Entropy and reliability of water use via a statistical approach of scarcity

Georgios Karakatsanis,
Nikos Mamassis,
Demetris Koutsoyannis,
& Andreas Efstratiadis

Department of Water Resources and Environmental Engineering
National Technical University of Athens (NTUA), Greece
Water scarcity: Natural and Anthropogenic

- Increasing water scarcity concerns the part of the developing world without storage capacity.
- Water scarcity is relative and should be examined in integrative terms (both natural and economic).

**Average Time Spent Carrying Water (Minutes per Day)**

<table>
<thead>
<tr>
<th>Location</th>
<th>Women</th>
<th>Men</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uganda (2007)</td>
<td>47</td>
<td>2</td>
</tr>
<tr>
<td>Guinea (2002)</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>Madagascar (2001)</td>
<td>27</td>
<td>9</td>
</tr>
<tr>
<td>South Africa (2000)</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Ghana (1999)</td>
<td>44</td>
<td>34</td>
</tr>
<tr>
<td>Benin (1998)</td>
<td>45</td>
<td>12</td>
</tr>
</tbody>
</table>

**Source:** Moria et al. 2007; Wodon et al. 2006

**Source:** Human Development Report (HDR), 2006

*Karakatsanis et al: Entropy and reliability of water use via a statistical approach of scarcity*
Entropy, water scarcity and economics

- The issue of industrial sustainability and reliability is immediately connected to *Entropy production* across natural resource use (*Roegen 1971*)
- Macroscopically, entropy is manifests as *energy unavailability* for further production of thermo-mechanical work
- Microscopically (statistically), entropy is manifested as *uncertainty*
- The economic utility of a natural resource is *reverse proportional to its entropy* or its uncertainty of availability (*Roegen 1986*)

- In Hydrology, the connection of entropy to scarcity requires the *examination of thermodynamic data* on hydrometeorological processes
- The adoption of *endogenous measures* (eg. water storage, efficiency and reuse) is the only way of (partially) controlling water availability, as the control of the natural phenomenon is not a feasible option
Natural availability and use: Mutual Information

Source: Human Development Report (HDR) 2006

- In the absence of water buffering infrastructure, **Mutual Information** between natural and economic phenomena is expected to be high (e.g., precipitation difference from mean can tell us much on the GDP growth of Ethiopia)
- Mutual Information is more accurate when there is **no time hysteresis**
- Methodologically, it is more convenient and accurate to calculate the **differential Mutual Information** in order to measure decoupling trends

\[
I(P;G) = \sum_{p\in P} \sum_{g\in G} P(p,g) \log \frac{P(p,g)}{P(p)P(g)}
\]

Mutual Information concerns *correlation* and not causality

Karakatsanis et al: Entropy and reliability of water use via a statistical approach of scarcity
A Pareto Frontier is a Production Possibility Frontier, which charts the *Marginal Rate of Substitution* (trade-off) ratio between two or more conflicting variables (e.g., Reservoir level decrease for increased water provision reliability).

Three (3) major types of Pareto Frontiers (per 2 criteria):

- Linear MRS (Constant Substitutability)
- Increasing MRS (Decreasing Substitutability and Increasing Complementarity)
- Decreasing MRS (Increasing Substitutability)

\[
MRS = \frac{\partial X}{\partial Y}
\]

*MRS Elasticity* is considered more convenient to use as it is independent of effects of scale.

\[
MRS_{Elasticity} = \left(\frac{\partial X}{X}\right) / \left(\frac{\partial Y}{Y}\right)
\]
Shifts in scales do not necessarily suggest statistical structural change (eg. shift towards non-stationarity), but perhaps persistence

However, even due to persistence, clustering of lows is probable at a small time-frame

Persistence further restricts the Pareto Frontier, as certain economic activities (eg. agriculture) cannot cope with it in the long-term → Reliability planning must concern longer periods

Source: Koutsoyannis 2011
Reliability and hydro-system topology

- Hydro-system topology deals mainly with *spatial variability* of precipitation
- Hydro-system topology determines the degree of *statistical independence* between the reservoirs:
  - Linear topologies suffer from *excessive statistical dependence* they are very sensitive to total structural failure due to only a partial failure
  - Parallel topologies suffer from *excessive statistical independence* and prevent reservoir complementarity under spatial variability of rainfall
  - Complex (combined) topologies have *increased cost* (in MRS terms) of construction (eg. Increased bounding of natural space and for more time)
- Hydro-system topology *affects the Pareto Frontier* (Possibility Production Curve), just as well as exogenous factors do (eg. Precipitation variability)
Embodied water and international trade

- Through international trade of water-intensive commodities the importing country actually *incorporates* a part of the exporting country’s water use reliability
- Activation of international trade of water-intensive commodities is *equivalent to a technological upgrade* via the upgrade of the Pareto Frontier
- Imports of water-intensive goods, *liberates resources* for other high added-value production *(eg. Import of agricultural products in the Middle-East and use of domestic water for oil production)*

*Source: Yang et al. 2006*
Decoupling water use reliability from natural scarcity

- Water recovery and reuse *increases immediate availability* and reduces the statistical dependence from natural recharge frequency
- Water recovery and reuse, *re-inserts* used water to the economic system (circular economy)
- Water recovery and reuse *buffers natural scarcity* in persistent draught phenomena (e.g., persistent downward Hurst currents)

**Reuse Multiplier** \( W_M \)

\[
W_M = \frac{W_0}{1 - m}
\]

- \( W_0 \): Initial amount of extracted water
- \( m \): Reuse coefficient \((0 < m < 1)\)

**Agriculture**: Demands 70-90% of total international freshwater use

**Population**: Estimated increase from 7 billion to 9 billion until 2050

**Reuse**: 80% of used water internationally is not reused


\[
W_0(t) = W_0 \cdot e^{(1-m) \cdot t}
\]
Entropy, water scarcity and economics again...

- In variable natural phenomena -such as the hydrological cycle- entropy cannot be connected directly to natural scarcity based only on precipitation statistics, as it might very well mean high probability of extreme precipitation events (over-availability)
- Entropy can parsimoniously connected to economic scarcity via the increased opportunity cost (trade-off ratio between conflicting variables)
  - Opportunity cost does not necessarily refer to financial cost
- Opportunity cost refers to the amount of production factors (reservoir level, reliability, natural space) that have to be bounded over time in order to produce a specific water availability state
  - Increased entropy signifies a larger amount of bounded production factors as the infrastructure has to be predicted to be reliable for a wider amplitude of events
- International trade via the comparative advantage that derives from water use specialization mitigates uncertainty of supply and scarcity as it is equivalent to the liberation of (previously) bounded production factors
- The fundamental base of economic science is its continuous effort to reduce the statistical dependence of human societies from natural phenomena
- Entropy is an evolutionary force (Koutsoyannis 2011) as it forces the economy to research and reduce its dependence from natural phenomena
Bibliography and References

1. de Moria, A., Fulford, A., Kabatereine, N., Kazibwe, F., Ouma, J., Dunne, D., and Booth, M. (2007), Microgeographical and Tribal Variations in Water Contact and Schistosoma mansoni Exposure within a Ugandan Fishing Community, Tropical Medicine and International Health 12 (6), 724-735
5. Koutsoyiannis, D. et al. (2009), Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability, Hydrology and Earth System Sciences 13, 247-257

Karakatsanis et al: Entropy and reliability of water use via a statistical approach of scarcity
Thank you for your attention!!!

karakas11361@gmail.com

Ready for Questions...