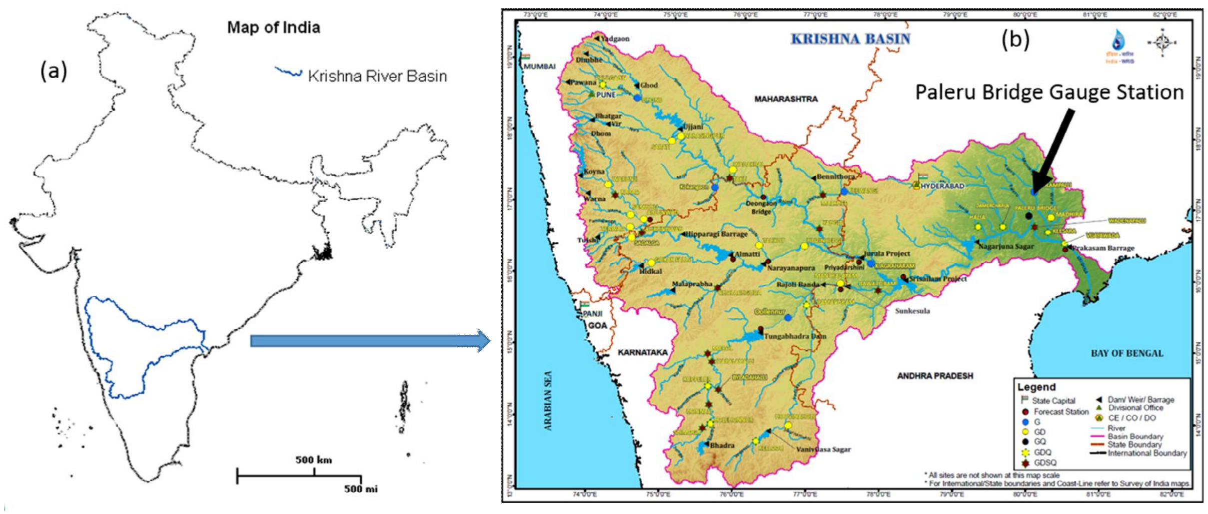
(Rootzen and Katz, 2013)

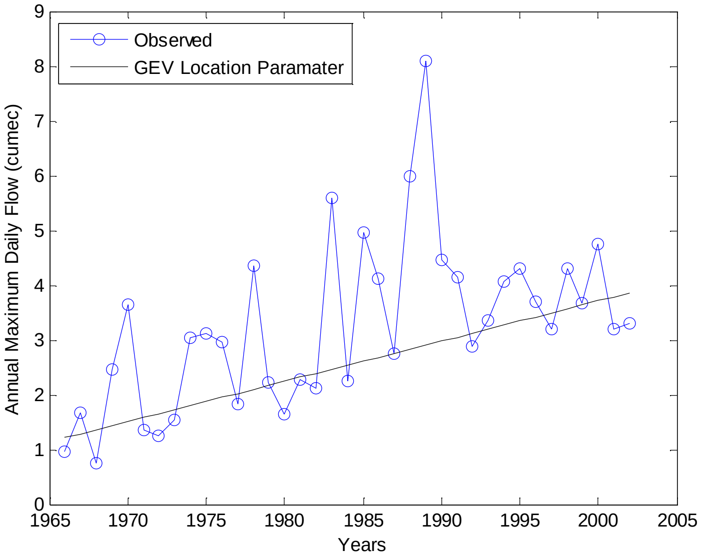
- Basic info needed for design: i) design life period (say, 2011-2060); ii) the risk of a hazardous event
- Thus, the design life level = T_1 - T_2 p_M% extreme level, e.g. *2011-2060 5% probability rainfall value is, say, 121 mm.*
- Estimate the CDF of the size of the largest daily rainfall in 2011-2060 as

$$\hat{F}_{2011-2060}(x) = \hat{G}_{2011}(x) \times \hat{G}_{2012}(x) \times \cdots \times \hat{G}_{2060}(x)$$

- The (1-p_M)th quantile of this distribution is an estimate of the design life level for the risk p_M.
- This is a special case of the risk-based design advocated by Serinaldi (2014).

An example application – Krishna River at Paleru Bridge





The stationary model $M_0 \sim$ GEV (μ, σ, ξ) can be rejected against the non-stationary model $M_1 \sim$ GEV ($\mu(t)$, σ, ξ), where $\mu(t) = \mu_0 + \mu_1 t$, at high confidence.

Diagnostic checks show that the non-stationary model is appropriate.

Design flood level under non-stationarity

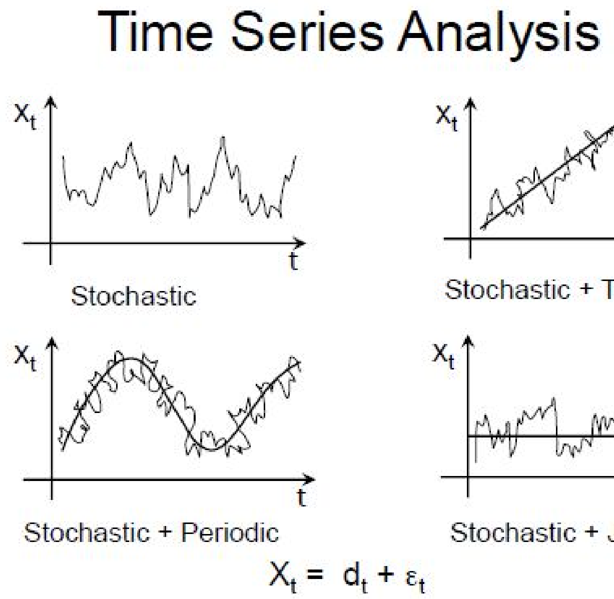
Mondal and Mujumdar, under preparation

Return period (or, design life)	Stationary return level	Highest effective return level (1965-2002)	Expected waiting time based return level (trend to stop at end of design life)*	Expected number of events based return level*	Design life level (10% risk)*
	(cumec)				
50 years	6.97	10.63	13.65	12.64	27.01
100 years	7.64	13.63	19.85	17.93	37.33

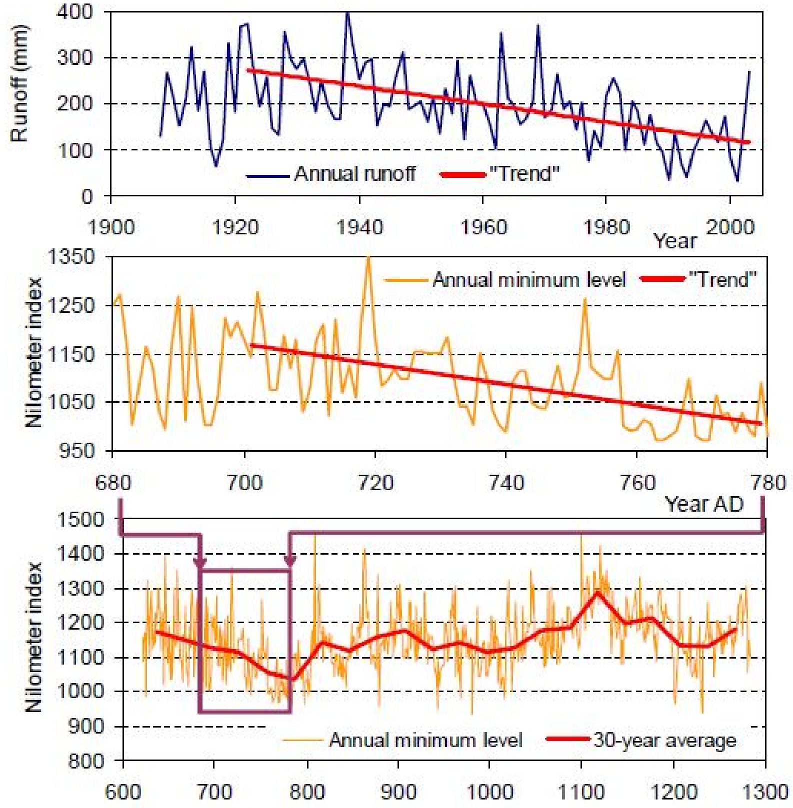
* Design life is assumed to begin at 2000

Some points of concern

A typical stochastic hydrology lecture



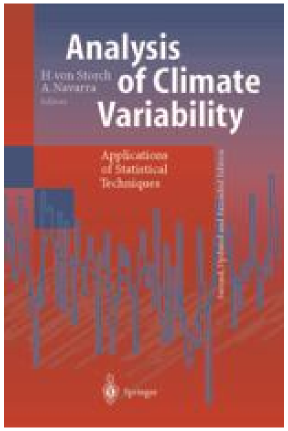
Source: Prof. P. P. Mujumdar's course on Stochastic Hydrology, NPTEL



Koutsoyiannis, 2011

The problem of ‘looking at the data’

Source: Google Images



Analysis of Climate Variability

H. von Storch
A. Navarra
Editors

Applications of Statistical Techniques

von Storch (1995)

- Is the Mexican Hat man-made? Null hypothesis: ‘Mexican hat is of natural origin’
- Test statistic $t(p) = \begin{cases} 1 & \text{if p forms a Mexican Hat} \\ 0 & \text{otherwise} \end{cases}$ for any pile of stones p
- For getting the distribution of t(p) under null hypothesis, examine a large number of $n = 10^6$ pile of stones.
- But the Mexican Hat is famous for good reasons: there is only one p with t(p) = 1.
- Thus, the distribution of t(p) not affected by man is given by

$$\text{prob}\,\{t(p)=k\} = \begin{cases} 10^{-6} & \text{for } k = 1 \\ 1 - 10^{-6} & \text{for } k = 0 \end{cases}$$

- Hence, we reject null hypothesis if t(Mexican Hat) = 1. Hence, the Mexican Hat is man-made!

Questions to pursue….

- How can we arrive at a unifying framework for risk assessment of hydrologic hazards such as floods and droughts under non-stationarity?
- Non-stationarity ⇒ deterministic relationship: can the future be deterministically known?
- Hypothesis of non-stationarity not independent of data!
- Complex models ⇒ less bias + more uncertainty: how to optimize this trade-off?
- How can these approaches based on *induction* be combined with physics-based *deduction*?
- What are the implications of these risk concepts for a large and complex basin such as the Ganga River Basin?

Relevant publications for this topic

Book chapter:

Mondal, A. and P. P. Mujumdar (2015), Extreme value analysis for modeling non-stationary hydrologic change, *Contingent Complexity and Prospects for Water Diplomacy: Understanding and Managing Risks and Opportunities for an Uncertain Water Future*, Eds. Shafiqul Islam and Kaveh Madani, Anthem Water Diplomacy Series (under review).

Journal articles:

Mondal, A. and P. P. Mujumdar (2015), Modeling non-stationarity in intensity, duration and frequency of extreme rainfall over India, *Journal of Hydrology*, 521, pp. 217-231.

Mondal, A. and P. P. Mujumdar (2015), Return levels of hydrologic droughts under climate change, *Advances in Water Resources*, 75, pp. 67-75.

Mondal, A. and P. P. Mujumdar (2015), Detection of change in flood return levels under global warming, *ASCE Journal of Hydrologic Engineering* (under review, manuscript# HEENG-2711).

Thank you!

Coupled Human And Natural Systems Environment (CHANSE) for water management under uncertainty in the Indo-Gangetic Plain

- Submitted to Newton-Bhaba Call on Sustaining Water Resources for Food Energy & Ecosystem Services in India (MINISTRY OF EARTH SCIENCES)
- Leaders: Imperial College, London (PI: Dr. Ana Mijic) and IIT Bombay (PI: Dr. Subimal Ghosh)

- British Geological Survey
- Exeter University
- Indian Institute of Science Bangalore
- Indian Institute of Tropical Meteorology, Pune
- ATREE, Bangalore
- Bhagalpur Univresity
- UNESCO
- Council of Energy, Environment and Water