International Symposium
"Hydrology delivering Earth System Science to Society"
Tsukuba, Japan, 28 February – 2 March 2007

# *Lessons from hydrology in the 20th century and messages to the next generation*


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**1 – The science of hydrology and its applications**

2 – Hydrological extremes: floods and droughts

3 – Mathematical modelling

4 – Barriers to development of hydrology: compartmentalization

5 – Milestones in development of hydrological sciences

**Hydrology is the science that treats the waters of the Earth, their occurrence, circulation and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living things**

**[Ad-hoc Committeee, the US Federal Council for Science and Technology, chaired by Walter Langbein, 1962]**

## Dual nature of hydrology:

- Earth science (geoscience);
- Scientific basis of water management

Water – major constituent of living matter, necessary, on a continuous basis, to sustain the processes of life and essential, in large quantities, to every human endeavor

# Sources of progress in hydrological sciences:

• Responding to essential gaps in knowledge and understanding [modelling hydrological processes, verifying simulation by observations, building theories];

• Responding to burning utilitarian needs of alleviating increasingly complex water problems, where new solutions may bring large tangible benefits.

Hydrology has aided humans in solving water-related problems, which used to be less intense in the past, due to lower population, anthropopressure, and water demand.

Now, water problems, such as:
**flood protection,**
**water for food,**
**water for environment,**
**water quality,**
has become more widespread and urgent.

Hence importance of hydrological sciences is on the rise.

Population growth: 1850 - **1.25** B; 1950 - **2.5** B; 1987 - **5** B; 1999 - **6** B
~ 7-8% of people ever populating the Earth are living now.
Ecological footprint!

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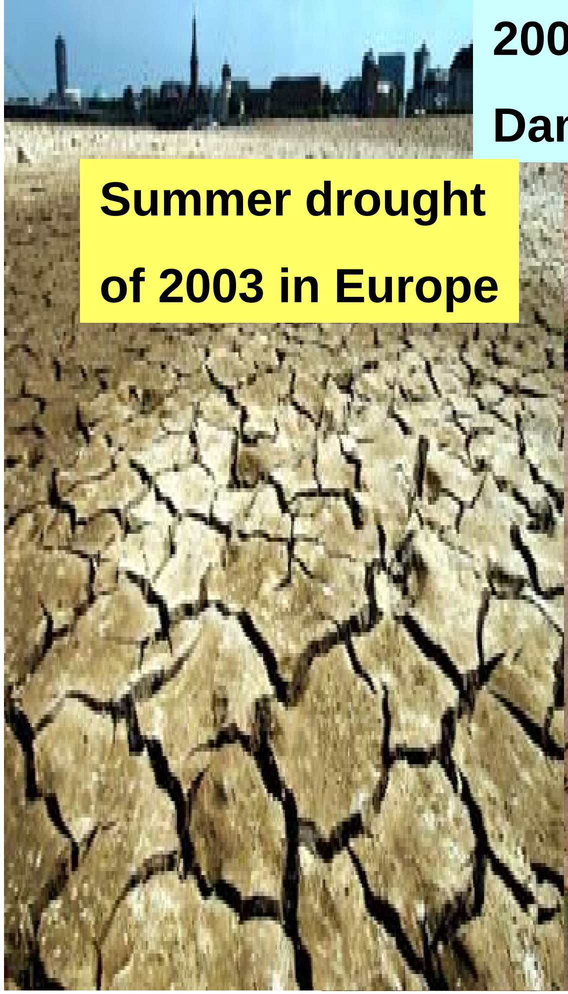
Three categories of aeternal water problems:

- Too much
- Too little
- Too dirty

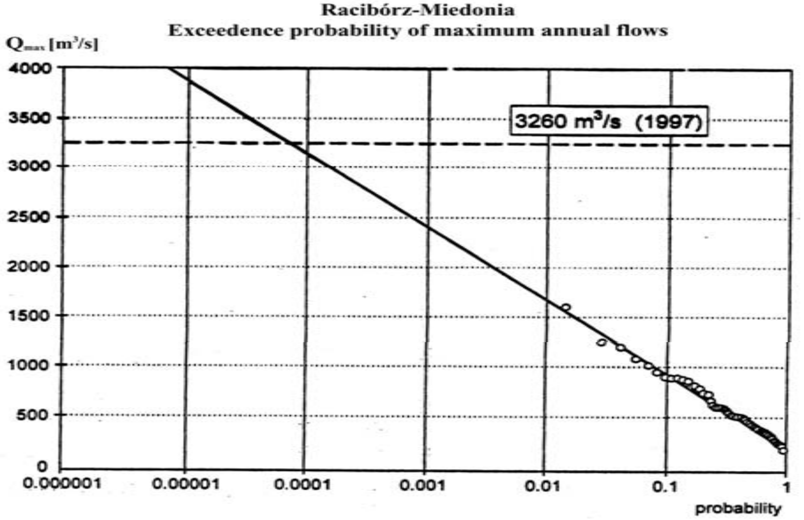




**FLOODS:** focus of 20th century hydrology:

* Flood control design – flood frequency studies, with the aim to guide selection of adequate distribution for flood protection design.

Attention: determination of a 1000 -year flood based on 30 years of data is **MISSION IMPOSSIBLE**, even under assumption of statio-narity! Klemes: **Unreliability of reliability estimates**



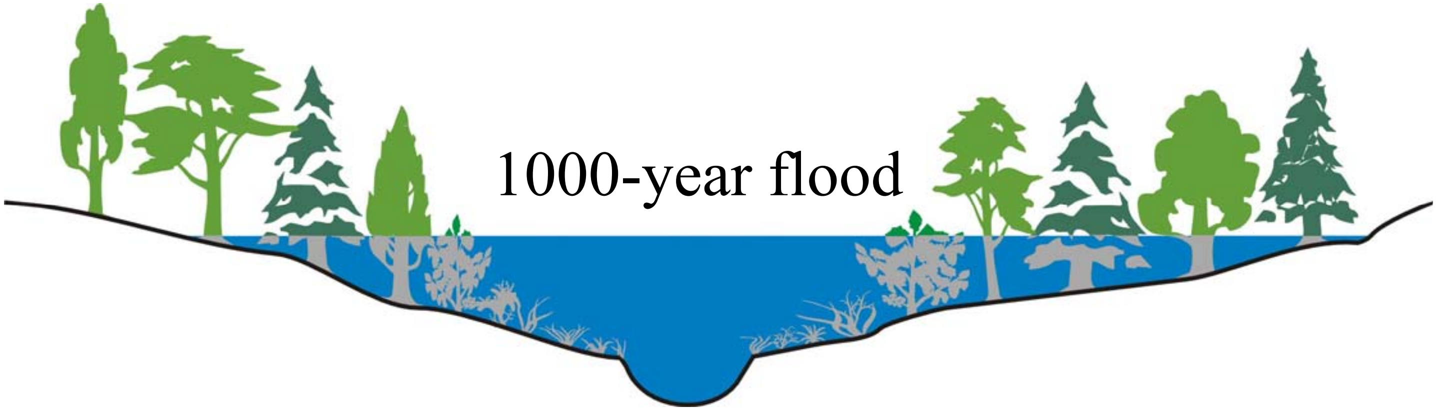

* Flood routing – important component of the foreast-warning system

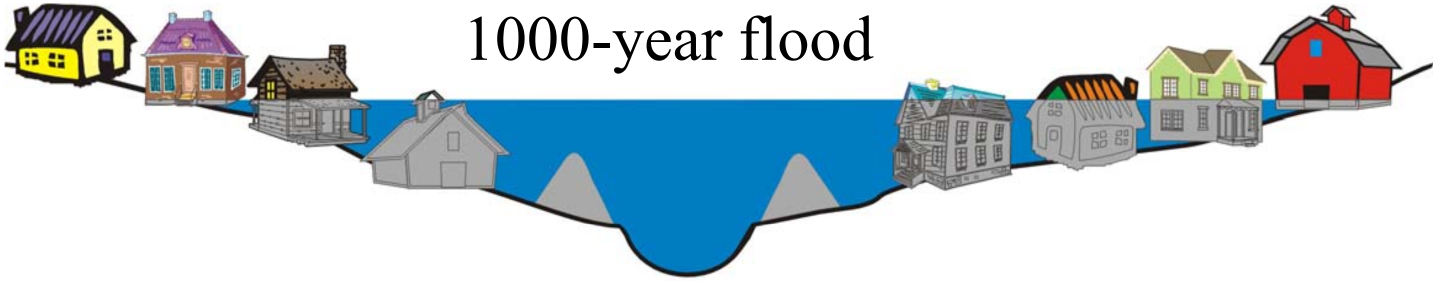
# Reasons for changes in flood risk and vulnerability

| | |
|---|---|
| **(i) Changes in socio-economic systems** | Land-use change, increasing exposure and damage potential – floodplain development, growing wealth in flood-prone areas, changing risk perception |
| **(ii) Changes in terrestrial systems** | Land-cover change - urbanization, deforestation, elimination of natural inundation areas (wetlands, floodplains), river regulation – channel straightening and shortening, embankments), damming rivers, adverse changes of conditions of transformation of precipitation into runoff |
| **(iii) Changes in climate and atmospheric system** | Holding capacity of the atmosphere, intense precipitation, seasonality, circulation patterns |

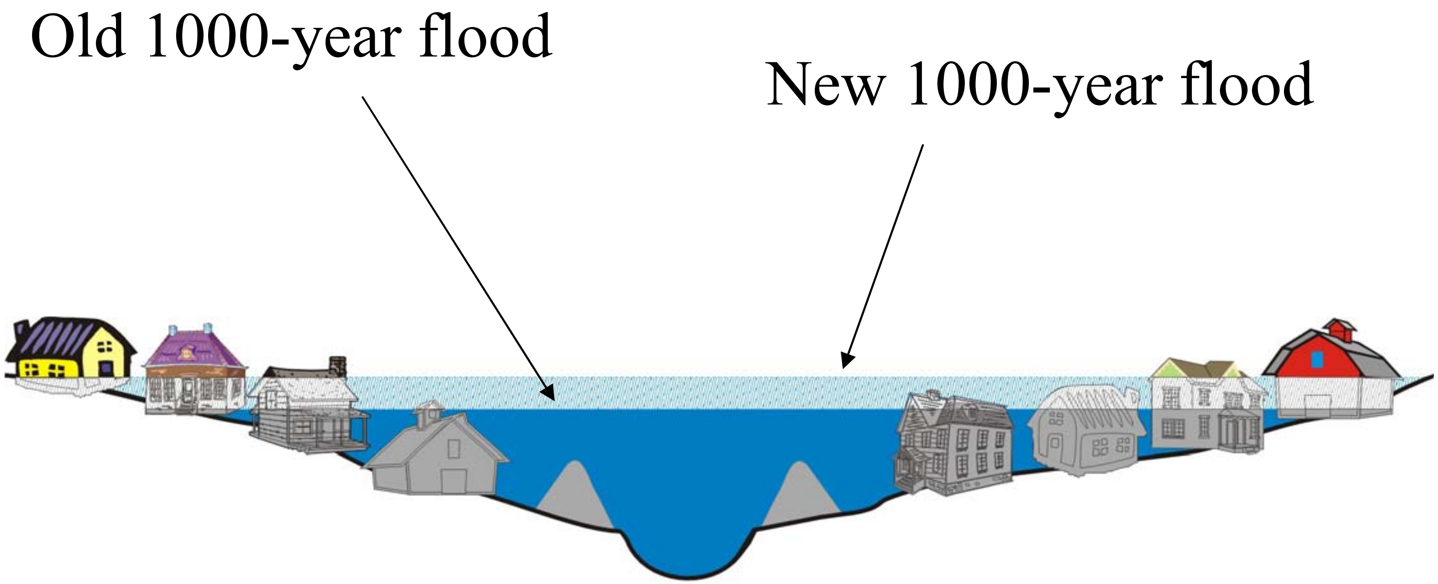


Source: Kundzewicz & Schellnhuber, 2004

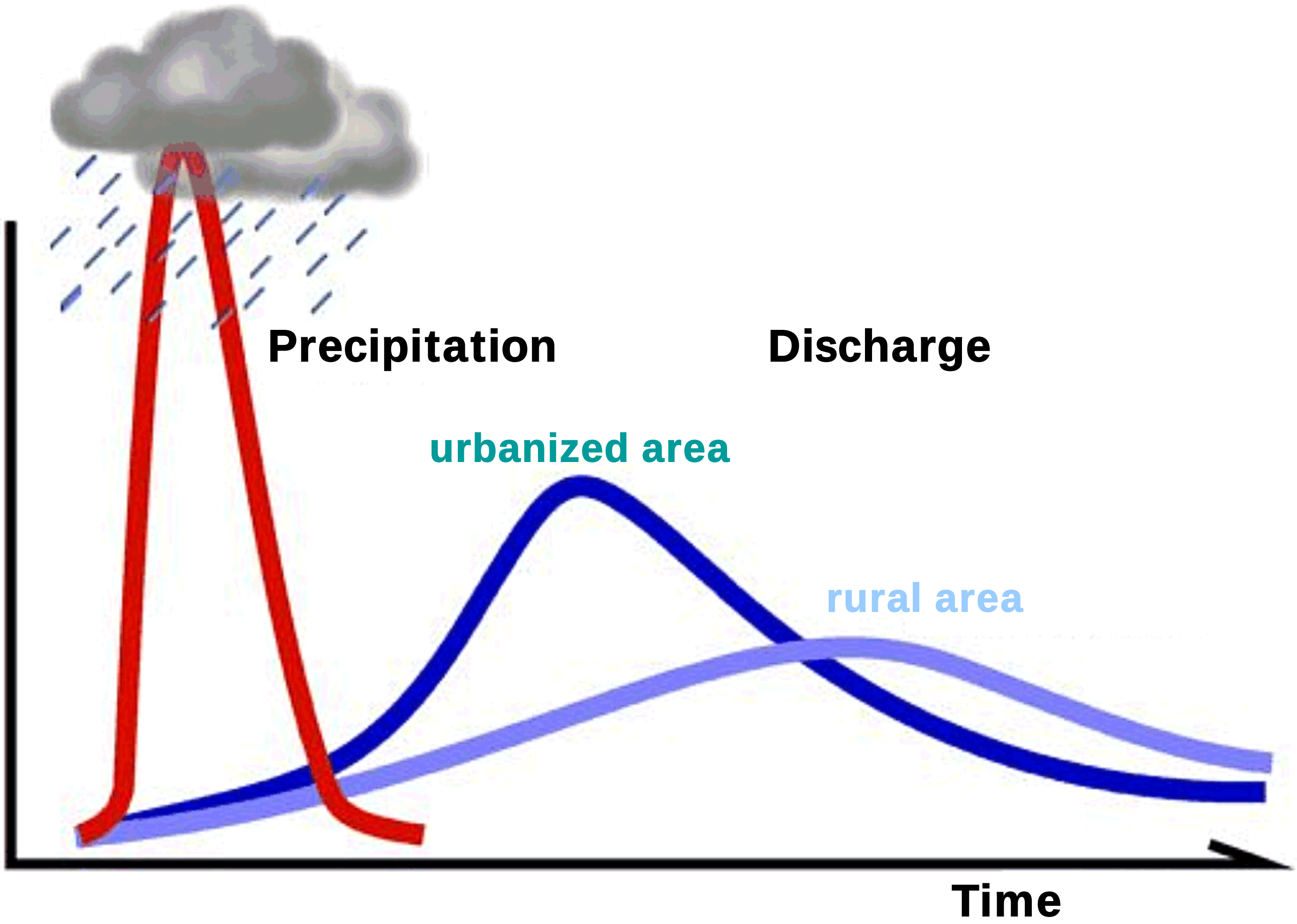



**Damage potential grows**


Old 1000-year flood
New 1000-year flood

# Impacts of land-use change on floods



# Water holding capacity of the atmosphere

## Clausius-Clapeyron equation

$$de_s(T) / e_s(T) = L\, dT / R\, T^2$$

where $e_s(T)$ is the saturation vapor pressure at temperature $T$,

$L$ is the latent heat of vaporization,

and $R$ is the gas constant.

$T$ ↗ $e_s(T)$ ↗

**1ºC 6-7%**

# Droughts

**Driving forces:**

Atmospheric circulation patterns

Precipitation deficiency

Evapotranspiration (temperature, …)

Catchment storage

Anthropogenics: water extraction and use:
over-abstraction, overcultivation, mis-management

# Facets of droughts:

**meteorological** (precipitation)

**agricultural** (soil moisture)

**hydrological** (surface waters: streamflow droughts – river stage, stream flow; lake level; groundwater – groundwater level)

**economic** (losses)

**Impacts:**

Water supply problems (agriculture, industry, municipal water) – damages

Energy – hydropower loss, lack of cooling water

Malnutrition, famine

Ecological consequences (e.g., rivers run dry)

Wildfire

Water quality

# 20th century – age of mathematical modelling

For much of the 20th century: a **single-input single-output** (SISO) approach [adequate in studying such problems as transformation of effective rainfall into river runoff, flood routing, infiltration, or sediment transport.]

## Criterion of classification – physical justification of models

- **Mechanistic, process-based** models expressing rigorous physical laws and theoretical concepts.
- **Conceptual** models, consisting of simple elements, which simulate, in an approximate way, processes occurring in the basin.
- **Black-box (system)** models, which match the input and output signals of the system, without mimicking the internal structure.

# St Venant equations of open channel flow (1870)

*Continuity equation*

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

where Q is the flow rate, A is the cross-sectional area of flow

*Momentum equation*

$$-\frac{1}{g}\frac{\partial V}{\partial t} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{\partial y}{\partial x} + S_o = S_f$$

where $V$ is the velocity, $y$ is the depth, $S_o$ is the bottom slope, and $S_f$ is the friction slope.

# Mathematics of a storage reservoir

## Continuity equation

$$dS(t) / dt = I(t) - O(t),$$

where S(t) is the volume of stored water,

I(t) is the inflow to the reservoir (incl. precipitation),

O(t) is the outflow from the reservoir (incl. evapotranspiration, water abstraction, infiltration),

t is the time instant

The convolution integral allows one to find the output of a linear system corresponding to any input.

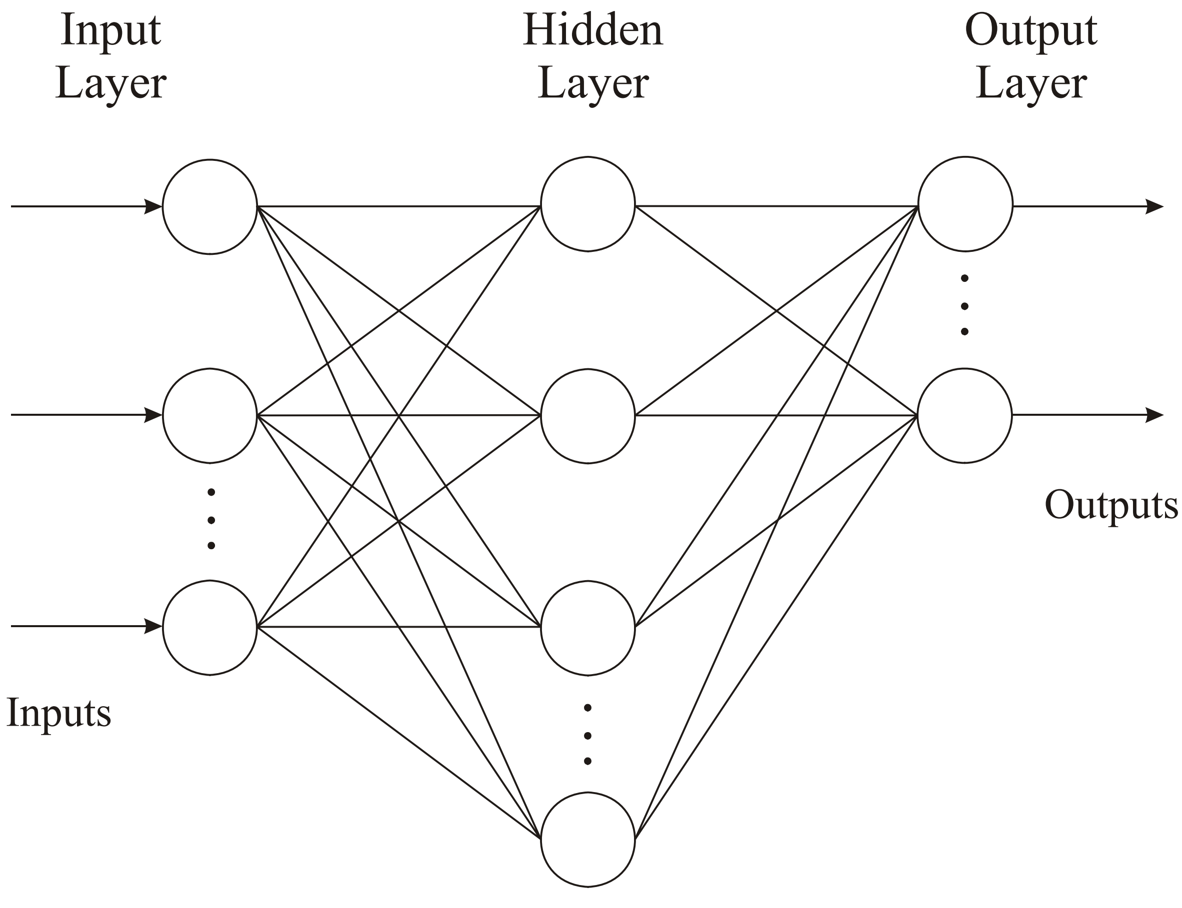
$$y(t) = \int_{0}^{t} x(t - \tau)\, h(\tau)\, d\tau$$

$$y(t) = \int_{0}^{\infty} x(t - \tau)\, h(\tau)\, d\tau$$

$$y(t) = \int_{0}^{T} x(t - \tau)\, h(\tau)\, d\tau$$

x – input; y – output; h – impulse response (kernel function)

Artificial neural networks have been used to model diverse hydrological proceses, therein open channel flow.



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Barriers to development of hydrology:

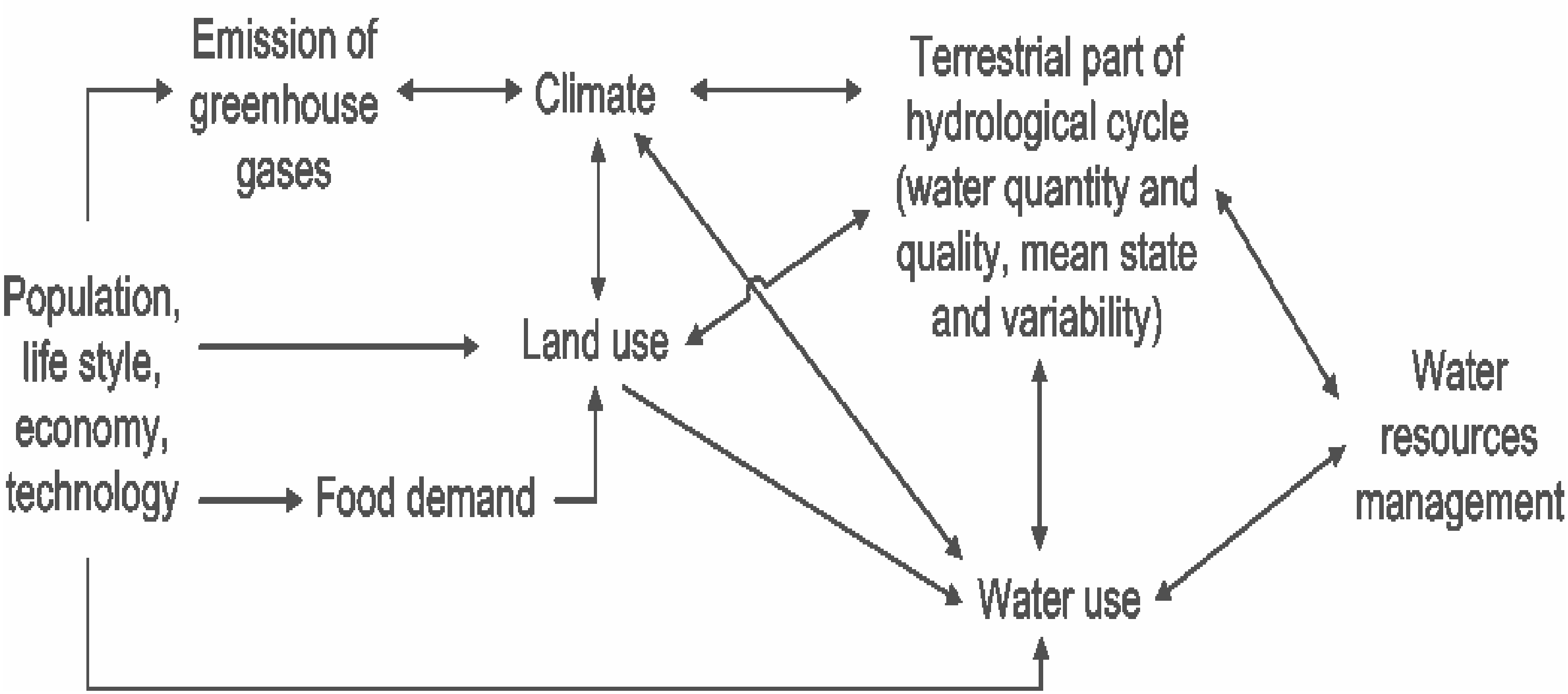
- data availability problems,
- lack of general theories,
- complexity of processes and feedbacks,
- irregular and heterogeneous environment,
- low signal-to-noise ratio,
- very limited possibility of active experiments,
- different roads to hydrology (barrier and opportunity)
- **compartmentalization**

In the 20th century, there were infrequent attempts of coupling compartments, and inter-disciplinary studies. Now, interfaces with other disciplines are being increasingly sought, leading to better integration of sciences. Among strong growth avenues are: global hydrology, climate-water interface, and water-environment interface.

# Need to overcome compartmentalization

In the global system, everything is connected to everything else. The climate and freshwater systems are interwoven in a complex way so that any change in one of these systems induces a change in the other.

[Figure by Taikan Oki]



## Infancy stage of development of hydrological sciences:

Systems and processes are conceptually isolated from their environments

## Further stage of development:

Reconstruction of broken interconnections and feedbacks

## Hydrology-meteorology/climatology interface

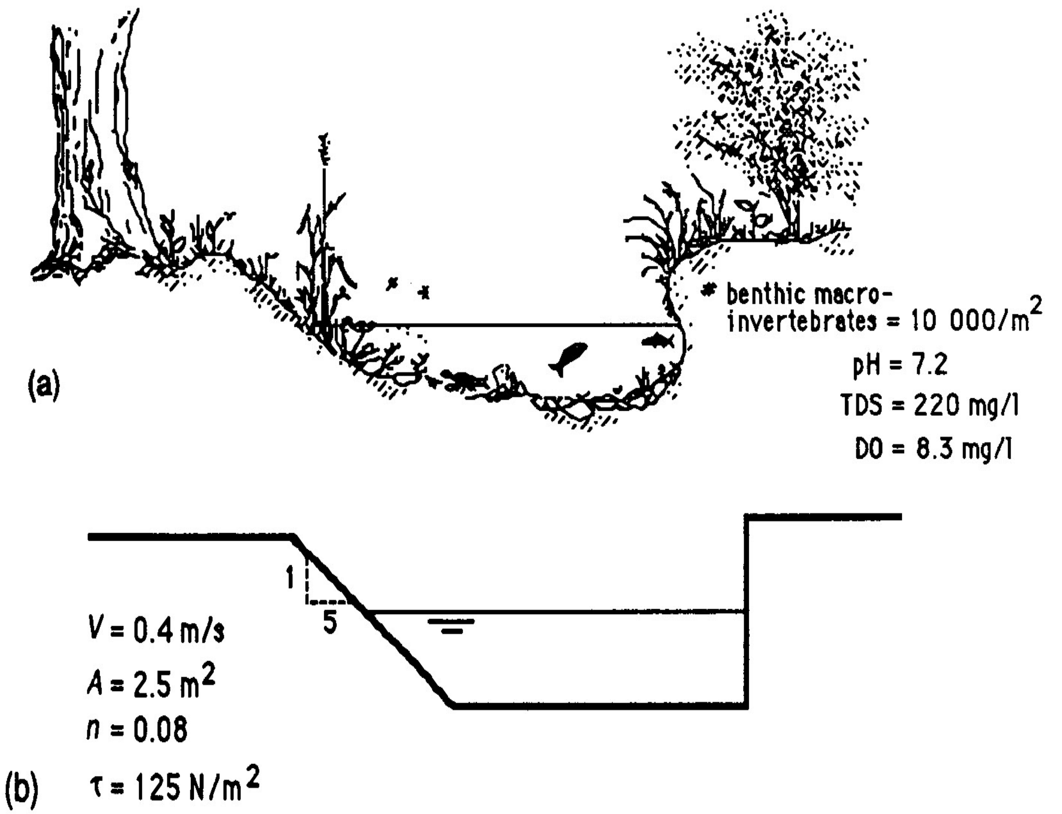
Precipitation:

- Output signal from meteorology / climatology
- Input signal to hydrology

### Precipitation changes:

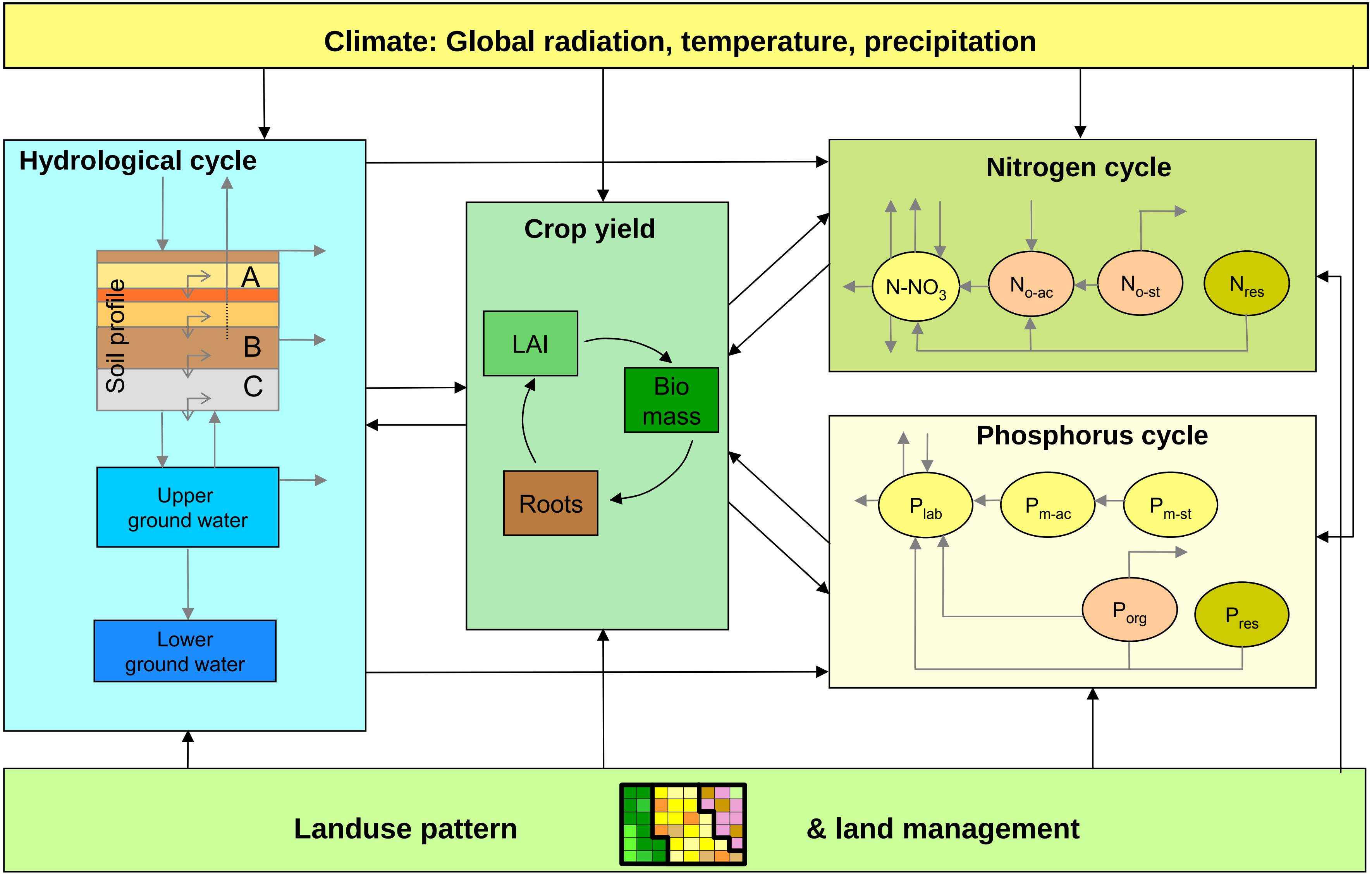
- Mean and variability in the amount
- Intensity
- Frequency
- Sequences
- Persistence
- Temporal distribution (seasonality)
- Spatial distribution (i.e, track of cyclones, intensity rates)
- Phase of precipitation (snow vs rain); snowpack

# Hydrology – ecology interface




Ecologist‘s and engineering hydrologist‘s view of a stream (from Gordon *et al*.)

# SWIM (Soil and Water Integrated Model) overview




Source: Valentina Krysanova

Integration in **Water Framework Directive** of the European Union :

- Environmental objectives combine quality, ecological and quantity objectives for protecting valuable aquatic ecosystems and ensuring a general good status of waters.
- The Directive embraces integration of all water resources (fresh surface water and groundwater) and integration of all water uses, functions and values.
- The notion also contains integration of disciplines, analyses and expertise (hydrology, hydraulics, ecology, chemistry, soil sciences, agronomy, forestry, technology, engineering and economics) to aid in implementation of the Directive in the most cost-effective manner.
- The Directive also requires integration of water legislation into a common and coherent framework and consideration of significant management and ecological aspects.
- It calls for the use of a wide range of measures, including economic and financial instruments, e.g. water pricing.
- Further, integration of stakeholders and the civil society in decision making is needed, as well as integration of different decision-making levels (local, regional or national), and integration of water management from different Member States, in case of international basins.

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## Milestones in hydrological sciences of the 19th century
## (short and subjective list)

1851 – Mulvaney – rational formula

1856 – Darcy – groundwater motion

1870 – St Venant – 1D open channel flow

1895 – Manning – friction in open channel flow

## Milestones in hydrological sciences of the 20th century (short and subjective list)

1925 – Streeter & Phelps – DO modelling
1931 – Richards – Unsaturated flow
1932 – Sherman – Instantaneous Unit Hydrograph
1944 – Piper – Geochemical water analysis
1948 – Penman – Evaporation
1950 – Einstein – Bed load formula
1951 – Hurst – Long-term storage
Post 1960 – Modelling: Stanford, Sacramento, SSARR, USGS MODFLOW, GWFLOW, SUTRA, Mike, EPIC, CREAMS, WATQUAL, Tank model, HBV
Post 1970 – Harnessing the products of technological revolution, in particular computer (hardware and software) technology, therein GIS; and remote sensing.

## Milestones in hydrological literature of the 20th century
## (short and subjective list)

1964 – Ven Te Chow (Ed.)  Handbook of Applied Hydrology

1970 – Eagleson – Dynamic Hydrology

1973 – Dooge – Linear Theory of Hydrologic Systems

1993 – Maidment (Ed.) – Handbook of Hydrology

Pre-1970 publications: mostly presentation of hydrological data; testing formulae; mathematical anal;yses – seeking a closed-form solution

Post-1970 publications: more advanced modelling efforts

Eagleson (1986, WRR): Research needs into global hydrology and incorporating global hydrological cycles (including oceanic branch)

- **What is the destination of water evaporating from here?**

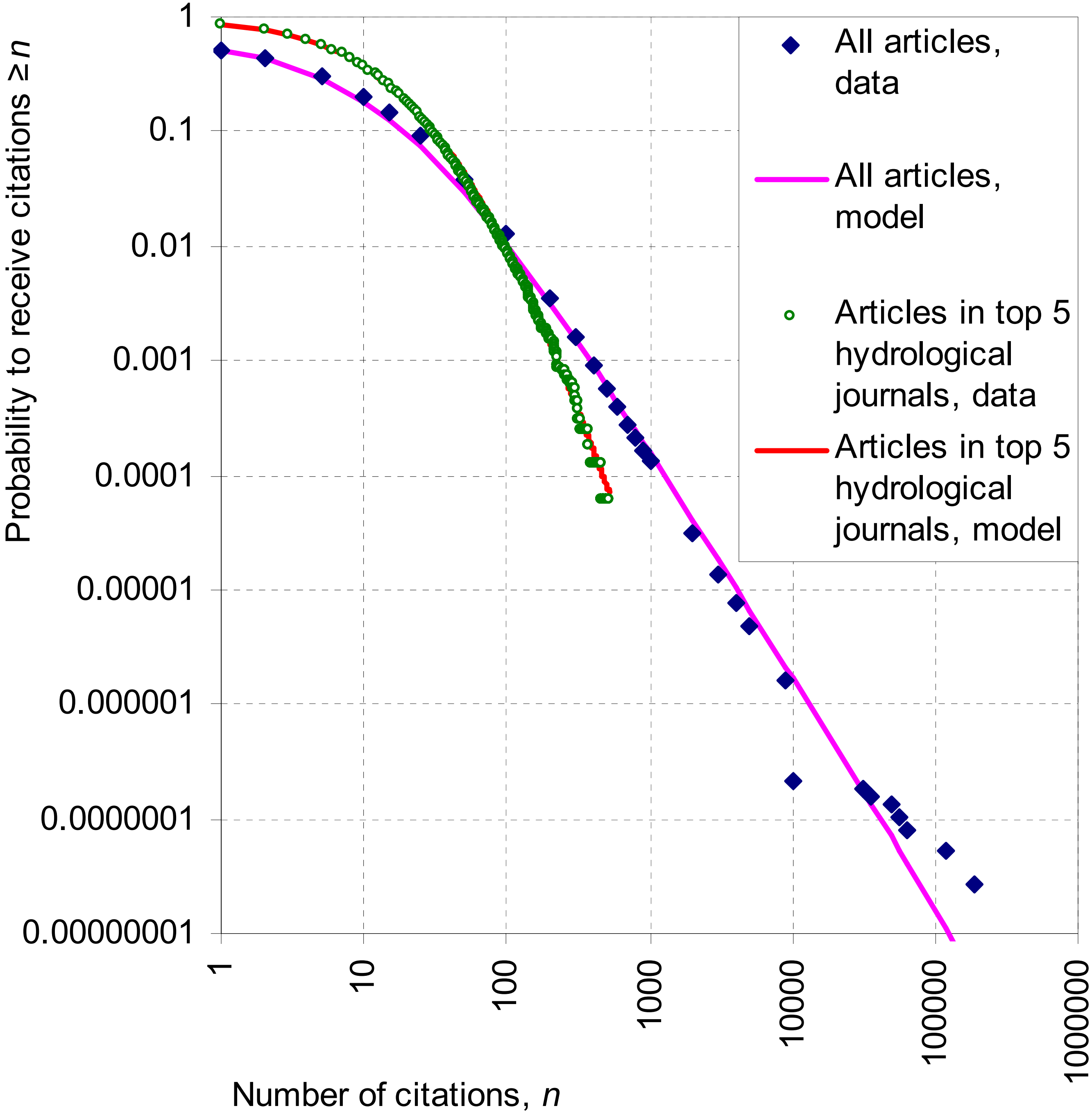
- **What is the source of water precipitating here?**

**Ills of the 20th century hydrology:**

Klemes: Dilletantism in Hydrology. Transition or Destiny? [Problem solving rather than understanding; fitting of a past flow hydrograph with greater finesse.]

Mathematistry – since more complex mathematical models can be implemented and effectively used with the powerful present computers, such models are being built. However, advantages of using complex models are not necessarily clear, especially in a data-scarcity situation.

In perspective, many hydrology publications reflect esoteric investigations, driven by "dissertability" concerns, "publish or perish" principle, or short-living fashions. Thoughtless imports from other sciences (e.g., dynamic systems theory).




Source: Koutsoyiannis & Kundzewicz (2007) *HSJ*

*Record:*

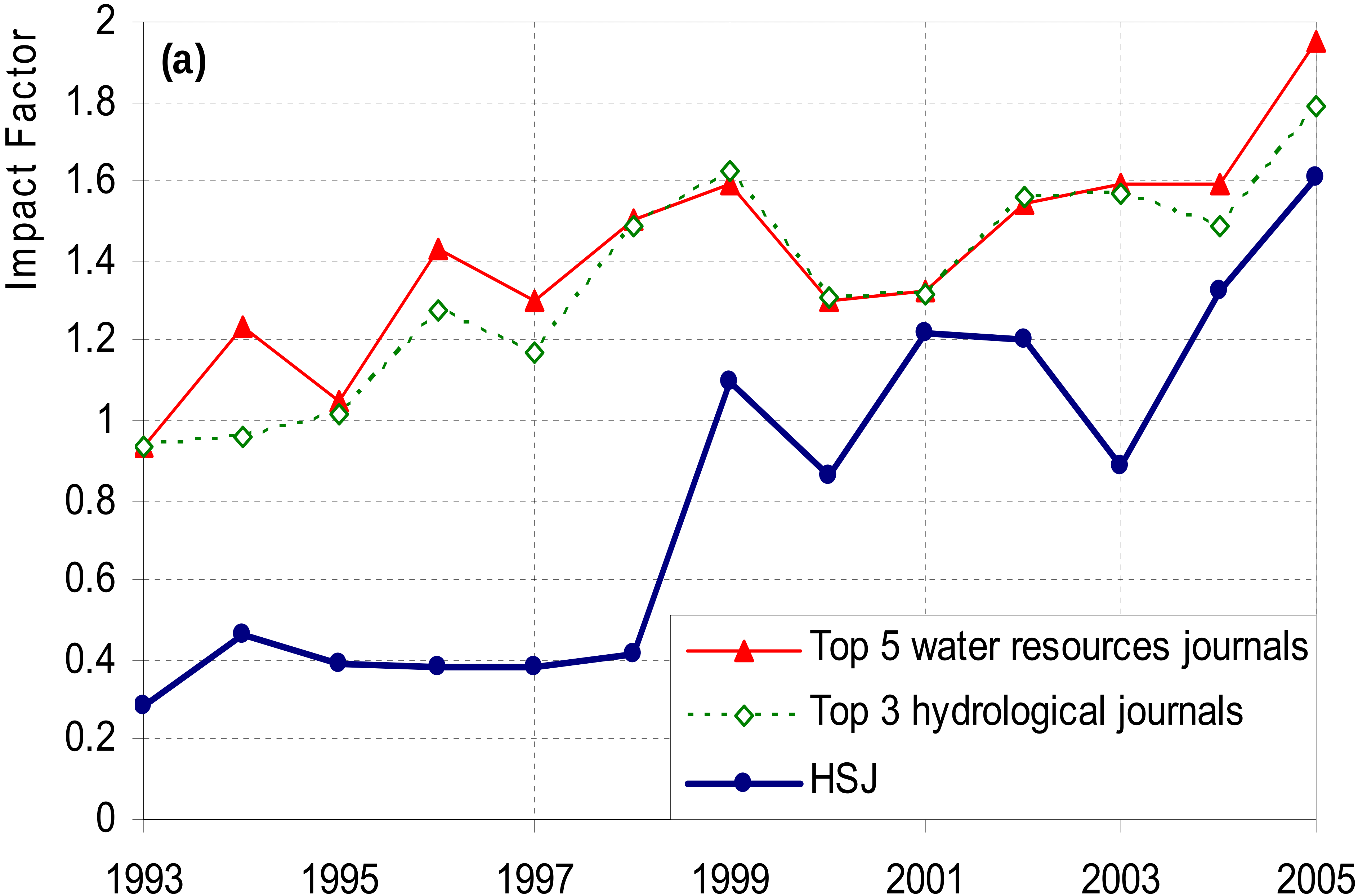
*number of citations to a biological article by Lowry et al., 1951:*

***293 328***

# Some most popular hydrological papers that have received more than 500 citations

| Authors and year of publication | Paper subject | Journal abbreviation | No. of citations* |
|---|---|---|---|
| *Hydrological papers in Water Resources journals:* | | | |
| Nash & Sutcliffe (1970) | Conceptual models | *J. Hydrol.* | 1140 / 1122 / 886 |
| Topp et al. (1980) | Soil water content | *Water Resour. Res.* | 1052 / 945 / 880 |
| Mualem (1976) | Unsaturated flow | *Water Resour. Res.* | 1003 / 773 / 747 |
| Beven & Kirkby (1979) | Contributing area model | *Hydrol. Sci. B.* | 844 / 840 / 799 |
| Beven & Germann (1982) | Flow in soils | *Water Resour. Res.* | 785 / 519 / 447 |
| Gelhar & Axness (1983) | Macrodispersion in aquifers | *Water Resour. Res.* | 784 / 465 / 313 |
| Ritchie (1972) | Crop evaporation | *Water Resour. Res.* | 708 / 393 / 304 |
| Clapp & Hornberger (1978) | Soil hydraulics | *Water Resour. Res.* | 704 / 500 / 389 |
| *Papers with relevance to hydrology in non-Water Resources journals:* | | | |
| van Genuchten (1980) | Hydraulic conductivity | *Soil Sci. Soc. Am. J.* | 2604 / 2276 / 1054 |
| Penman (1948) | Evaporation | *Proc. Royal Soc. Lond.* | 1556 / 778 / 769 |
| Mandelbrot & van Ness (1968) | Fractional Brownian noise | *SIAM Review* | 1258 / 966 / 1366 |
| Milliman & Meade (1983) | Sediment delivery | *J. Geol.* | 779 / 613 / 449 |
| Hurst (1951) | Long-term persistence | *Trans. ASCE* | 726 / 636 / 803 |
| Xie & Arkin (1997) | Global precipitation | *B. Am. Meteorol. Soc.* | 654 / 687 / 647 |
| Hosking (1981) | Fractional differencing | *Biometrika* | 523 / 487 / 868 |

*** ISI / Scopus / Google Scholar.** **Koutsoyiannis & Kundzewicz, 2007 (HSJ)**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Top 5 water resources journals
Top 3 hydrological journals
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