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“Solutions for the Water-Related Problems in Asian Metropolitan Areas”

Water resources development and management for developing countries in the 21st century: revisiting older and newer ideas

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Presentation available online: **itia.ntua.gr/1402/**

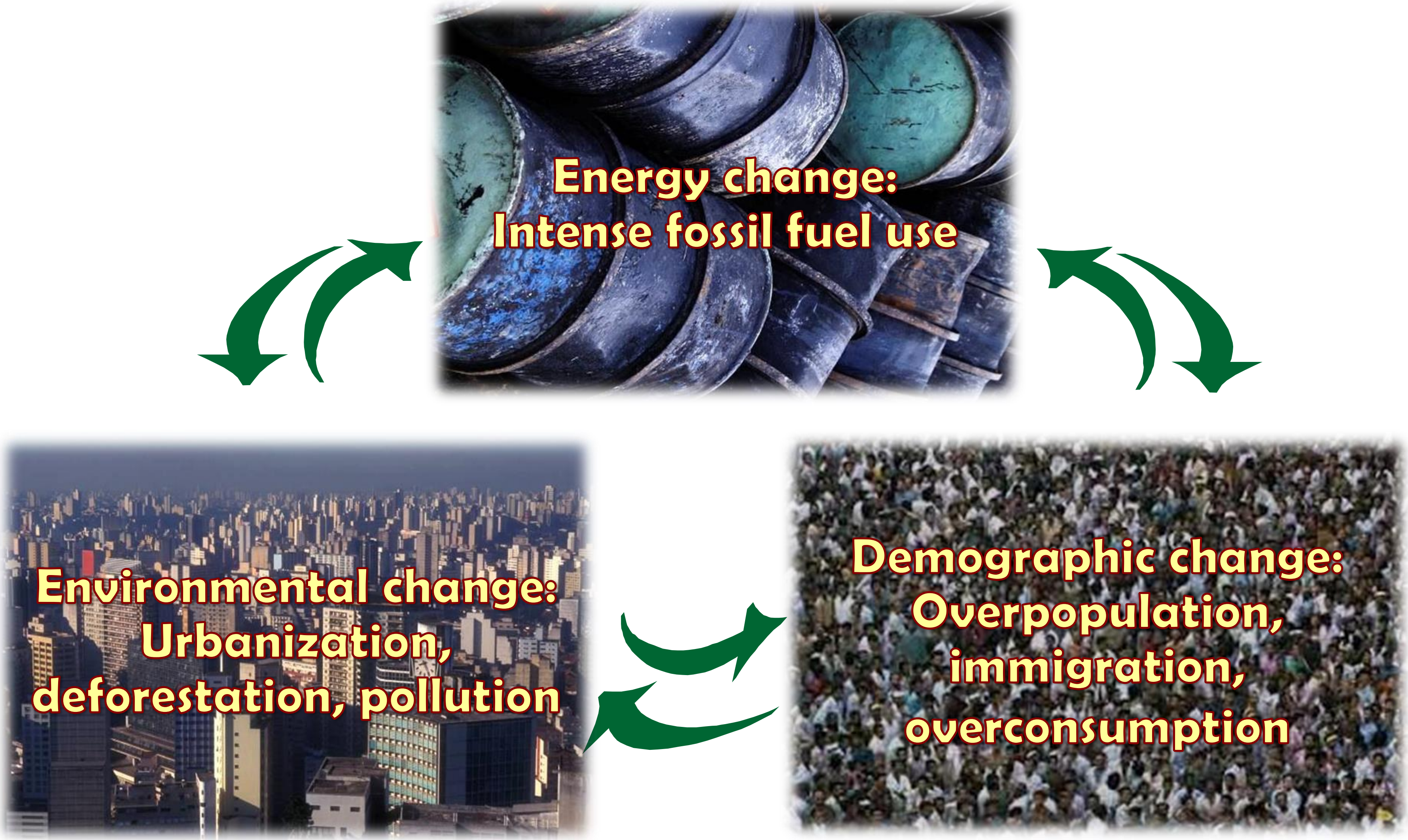
Water resources development and management for developing countries in the 21st century: revisiting older and newer ideas
Parts of the presentation

1. **Economic, political and ideological influences**
   Soft path and hard hypocrisy
2. **Logical and philosophical aspects**
   Certainties and uncertainties
   Inflation and parsimony
   Monomeric and holistic approaches
3. **Methodological and technical aspects**
   Modelling and management of hydrosystems

Part 1:
Economic, political and ideological influences

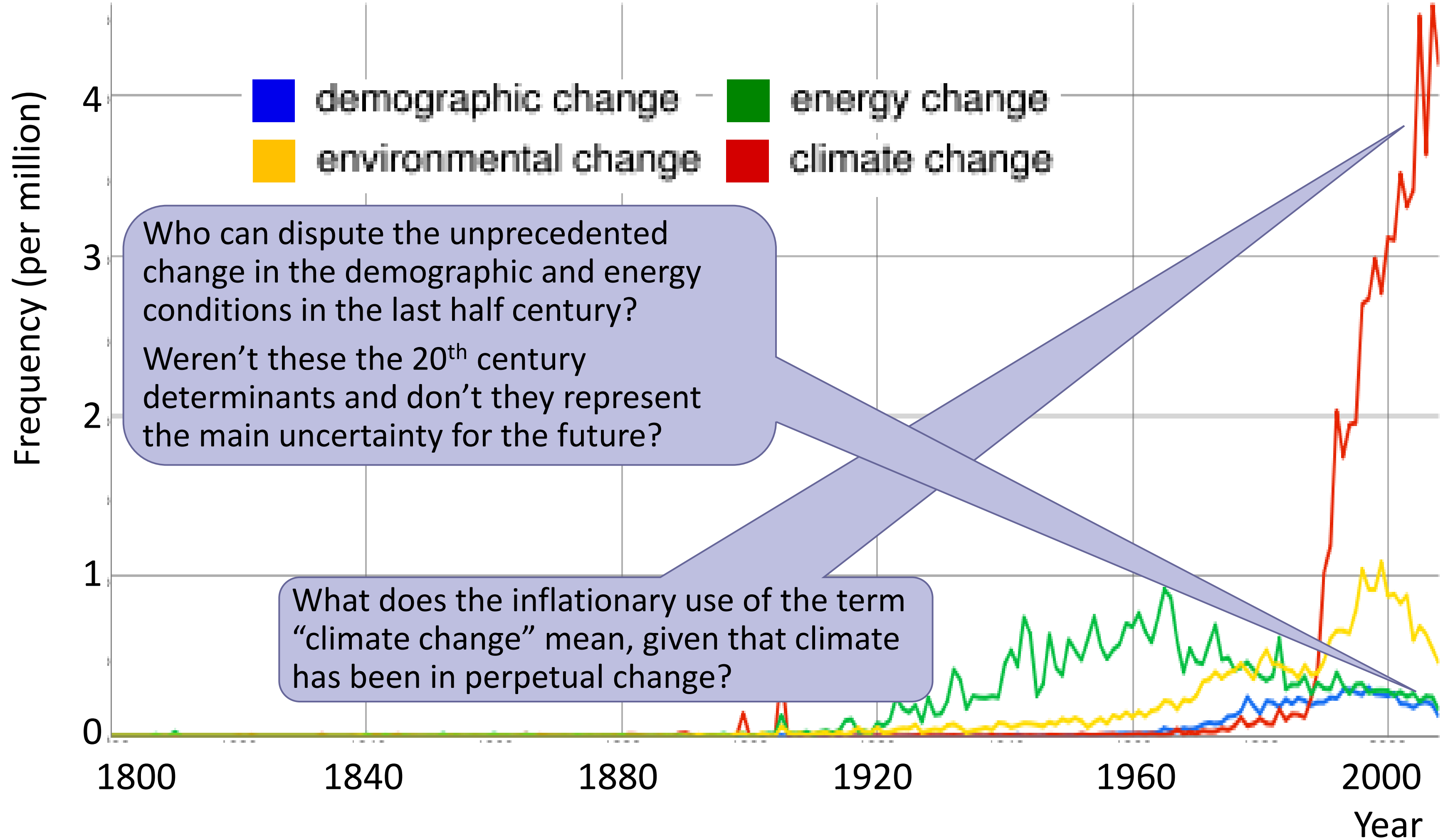
See also Koutsoyiannis (2011)

Introduction: the *real* contemporary problems



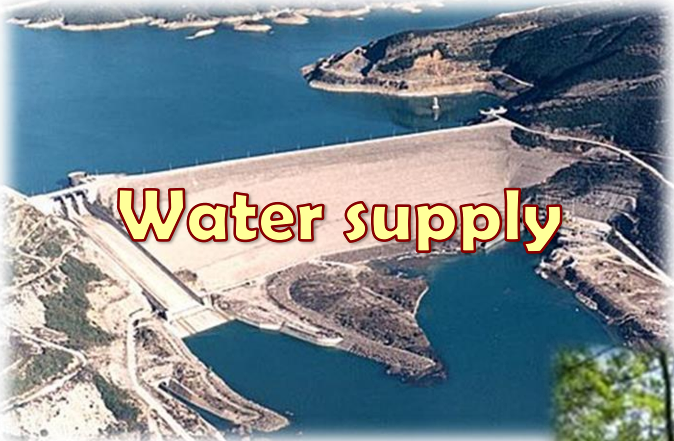
Adapted from Koutsoyiannis *et al.* (2009)

Is our focus opposite to importance?

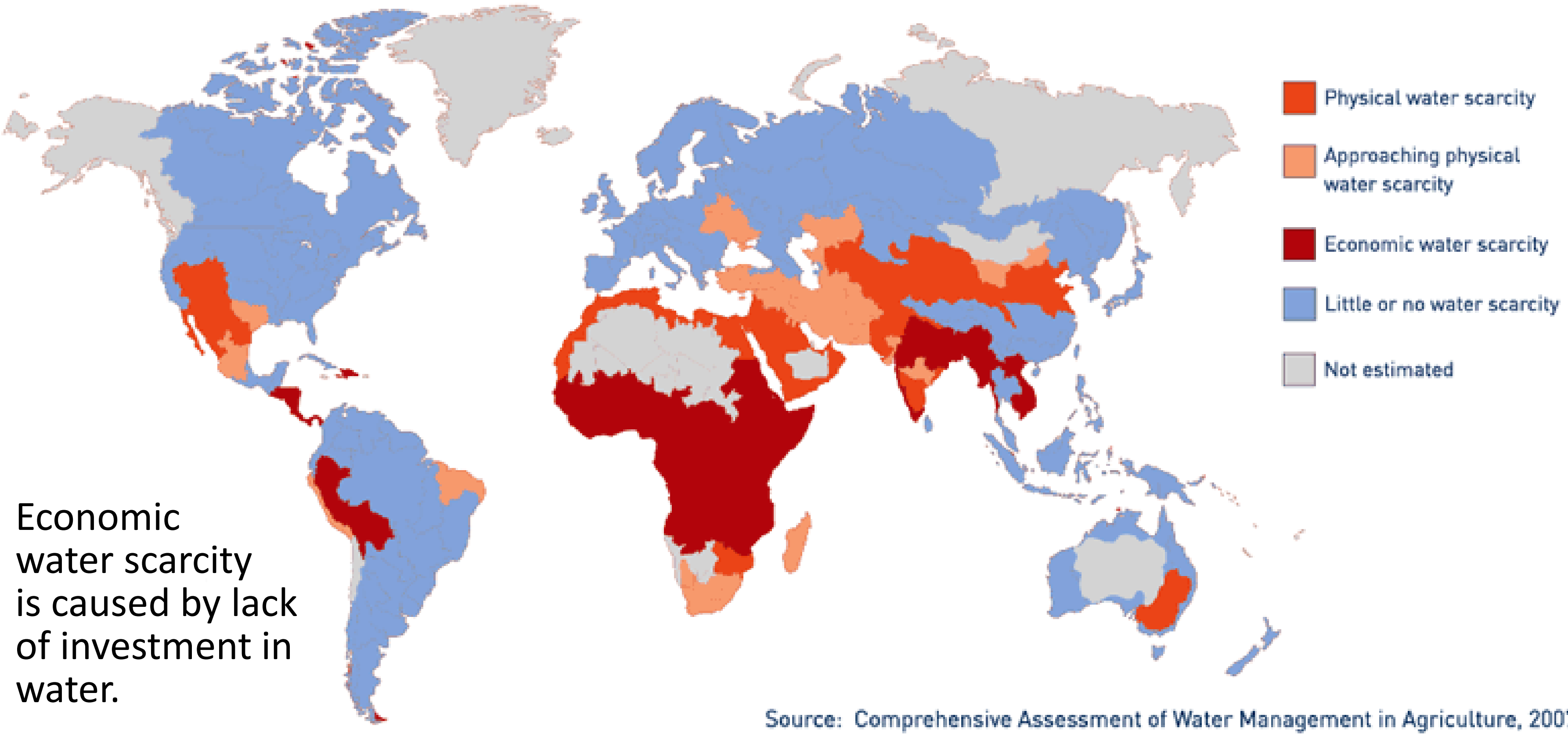


Frequency per year of each phrase in some millions of books.
Data and visualization by Google Books; https://books.google.com/ngrams/

Major *real* challenges of the 21st century



Water scarcity is (mostly) economically driven

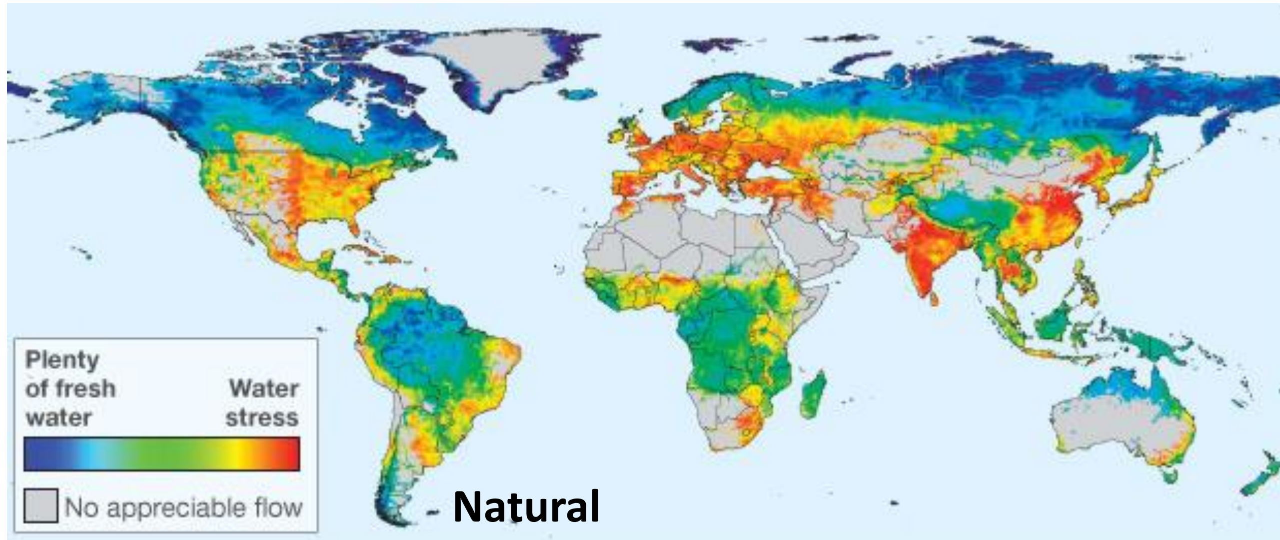


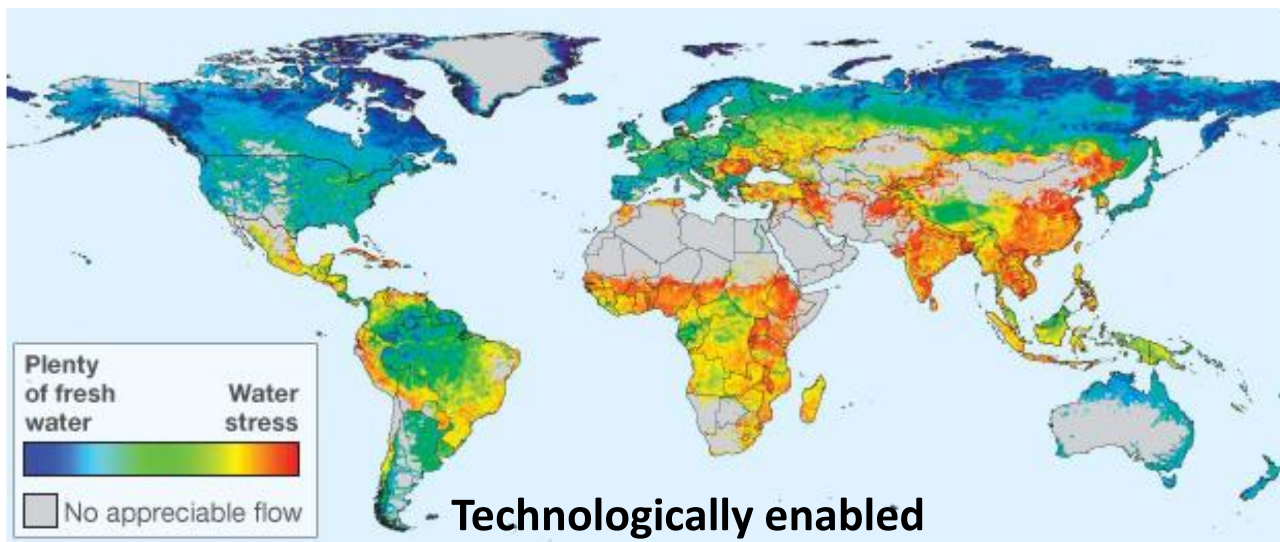
Economic water scarcity is caused by lack of investment in water.

Source: Comprehensive Assessment of Water Management in Agriculture, 2007 & http://www.fao.org/nr/water/art/2007/scarcity.html

Water scarcity = lack of technological infrastructure for water

- Vörösmarty *et al.* (2010), who constructed these graphs, advocate, for developing countries, *"integrated water resource management that expressly balances the needs of humans and nature"*.
- However, they do not seem to suggest technological means different from those already used in developed countries.

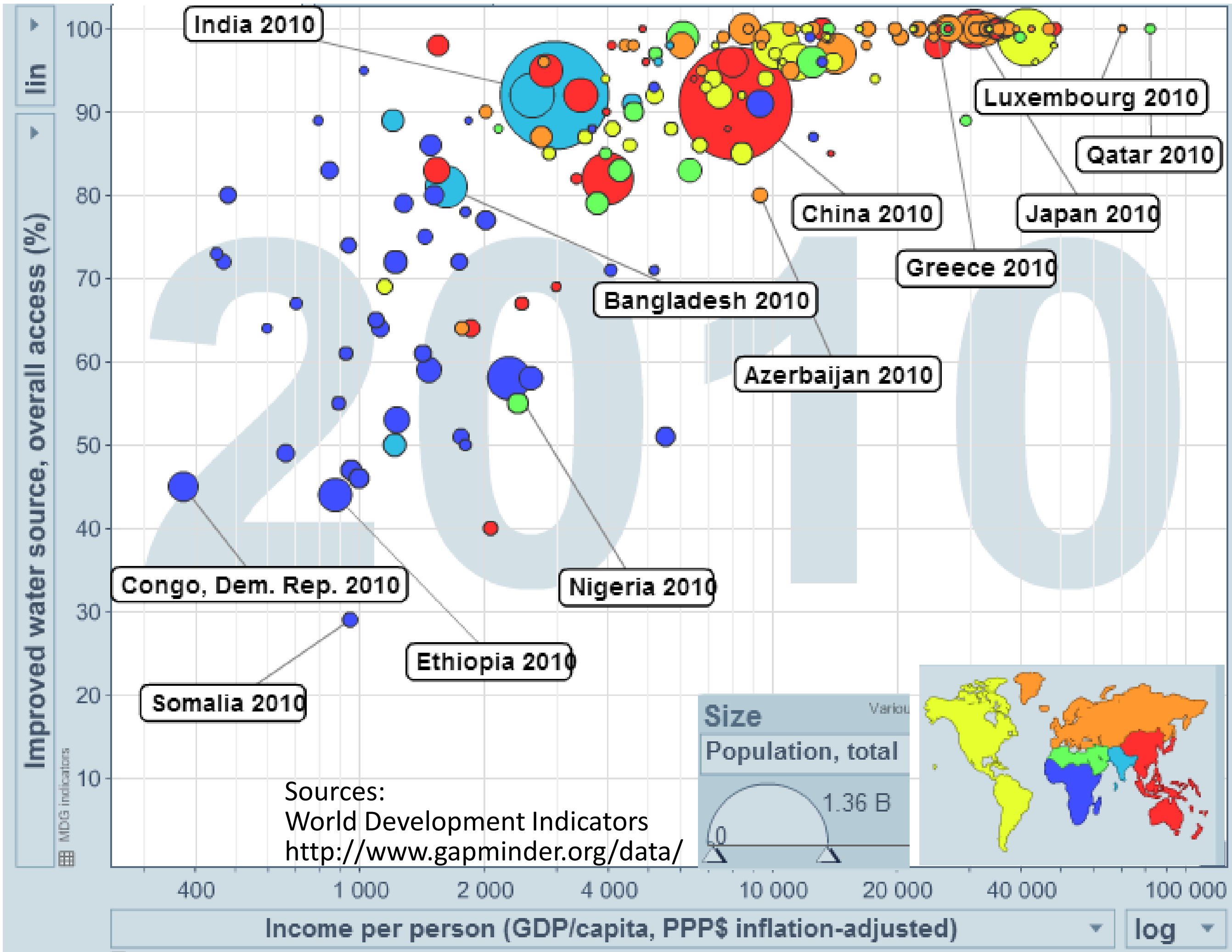




Source: Vörösmarty *et al.* (2010) as adapted in www.bbc.co.uk/news/science-environment-11435522

Disparities in water supply among different areas are marked

- In developed countries, 100% of the population has proper water supply.
- In developing countries, this percentage depends on the income (GDP).
- This percentage is very low in African countries.

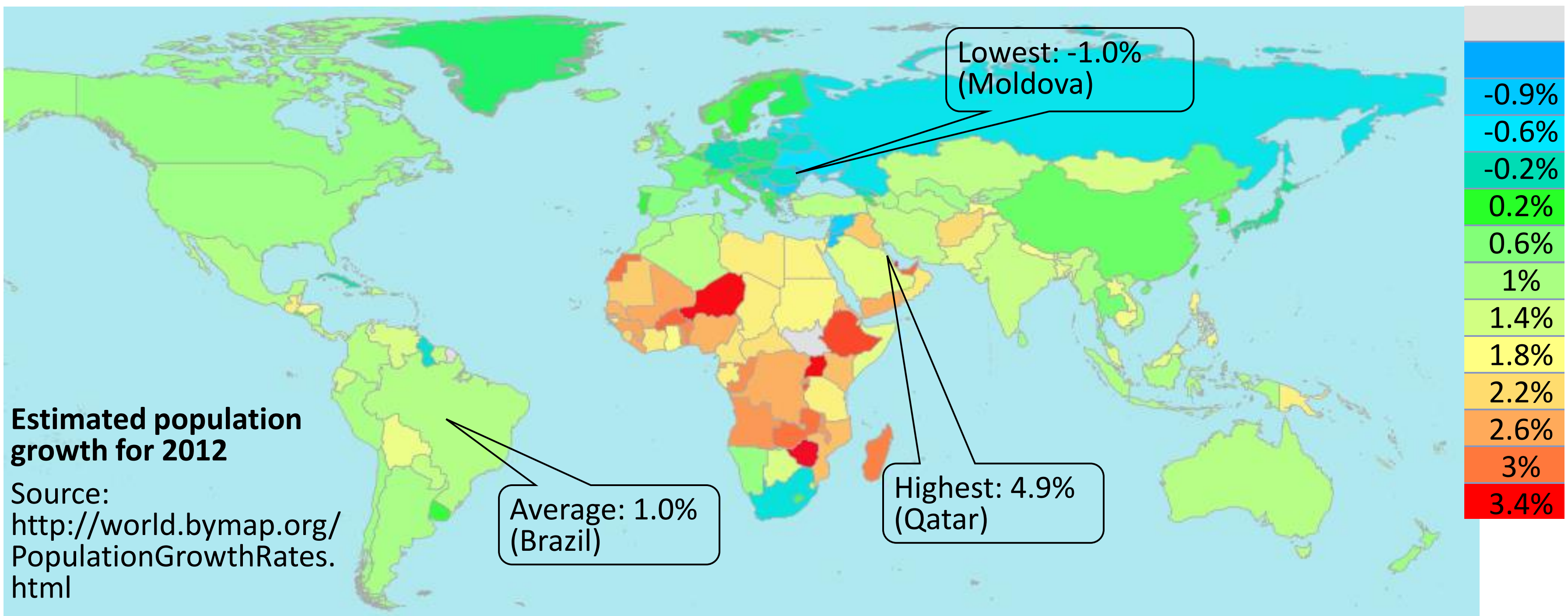


Sources:
World Development Indicators
http://www.gapminder.org/data/

Areas with large population growth suffer more from water scarcity

The rate of population growth varies.

- Negative rate in 37 countries, mostly Eastern European (Moldova, Bulgaria, Ukraine, Montenegro, Latvia, Russia, Serbia ...).
- Very high rate (> 3%) in 10 countries, mostly African and Southern Asian (Qatar, Zimbabwe, Niger, Uganda, Ethiopia, Burundi ...). Many of these suffer from water scarcity.

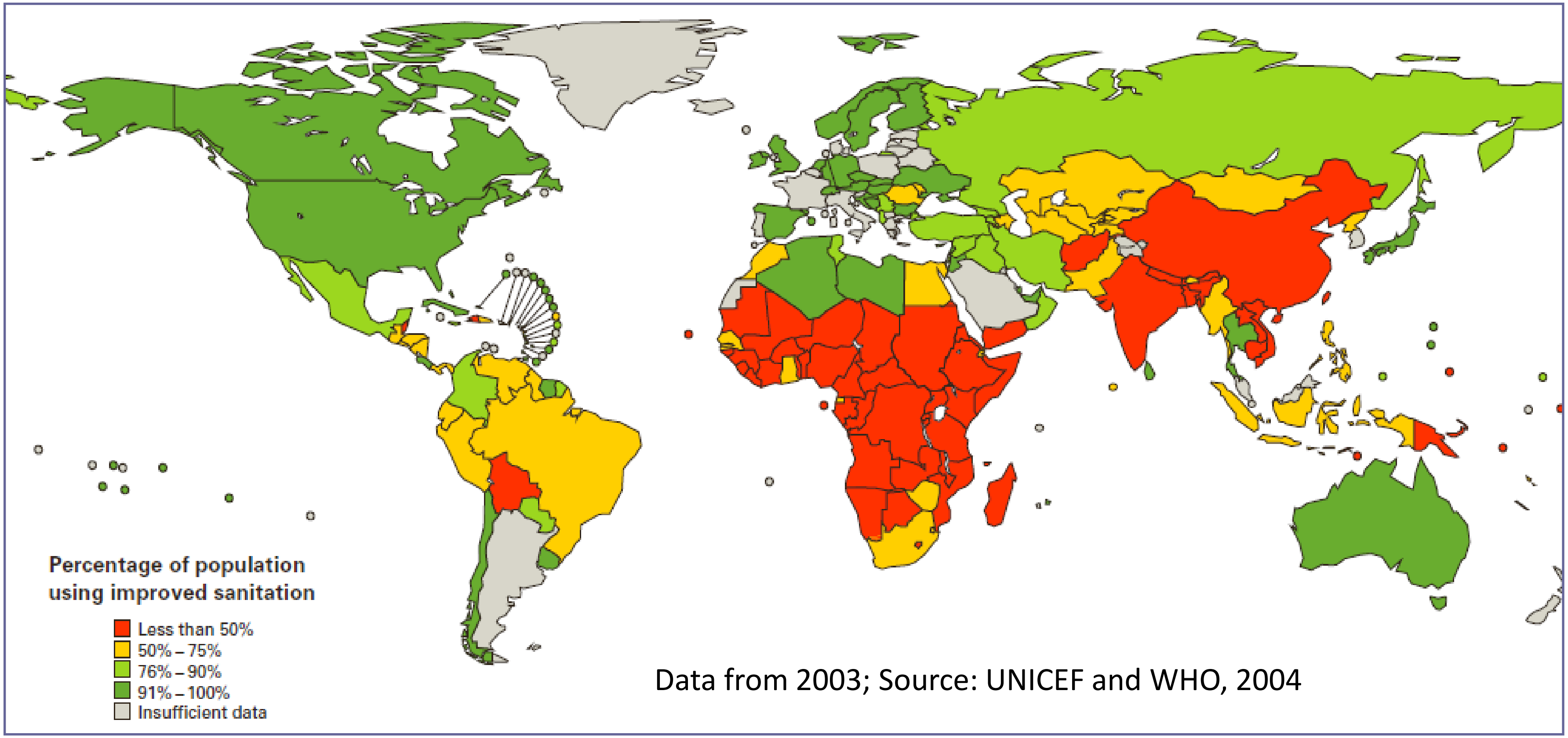


Estimated population growth for 2012

Source: http://world.bymap.org/PopulationGrowthRates.html

Areas with water scarcity (insufficient water infrastructure) have low level of public health

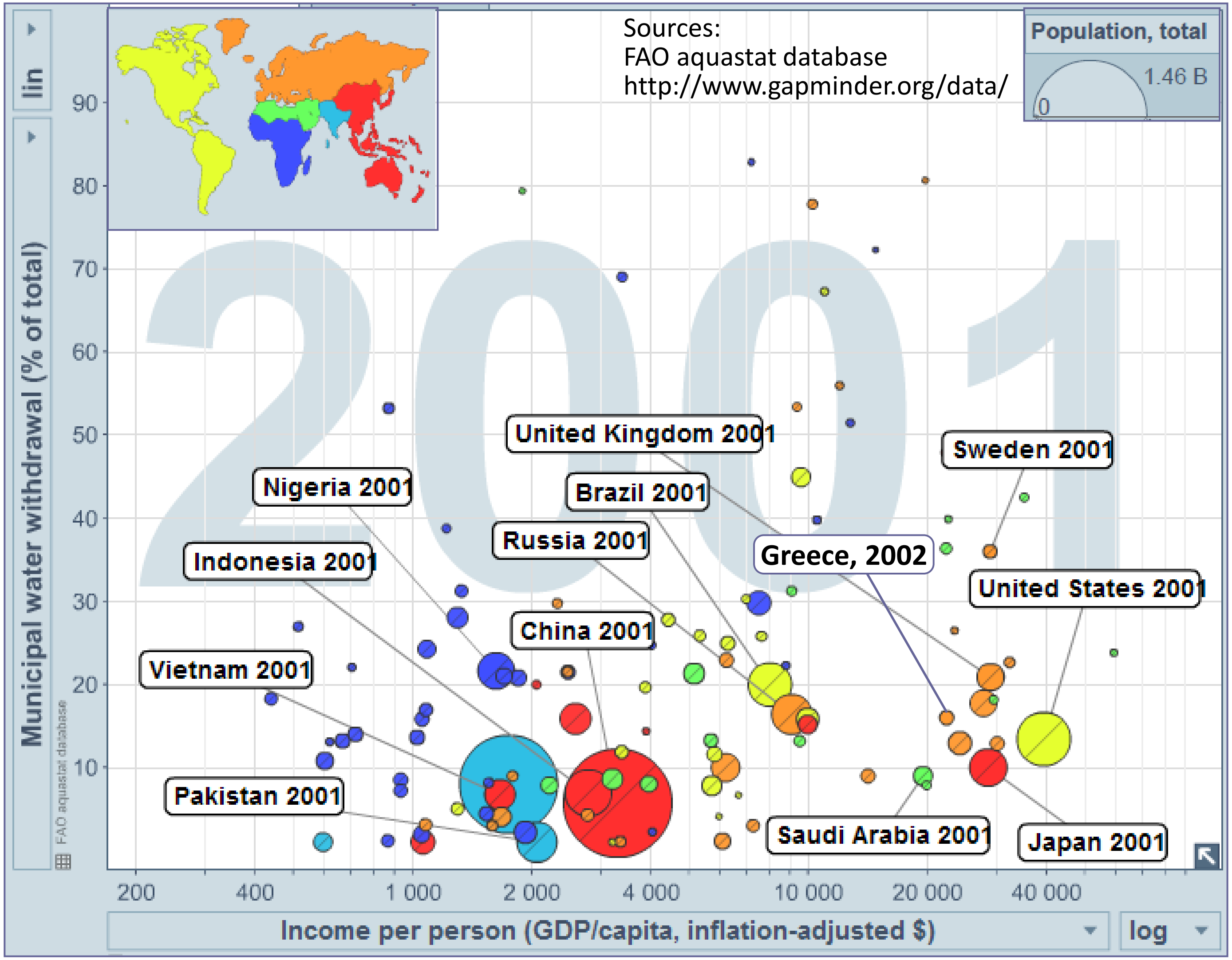
Half of the urban population in Africa, Asia, and Latin America suffers from diseases associated with inadequate water and sanitation (Vörösmarty *et al.*, 2005).



Data from 2003; Source: UNICEF and WHO, 2004

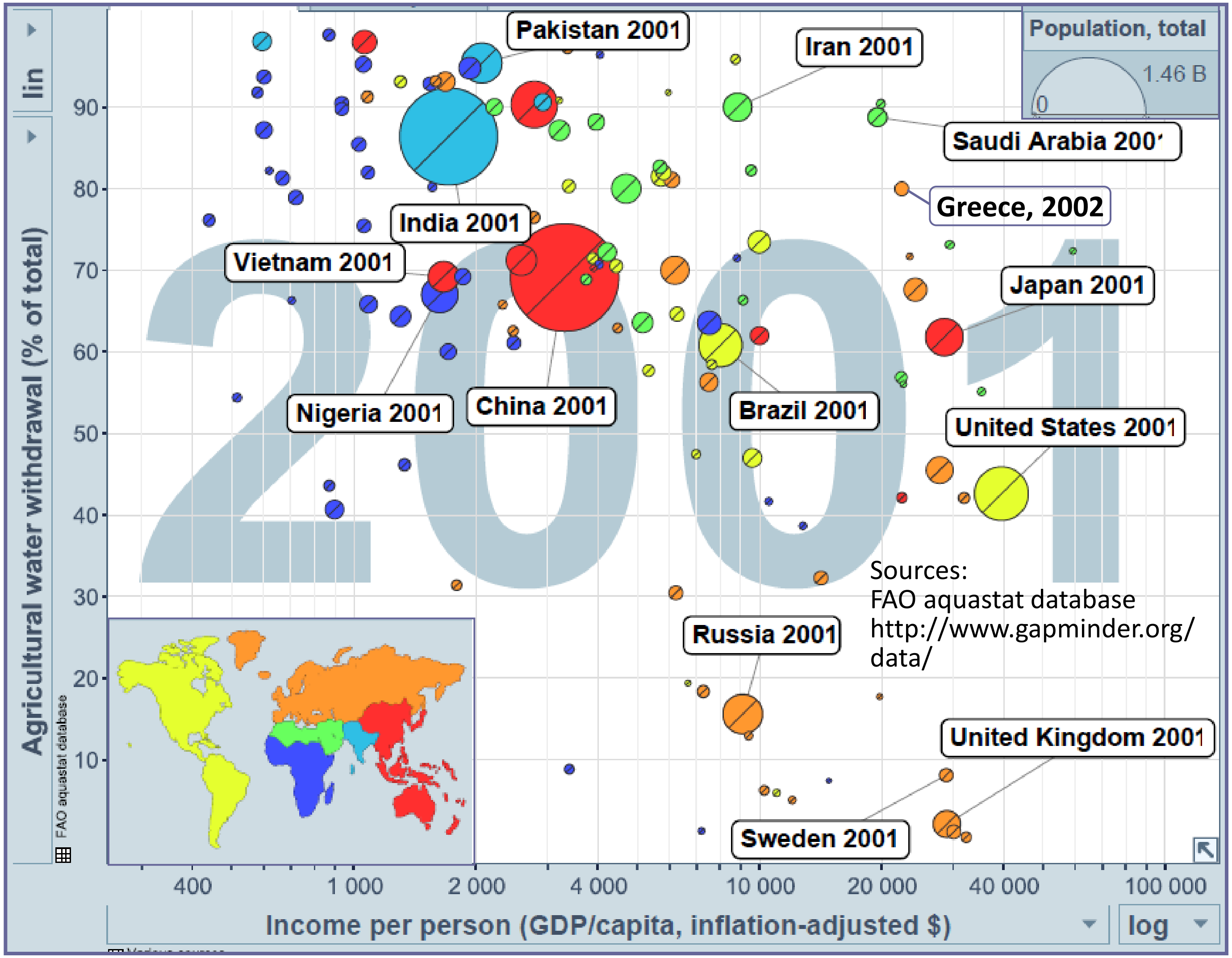
Drinking water and sanitation represent a small percentage of the total water needs

- Municipal water supply has the highest quality requirements.
- However, in terms of quantity, it constitutes a small percentage of total water withdrawals.



Food production depends on water

- Most of water consumed worldwide goes to irrigation.
- The portion of agricultural water use depends on climate—not on income.

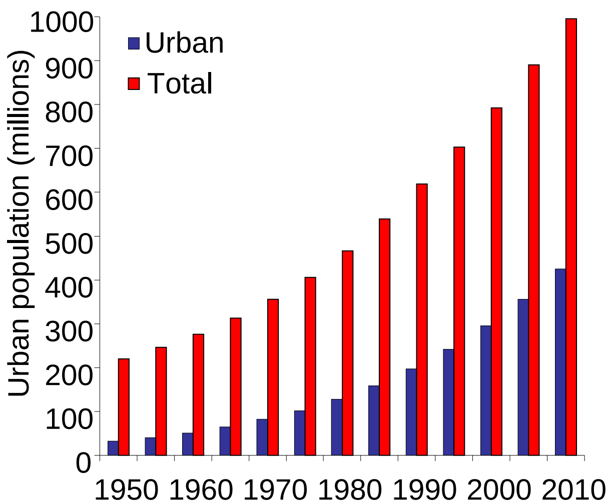


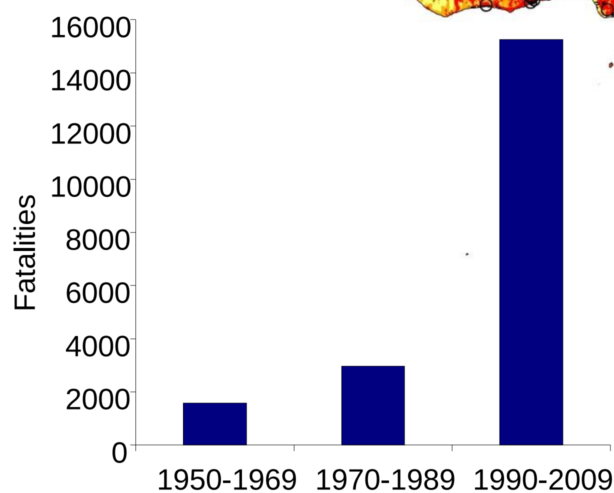
Sources:
FAO aquastat database
http://www.gapminder.org/data/

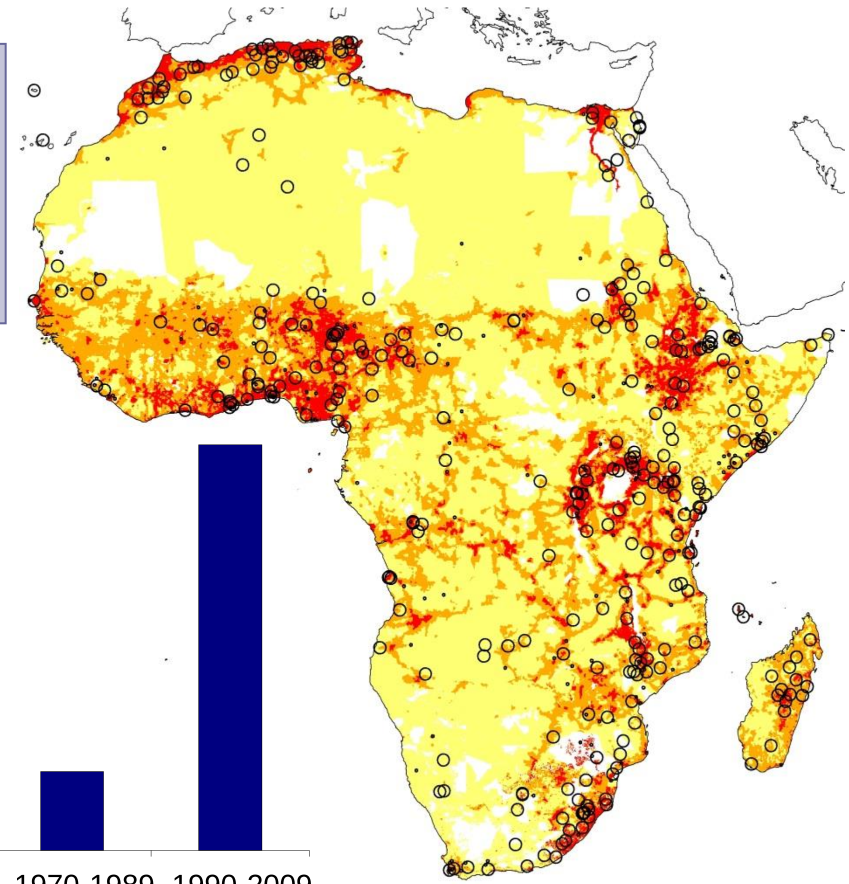
Protection from floods needs infrastructure

- When urbanization is not combined with urban water infrastructure, the results are tragic.
- Engineering infrastructure should include flood protection works and urban planning.

Population growth in the period 1960-2000 in Africa: yellow, less than 100 inhabitants per cell (2.5'); orange, 100-1000; red, more than 1000. The figure also shows the location of floods (dots) and deadly floods (large circles) in the period 1985-2009 (Di Baltrassarre *et al.*, 2010).







Protection from droughts and "food availability decline" (famines) needs infrastructure

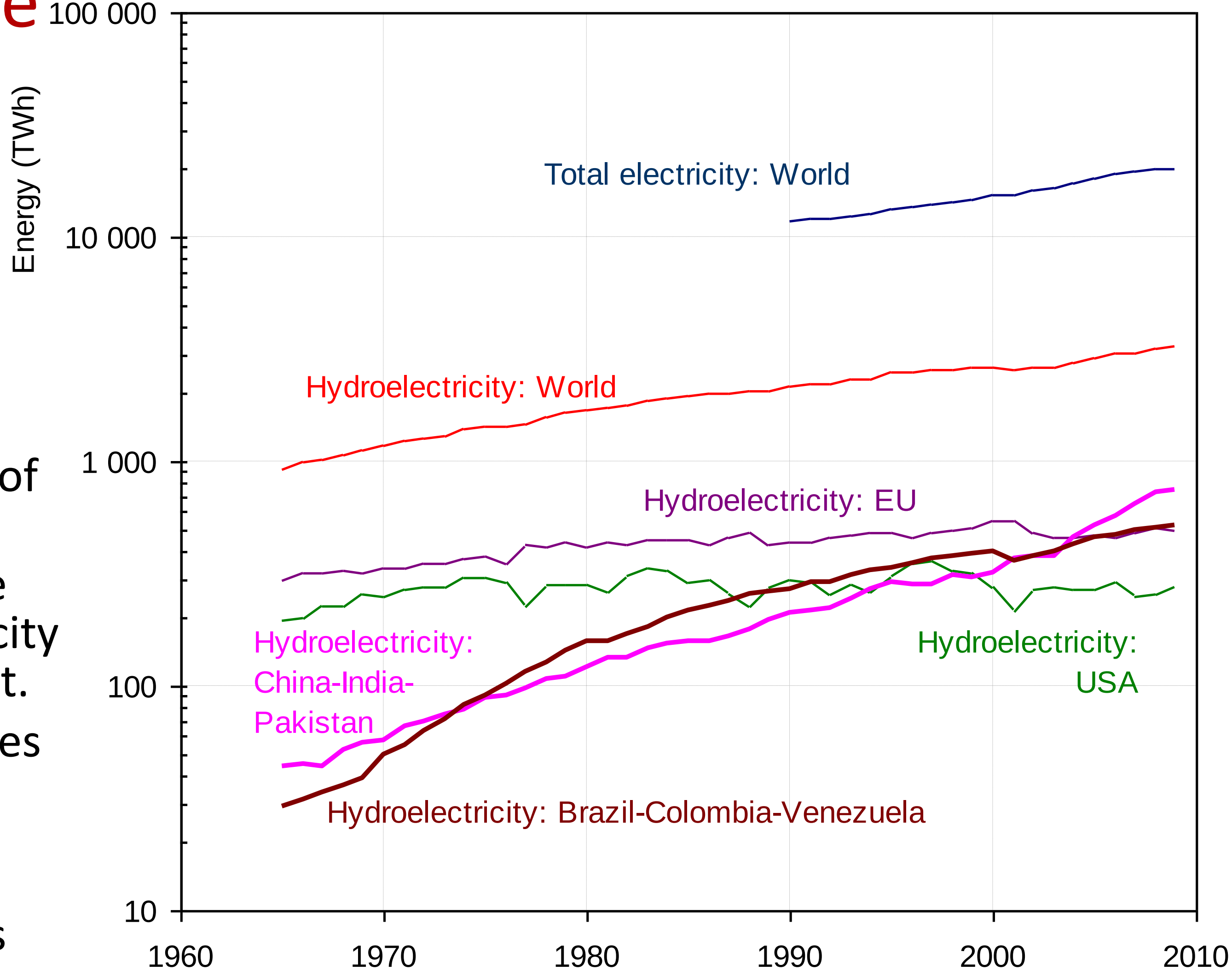
Period	Area	Fatalities (million)	Fatalities (% of world population)
1876-1879	India China Brazil Africa Total	10 20 1 ? >30	>2.2%
1896-1902	India China Brazil Total	20 10 ? >30	>1.9%
1921-1922	Soviet Union	9	0.5%
1929	China	2	0.1%
1983-1985	Ethiopia	≤1	0.02%

Sources: de Marsily (2008); Devereux (2000)

- Long-lasting droughts of large extent are intrinsic to climate (cf. Hurst-Kolmogorov dynamics).
- Such droughts may have dramatic consequences, even to human lives, as shown in the table, which refers to drought-related historical famines.
- Large-scale water infrastructure, which enables multi-year regulation of flows, is a weapon against droughts and famines.
- As shown in table, famines and their consequences have been alleviated through the years owing to improving water infrastructure and international collaboration.

Electric energy is tightly connected to water infrastructure

- Electricity and hydro-electricity increase by 3% and 2.6% per year, respectively.
- Hydroelectricity represents ~16% of world electricity.
- In Europe and the USA hydroelectricity has been stagnant.
- In several countries in Asia and South America the increase of hydroelectricity is spectacular (> 6% per year).



Data source: www.bp.com/productlanding.do?categoryId=6929&contentId=7044622

Obscuring of real problems by current ideological currents

- During the 20th century, **engineering solutions to real world problems** had a prominent position: By modifying the natural environment using **engineering means**, societies in the developed countries benefited substantially.
- This allowed increase of the **population and its wealth**, better **quality of life**, more **hygienic life style** and, most importantly, **spectacularly increased life expectation**.
- Toward the end of the 20th century, as the infrastructures were completed to a large extent in the developed world, engineering started to lose importance and engineering solutions were replaced by virtual reality games.
- **Environmentalism**, the now dominant ideological current and social movement, focusing on environmental conservation and improvement, and emphasizing a duty to **save the planet from diverse threat**s, has also determined the social views of water related problems and solutions.
- Most of these views are regarded “politically correct”, but sometimes this “correctness” may be a euphemism, if not a synonym for irrationality.
- Research funding is directed in subjects dictated by the dominant political agendas (e.g. in studying hypothetical climate-related threats and impacts).

The "soft path"

- The change of perspective has been epitomized in the so-called "**soft path**" for water (Gleick, 2002, 2003), which,

  "by investing in decentralized facilities, efficient technologies and policies, and human capital [...] will seek to improve overall productivity rather than to find new sources of supply [and] will deliver water services that are matched to the needs of end users, on both local and community scales."

- This has been promoted as a contrasting alterative to engineering solutions to problems that rely on infrastructure development, which Gleick (2002) calls the "hard path" and criticizes for:

  "spawning ecologically damaging, socially intrusive and capital-intensive projects that fail to deliver their promised benefits."

- In one of the rare instances that the concept was criticized, Stakhiv (2011) found it wholly inadequate for the needs of most of the developing world.
- Interestingly, the groups that project threats like bigger floods and droughts of greater duration due to climate change, and highlight the need for adaptation to climate change, are the same groups that discourage building new water projects and promote their "soft path" for developing nations.
- The promotion of the related ideas has been largely based on **hype**.

Hype 1: Water transfer is non-sustainable

- “*[Non-sustainable Water Use] can also embody the interbasin transport of fresh water from water rich to water poor areas*” (Vörösmarty *et al.*, 2005, p. 169).
- “*Interbasin water transfers represent yet another form of securing water supplies that can greatly alleviate water scarcity*” (*ibid.*, p. 184).
- Question 1: Can water be used by humans (as opposed to fish) without having been transported?
- Question 2: What does the stereotype of ‘interbasin transport’ represent?
  - Is it ‘interbasin transport’ when water is transferred between two neighbouring catchments of different streams, each having an area of, say, 1 km^2, at a length of, say, 1 km?
  - Is it not ‘interbasin transport’ when water is transferred between two neighbouring sub-catchments of the same river, each having an area of, say, 10^4 km^2, at a length of, say, 100 km?
- Question 3: What is the essential difference of ‘interbasin transport’ from ‘intrabasin transport’?
- Question 4: Is it non-sustainable to alleviate water scarcity and to substitute transferred surface water for water from overexploited groundwater sources?
- Question 5: In an era of open skies and globalization, will we convert hydrological basins into entrenchments?

Hype 2: Virtual water trade is more sustainable than real water transfer

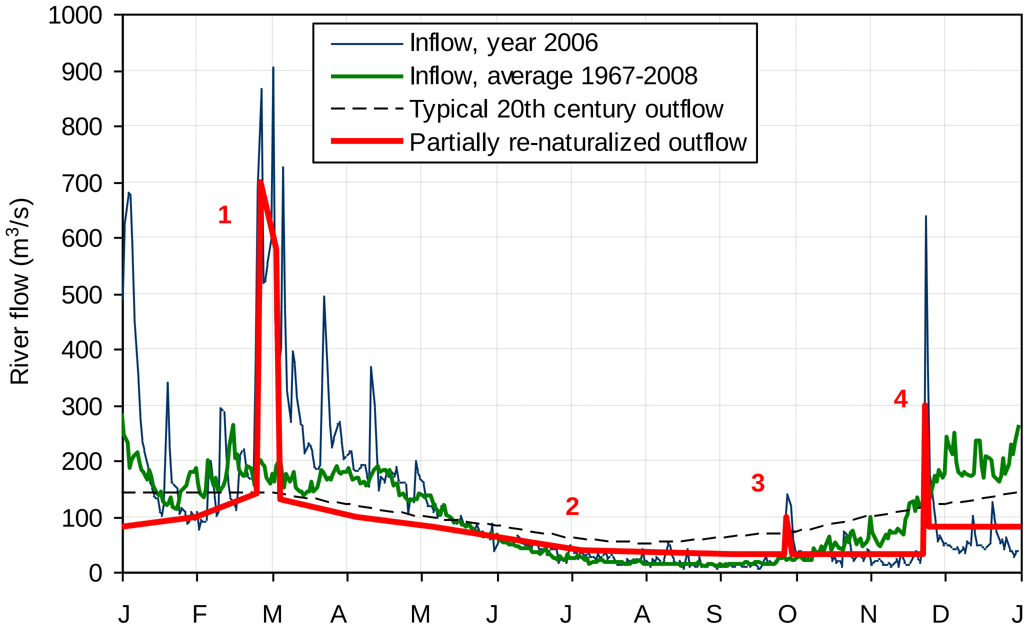
- Virtual water is the water ‘embodied’ in a product, i.e., the water needed for the production of the product; it is also known as ‘embedded water’ or ‘exogenous water’, the latter referring to the fact that import of virtual water into a country means using water that is exogenous to the importing country (to be added to a country’s ‘indigenous water’; Hoekstra, 2003).
- “*[V]irtual water trade is a realistic, sustainable and more environmentally friendly alternative to real water transfer schemes*” (Hoekstra, 2003).
- Question 1: Assuming that virtual water transfer is realistic and sustainable, why real water transfer is not?
- Question 2: Can the two transfer options, virtual water and real water, be compared in general and stereotypical terms (i.e. without referring to specifics, such as quantity, distance, energy, etc.)?
- Question 3: Is it really more sustainable and more environmentally friendly to transport agricultural products at distances of thousands of kilometres, wasting fossil fuel energy, than to transfer water at distances of a few kilometres, producing energy, boosting local agriculture, improving local economy and strengthening the resilience in crisis situations? (Cf. the current global economical crisis and Greece’s crisis in particular).

Hype 3: Environmental problems created by dams are irresolvable

There has been progress in finding solutions for real problems created by dams (and environmental concerns about dams have helped to this aim):

- Improved ecological functioning (permanent flow for habitats downstream, improved conditions for habitats in reservoir, passages of migratory fish).
- Sediment management by appropriate design and operation (**sediment routing, by-pass or pass-through**, sediment **dredging** and transport downstream; e.g. Alam, 2004).
- Revision/increase of non-emptied reservoir storage for improved quality of water, ecosystems and landscape (Christofides *et al.*, 2005).
- Re-naturalization of outflow regime (see below).

21st century re-naturalization of dammed river flows (Koutsoyiannis, 2011; Vörösmarty *et al.*, 2005; Tharme and King, 1998):
Partially re-naturalized flow regime, can retain important hydrologic characteristics: (1) peak wet season flood, (2) baseflow during the dry season, (3) flushing flow at the start of the wet season to cue life cycles, and (4) variable flows during the early wet season.



Hype 4: Hydroelectric energy is not renewable

- Business lobbying and "green" ideological influences have resulted in laws or regulations that define "small hydro" as renewable and sustainable, whereas "large hydro" is labelled as **not** renewable/sustainable (Frey & Linke, 2002).
- An example from Greek legislation "*The hydraulic power generated by hydroelectric plants, which have a total installed capacity more than 15 MW, is excluded from the provisions of this Act*" (Act 3468/2006, Art. 27, par. 4, www.rae.gr/downloads/sub2/129(27-6-06)_3468.pdf)
- Related grey literature abounds (e.g. "*Hydro power is not renewable. Hydroelectric power depends on dams, and dams have a limited life […] because the reservoir fills with silt*"; http://web.archive.org/web/20090711160342/http://letters.salon.com/tech/htww/2009/07/07/wild_salmon_cause_global_warming/view/?)
- Question 1: Even assuming that dams have destroyed river environments, does this make the energy they produce non-renewable?
- Question 2: Does any human construction have unlimited life?
- Question 3: Will energy production stop if a reservoir is silted? (Will the hydraulic head disappear?)
- Question 4: Why Greek legislation **excludes** large-scale hydropower stations—but, notably, not in reporting to the EU about progress in achieving renewable energy targets? (Hint: Think of who will get the money and how).

Is Europe’s stagnancy of hydroelectric production related to its “non-sustainable” feature?

Country*	Economically feasible hydro potential (TWh/year)	Production from hydro plants (TWh/year)	Exploitation percentage (%)
Germany	25	25	100
France	72	70	97
Italy	55	52	95
Switzerland	36	34	94
Spain	40	35	88
Sweden	85	68	80
Norway**	180	120	67
…			
Greece	15	4.7	31

The most developed countries have already developed almost all economically feasible hydro potential.

* Data from Leckscheidt and Tjaroko (2003) in general and Stefanakos (2008) for Greece.
** Norway’s hydroelectricity production is about ~99% of its total electricity (data from www.bp.com/productlanding.do?categoryId=6929&contentId=7044622).

Who is the target of the hype about hydroelectric development?

Continent	Economically feasible hydro potential (% of world)	Exploitation percentage (%)
Europe	10	75
North & Central America	13	75
South America	20	30
Asia	45	25
Africa	12	8

Source: Leckscheidt and Tjaroko (2003)

An encouraging brand new development

- In July 2013 the World Bank (2013) decided to re-engage in large-scale hydropower infrastructure after having withdrawn from it for the past two decades.
- The report of the World Bank (2013) highlights the fact that nearly 3/4 of potential hydropower resources in the developing world are yet to be realized, including more than 90% in Sub-Saharan Africa and about 70% in South Asia.
- The report now recognizes that for many countries, hydropower is the largest source of affordable renewable energy and that reservoir hydropower can pave the way for the later introduction of other forms of renewable energy.
- Furthermore it recognizes the unique ability of hydropower to instantly offset variability of other parts of the electric power system, as well as the potential for pumped storage to store, for example, wind energy during periods of surplus.
- It is very positive that these unique abilities of hydropower (Koutsoyiannis *et al.*, 2008a, 2009; Koutsoyiannis, 2011) are now understood by the World Bank and this creates hopes that it may be understood by others too.
- While this strategic change of World Bank has been carefully assessed and reported by some groups (Appleyard, 2013), naturally it disappointed other groups (Bosshard, 2013).

Hype 5: Large-scale energy storage is beyond current technology

- “*Engineers haven’t yet developed energy storage devices suitable for storing solar and wind power*” (Kerr, 2010).
- However, pumping water to an upstream location consuming available energy, which will be retrieved later as hydropower, is a proven and very old technology with very high efficiency (see below).
- This feature of hydropower makes it unique among all renewable energies.
- This technology can be implemented even in small autonomous hybrid systems (e.g. Bakos, 2002).
- However it is substantially more advantageous in large-scale projects (see below).

Hype 6: Hydroelectric energy has worse characteristics than wind and solar energies

- Large-scale hydroelectric energy has unique characteristics among all renewable energies.
  - It is the only fully controllable/regulated (as contrasted to the highly variable and uncontrollable wind and solar, and even small-scale hydro, energy).
  - It offers high-value primary energy for peak demand.
  - It offers the unique option of energy storage, which is an essential need for an energy system that includes renewable energy production.
- In addition, it offers the only energy conversion with really high efficiency:
  - Hydro (large-scale): 90-95%.
  - Wind turbines:
    - Betz limit 59% (theoretical upper limit);
    - achieved in practice 10-30%.
  - Solar cells:
    - commercially available (multicrystalline Si) ~14-19%;
    - best research cells (three junction concentrators) 41.6%.
  - Non-renewable (for comparison):
    - combined cycle plants (gas turbine plus steam turbine) ~60%;
    - combustion engines 10-50%.

Hype 7: Small projects are better than large

- The debate about large- vs. small projects seems to have been won by the latter; this is evident from everyday news, from scientific documents and, particularly from legislation.
- As mentioned earlier, in Greek legislation only small hydropower plants (< 15 MW) are regarded as renewable; but similar provisions exist in other European countries and North American states, where the border between small and large hydropower plants is:
  - 10 MW in the UK (Reiche & Bechberger, 2004);
  - 5 MW in Germany (Reiche & Bechberger, 2004);
  - 30 MW in California and Maine (Égré *et al.*, 1999; Égré and Milewski, 2002);
  - 80 MW in Vermont (Égré *et al.*, 1999);
  - 100 MW Rhode Island and New Jersey (Égré *et al.*, 1999; Égré and Milewski, 2002).
- The comparison of the impacts of small vs. large projects should be done on a cumulative basis rather than on the basis of an individual project.
- In Greece, a total of 250 small hydropower plants have been licensed with a total installed capacity of 430 MW (Douridas, 2006).
- Notably, the installed capacity of just one large plant (the old Kremasta hydropower plant in Acheloos) is 437 MW.

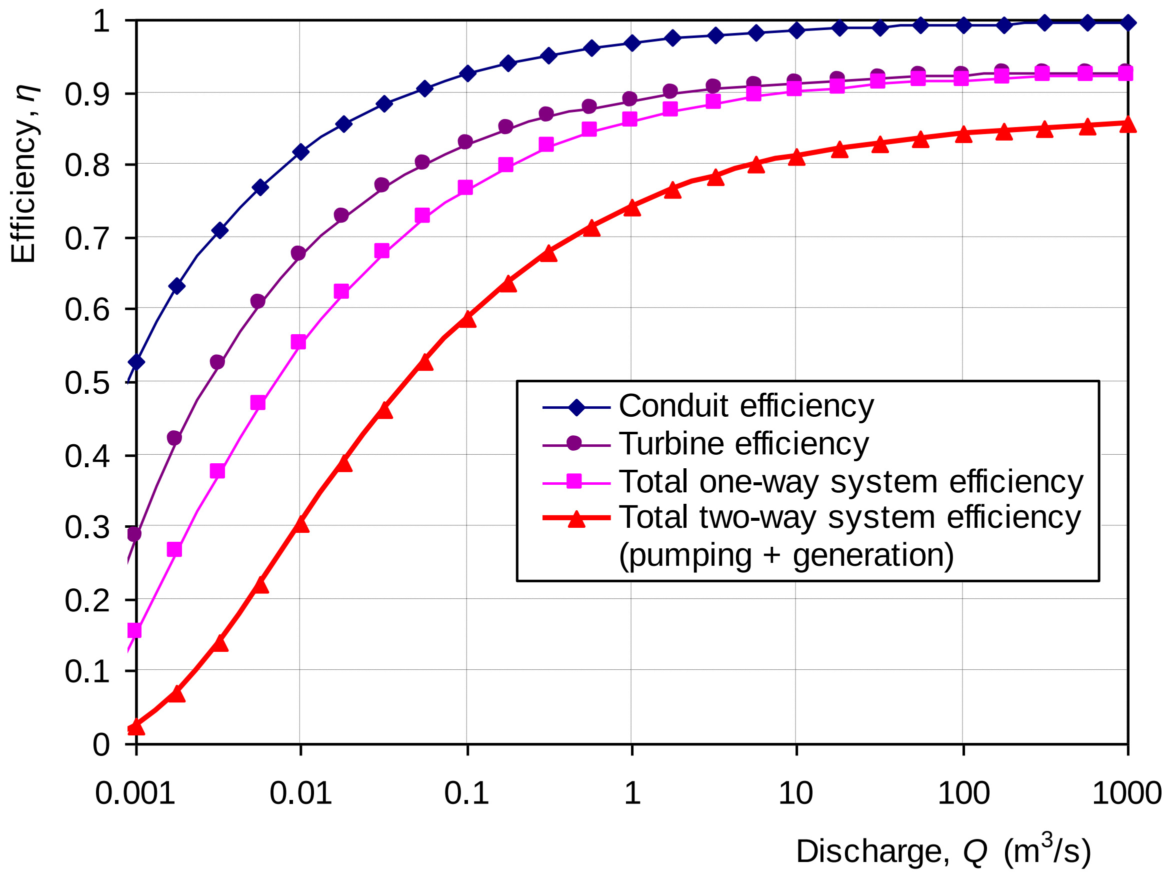
Only large-scale systems can efficiently store energy

The example below, calculated using plausible assumptions and commercial pump/turbine characteristics, shows that for large discharge (> 10 m^3/s) we can achieve efficient storage of energy (η > 0.8), while for discharge Q < 1 m^3/s the efficiency degrades rapidly.

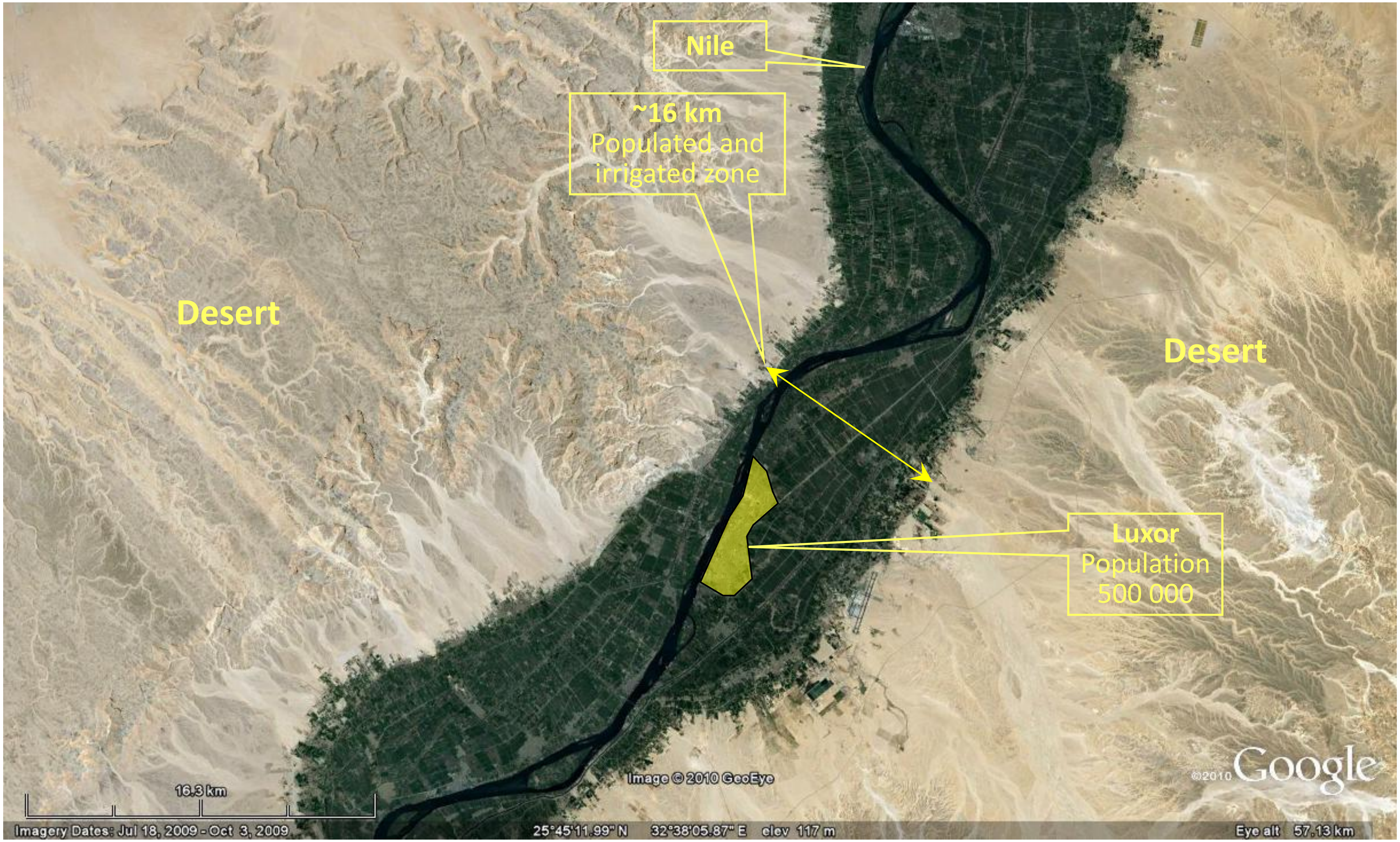
Assumptions

(Koutsoyiannis, 2011)

- Turbine/pump efficiency according to the average curve [$\eta = 0.93 - (3000 \text{ m}^{-3} \text{ s } Q)^{-0.4}$].
- Conduit length 2 km and roughness 1 mm.
- Hydraulic head 100 m.
- Conduit velocity V varying as a power function $V(Q)$ of the discharge Q with $V(0.001 \text{ m}^3/\text{s}) = 0.6$ m/s, $V(1000 \text{ m}^3/\text{s}) = 2.5$ m/s.



“*Nothing can be green without water – except ‘green’ politics*” (Vít Klemeš)



⇩ **To Aswan dam** (hydroelectricity, storage of irrigation water, flood control)

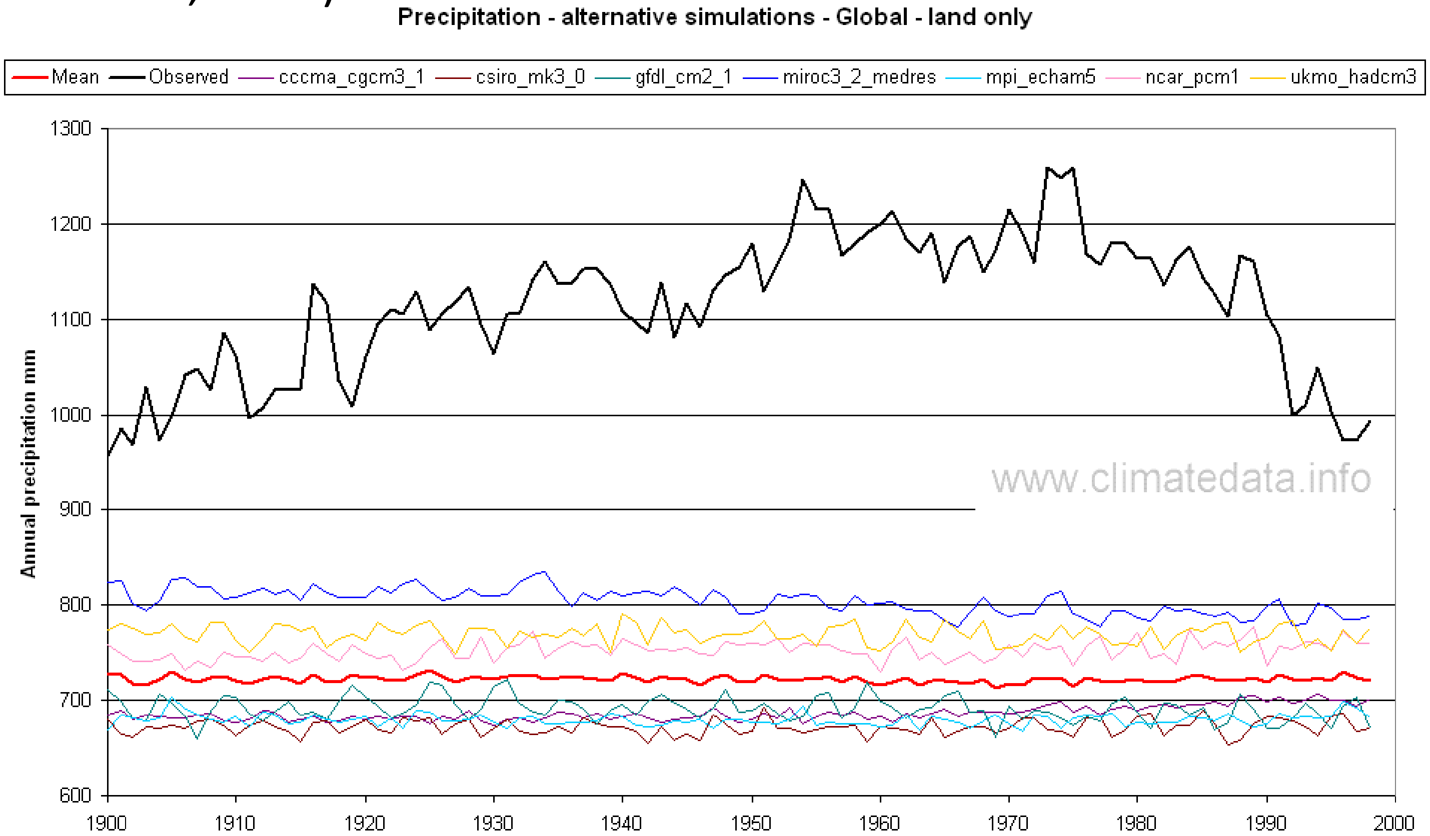
Part 2:
Logical and philosophical aspects

The delusion of uncertainty elimination

- An impressive engineering achievement in the **developed countries** during the 20th century is the **transformation**, through large-scale constructions (dams, reservoirs and hydropower plants), of **highly varying and uncertain natural flows** into **regular**, often constant, outflows that satisfy the water and energy **demands** of the society.
- A negative consequence may be the implied **delusion for uncertainty elimination**.
- However, the infrastructure-enabled reduction of the high variability of the natural processes does not mean that uncertainty is, or can be, eliminated.
- If it could, this would have destructive effects as **evolution and progress have been made possible because of change and the implied uncertainty**.
- Also, **uncertainty makes our world liveable**: Were the future predictable without uncertainty, it would also be controllable and this would give an enormous power to an elite of technocrats for whom the future would have no secrets.

The modern quest for a predictable future: The culture of climate models and predictions

- The climate change agenda has enforced the use of the climate models as a guide to the future; however their simulations for past years are irrelevant to reality (particularly with respect to rainfall; Koutsoyiannis *et al.*, 2008b, 2011; Anagnostopoulos *et al.*, 2010).
- How can one trust their future predictions (with or without down-scaling) and pretend that the results have some value?



An engineering frame for viewing the future

- In water resources **engineering** and management decisions are made with **reference to the future**.
- In engineering planning and design, prediction horizons are very long (several decades—this is tradition, not a new development).
- In water management, prediction horizons can also be long because present decisions affect the future states of hydrosystems.
- **The distant future is (and will always be) unknown**. Methods assuming known future conditions are common but **inappropriate**.
- In **long time horizons**, engineering constructions and hydrosystems are subject to **uncertain** loadings and are inescapably associated with **risk**.
- Long prediction horizons, uncertainty and risk are challenging but can be effectively dealt with.
- Only **stochastic approaches** offer a scientifically rigorous method to cope with future uncertainty.

Relevant lessons from advances in physics, mathematics and natural sciences

- The **dynamical systems** theory has shown that uncertainty can emerge even from pure, simple and fully known deterministic (chaotic) dynamics, and cannot be eliminated.
- **Statistical physics** used the probabilistic concept of entropy (= uncertainty quantified through the probability theory) to explain fundamental physical laws (most notably the Second Law of Thermodynamics), thus leading to powerful predictions of macroscopic phenomena, despite microscopic uncertainty.
- **Quantum theory** has emphasized the intrinsic character of uncertainty and the necessity of probability in the description of nature.
- Developments in **mathematical logic**, and particularly Gödel's incompleteness theorem, challenged the almightiness of deduction (inference by mathematical proof) thus paving the road to inductive inference, characterized by uncertainty.
- Developments in **numerical mathematics** highlighted the effectiveness of stochastic methods in solving even purely deterministic problems, such as numerical integration in high-dimensional spaces and global optimization of non-convex functions .
- Advances in **evolutionary biology** emphasize the importance of stochasticity as a driver of evolution.

The inflationary reductionist approach in modelling

- It has been a common fallacy that a complex system can be effectively modelled, even without data, by
  - cutting it into small nearly-homogeneous pieces,
  - describing the natural processes in each piece using differential equations which implement “first principles”, and
  - solving the differential equations numerically thanks to the ever increasing computer power.
- This reductionist philosophical view constitutes the basis of the so-named “physically-based” hydrological modelling (e.g. Abbott *et al.*, 1986) and has been highly promoted in the initial document of the decade-long IAHS initiative for Prediction in Ungauged Basins (PUB; Sivapalan *et al.*, 2003).
- However, pragmatism and experience may help us see that the more detailed an approach is, the more data it needs to calibrate.
- Also, common sense may help us understand that it is infeasible to estimate the evapotranspiration of a forested area by “cutting” the forest into trees and then each tree into individual leaves.

The parsimonious approach

- History of science teaches that feasible and convenient macroscopic descriptions can only be achieved using principles of probability theory like the law of large numbers and the principle of maximum entropy (cf. statistical thermophysics), as well as parsimonious conceptual and systems approaches.
- There are several examples where simpler and more parsimonious models gave better fits and better predictions in complex hydrological systems.
- An interesting example is the modelling of a karstic basin in Bosnia and Herzegovina with a complex system of surface poljes and underground natural conduits (Makropoulos *et al.*, 2008).
  - Three different research teams worked independently from each other adopting different approaches but using the same data.
  - One of the approaches was "physically-based", one was based on a detailed conceptual description of the processes and the third was a "toy model", lumping similar elements of the system into a single substitute element.
  - Naturally, the "toy model" performed best, while the "physically-based" model gave the worst predictions.

Monomeric versus holistic modelling

- Often the detailed (at a micro-scale) models for complex systems are in fact detailed only for parts of the system: those ones for which theories allow inflationary description.
- For other parts oversimplified models or rough and naïve assumptions are used.
- Such approaches, which have been called monomeric (from the Greek "μόνος", i.e. "solely" and "μέρος", i.e. "part"), can be misleading because of the uneven treatment of the different system elements.
- Conversely, when all parts of the studied system are modelled in similar detail and are linked via feedback mechanisms, the approach is called holistic (from the Greek "όλον", which means "whole").
- A holistic modelling strategy involves model integration for all processes for all system parts (instead of isolation of certain system parts and study thereof as individual entities), parsimonious parameterization and effective parameter optimization based on multiple objectives.
- A holistic approach is superior compared to a monomeric one (Nalbantis *et al.*, 2011).

On understanding and misunderstanding

- ‘Understanding’ seems to have become the Holy Grail of modern science, including hydrology, as testified by the frequent and emphatic use of this word in scientific papers.
- For example, a Google Scholar search reveals that out of 31 200 papers published since 2009 that contain the word ‘**hydrologic**’ (as of January 2013), **64% also contain the word ‘understanding’**.
- This is an infelicitous development, because ‘understanding’ is a vague and obscure term per se. In particular, ‘understanding’ is a subjective cognitive procedure rather than anything objective.
- Perhaps a more relevant term is ‘**interpretation**’, which is also subjective, but more **honest** in admitting the subjectivity: while fans of the term ‘understanding’ would pretend to target a unique type of understanding (characterizing other views as ‘misunderstanding’), they would be less reluctant to allow multiple interpretations of a phenomenon as legitimate.
- In addition, as ‘understanding’ is typically used within a deterministic point of view, it leaves out important targets as the understanding of randomness and uncertainty.

From understanding to overstanding

- In science, understanding is not a primary goal (cf. quantum physics).
- In engineering, understanding is clearly a secondary goal; the primary one is to solve a problem in a reliable manner.
- As history teaches, full understanding has not been a prerequisite to act.
- As understanding is typically associated with deterministic detailed descriptions of phenomena, it may lead to failure in constructing the big picture.
- For the latter, the term *overstanding* has been coined (Koutsoyiannis, 2010) which highlights the importance of macroscopic views of complex phenomena—the view of the forest than of the tree (Note: a literal translation of the Greek word *episteme* would be overstanding).

Credit for sketches: Demetris Jr. (from Koutsoyiannis, 2009).

Part 3:
Methodological and technical aspects

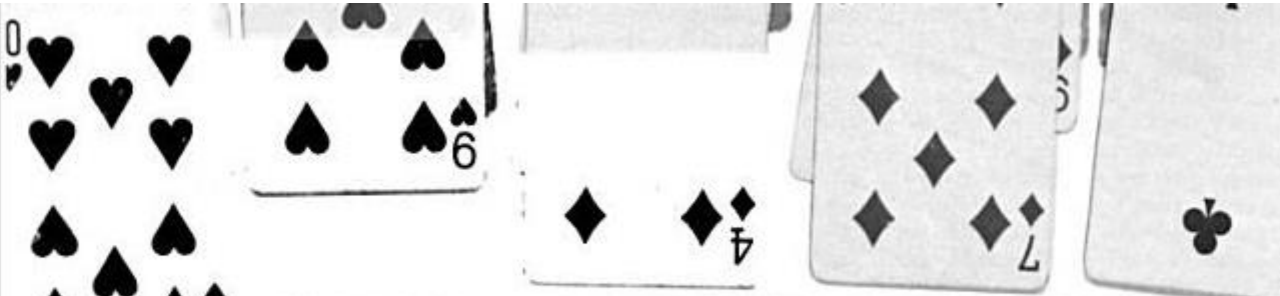
General characteristics of water management problems

- Hydrosystems are **nonlinear** with respect to their dynamics, operation constraints and objectives.
  - **Linear programming** methods are extremely effective but are inappropriate except for simple sub-problems within water management.
- Water management problems **cannot be divided into sequential stages**.
  - The overall reliability and performance cannot be assessed unless a global view is acquired; thus, **dynamic programming** methods are inappropriate.
- Water control problems may involve **many variables**.
  - However, a **parsimonious** representation, in which the number of control variables is kept at a minimum has advantages.
- Typical problems are highly **nonconvex** in terms of objective functions and constraints, so that numerous local optima appear very often.
  - This renders classical (**deterministic**) optimization methods useless.
- **Uncertainty** is always present, albeit often missed to include in modelling.
  - Deterministic methods cannot deal with the uncertainty of future conditions (inflows, demands, etc.); even stochastic extensions of these methods (e.g. linear-quadratic-Gaussian control) necessitate drastic oversimplifications that make the obtained results irrelevant to reality.
- Problems may be **multiobjective** (may involve several performance criteria).

From regularity to the Monte Carlo method

- **Definition** (adapted from Wikipedia): The **Monte Carlo** method is a class of computational algorithms that rely on repeated random sampling to compute their results.
- Note: "**Monte Carlo**" is synonymous to "**stochastic**".
- In other words, the Monte Carlo method is a numerical method which, like other numerical methods, becomes useful when analytical solutions do not exit (that is, almost always...).
- While the Monte Carlo method seems to be a natural choice when the problem studied involves randomness, it is also powerful even for purely deterministic problems.

Stanislaw Ulam, the solitaire and the conception of the Monte Carlo method



STAN ULAM, JOHN VON NEUMANN, *and the* MONTE CARLO METHOD

by Roger Eckhardt

The Monte Carlo method is a statistical sampling technique that over the years has been applied successfully to a vast number of scientific problems. Although the computer codes that implement Monte Carlo have grown ever more sophisticated, the essence of the method is captured in some unpublished remarks Stan made in 1983 about solitaire.

"The first thoughts and attempts I made to practice [the Monte Carlo method] were suggested by a question which occurred to me in 1946 as I was convalescing from an illness and playing solitaires. The question was what are the chances that a Canfield solitaire laid out with 52 cards will come out successfully? After spending a lot of time trying to estimate them by pure combinatorial calculations, I wondered whether a more practical method than "abstract thinking" might not be to lay it out say one hundred times and simply observe and count the number of successful plays. This was already possible to envisage with the beginning of the new era of fast computers, and I immediately thought of problems of neutron diffusion and other questions of mathematical physics, and more generally how to change processes described by certain differential equations into an equivalent form interpretable as a succession of random operations. Later... [in 1946, I] described the idea to John von Neumann and we began to plan actual calculations."

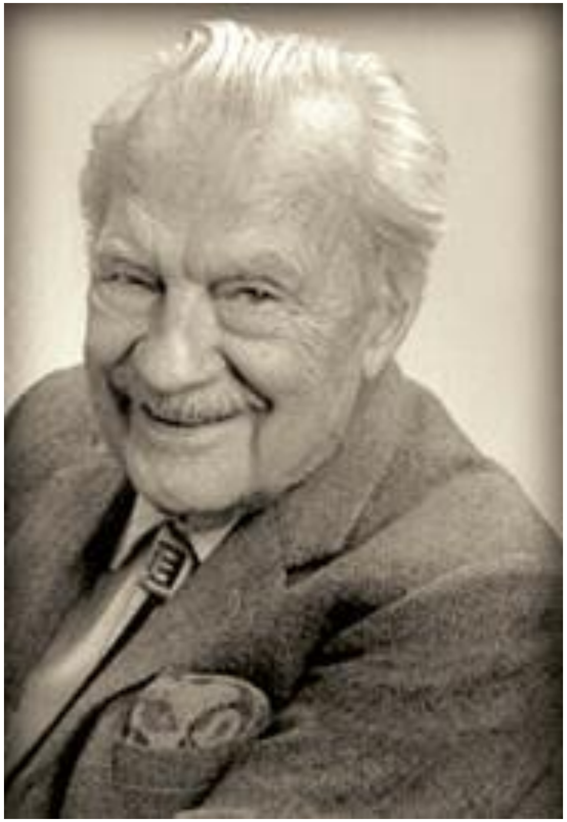
Von Neumann was intrigued. Statistical sampling was already well known in mathematics, but he was taken by the idea of doing such sampling using the newly developed electronic computing techniques. The approach seemed especially suitable for exploring the behavior of neutron chain reactions in fission devices. In particular, neutron multiplication rates could be estimated and used to predict the explosive behavior of the various fission weapons then being designed.

In March of 1947, he wrote to Robert Richtmyer, at that time the Theoretical Division Leader at Los Alamos (Fig. 1). He had concluded that "the statistical approach is very well suited to a digital treatment," and he outlined in some detail how this method could be used to solve neutron diffusion and multiplication problems in fission devices for the case "of 'inert' criticality" (that is, approximated as momentarily static config-

Stanislaw Ulam (13 April 1909 – 13 May 1984): Polish-American mathematician; since 1943 he worked in Los Alamos National Laboratory (Manhattan Project under leadership of Robert Oppenheimer)

Source: Eckhardt (1989)

Nicholas Metropolis and the “birth certificate” of the Monte Carlo method



Nicholas Metropolis (11 June 1915 – 17 October 1999): Greek-American physicist; since April 1943 he worked in the Manhattan Project in Los Alamos

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THE MONTE CARLO METHOD

NICHOLAS METROPOLIS AND S. ULAM

Los Alamos Laboratory

We shall present here the motivation and a general description of a method dealing with a class of problems in mathematical physics. The method is, essentially, a statistical approach to the study of differential equations, or more generally, of integro-differential equations that occur in various branches of the natural sciences.

ALREADY in the nineteenth century a sharp distinction began to appear between two different mathematical methods of treating physical phenomena. Problems involving only a few particles were studied in classical mechanics, through the study of systems of ordinary differential equations. For the description of systems with very many particles, an entirely different technique was used, namely, the method of statistical mechanics. In this latter approach, one does not concentrate on the individual particles but studies the properties of *sets of particles*. In pure mathematics an intensive study of the properties of

Integration: Classical numerical method

- In the numerical integration of a function *f* of a scalar variable *u*, a definite integral is approximated by the relationship (known as the trapezoidal rule)

$$\int_0^1 f(u)\, du \approx \sum_{n=0}^{m} w_n f\left(\frac{n}{m}\right)$$

where *m* is a positive integer and w_n denotes a weight, equal to 1 / 2*m* for the endpoints *n* = 0 and *n* = *m*, and equal to 1 / *m* for all intermediate *n*.

- Likewise, in the numerical integration of a function of a vector variable of size *s* in the space $I^s := [0, 1]^s$, the relationship becomes

$$\int_{I^s} f(\mathbf{u})\, d\mathbf{u} \approx \sum_{n_1=0}^{m} \dots \sum_{n_s=0}^{m} w_{n_1} \dots w_{n_s} f\left(\frac{n_1}{m}, \dots, \frac{n_s}{m}\right)$$

- The computational nodes form a rectangular grid with equidistance 1/*m*.
- Their number is $N = (m + 1)^s$ and the computational error is $O(m^{-2}) = O(N^{-2/s})$.
- Consequently, for a specified acceptable error, *N* increases exponentially with *s* (**curse of dimensionality**).

Integration: The Monte Carlo method

- In the Monte Carlo integration, the N points for the evaluation of $f(u)$ are taken at random (rather than at the nodes of a grid) and the weight is $1/N$, so that (Niederreiter, 1992)

$$\int_{I^s} f(\boldsymbol{u})\, d\boldsymbol{u} \approx \frac{1}{N} \sum_{n=1}^{N} f(\boldsymbol{x}_n)$$

  where $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_N$ are independent random points over the space I^s.

- For an arbitrary integration space B the relationship becomes

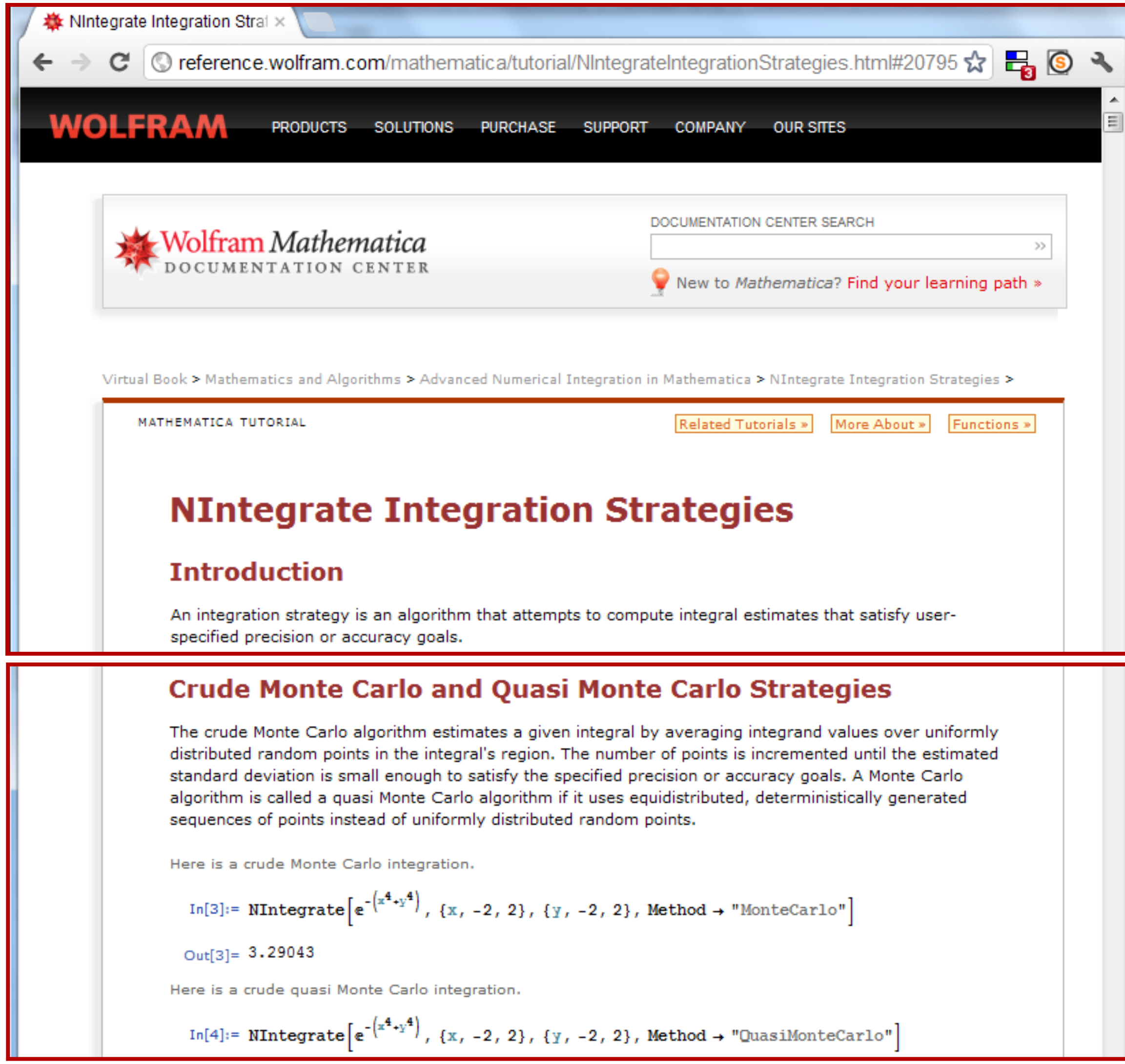
$$\int_{B} f(\boldsymbol{u})\, d\boldsymbol{u} \approx \frac{1}{N} \sum_{n=1}^{N} f(\boldsymbol{x}_n)\, U_B(\boldsymbol{x}_n)$$

  where $U_{\mathrm{B}}(\mathbf{x}_n) = 1$ if $\mathbf{x}_n \in B$ while $U_{\mathrm{B}}(\mathbf{x}_n) = 0$ if $\mathbf{x}_n \notin B$; according to a classical statistical law, the computational error is $O(N^{-1/2})$.

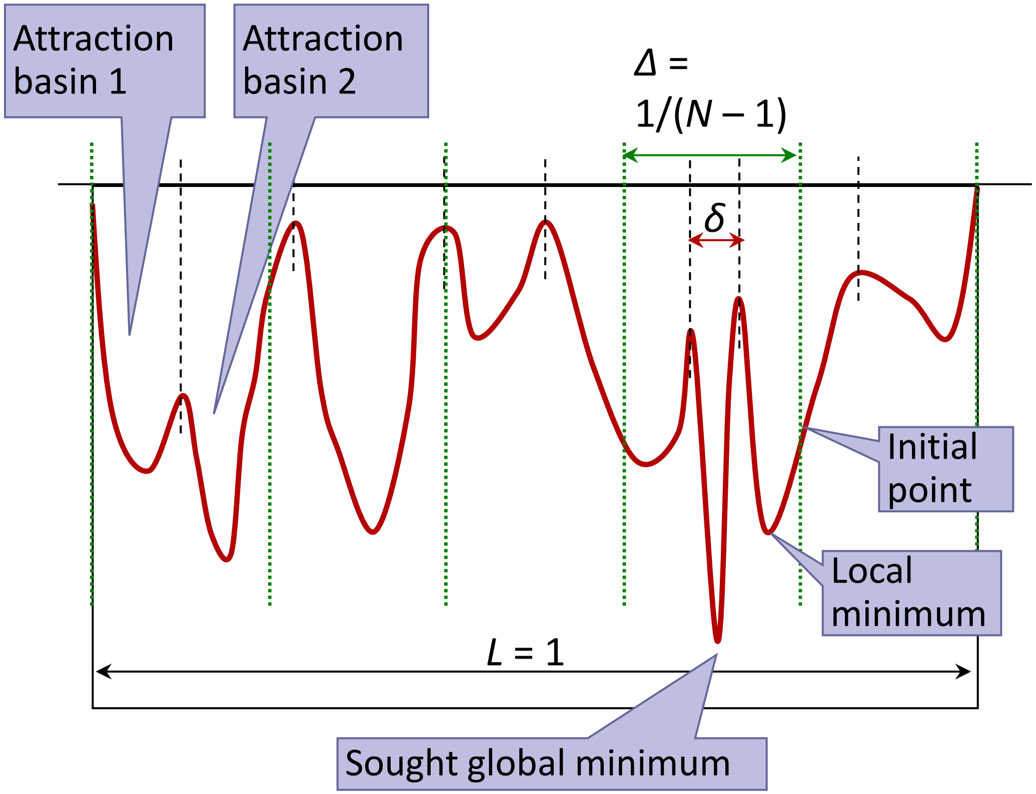
- **Observation**: The error **does not depend on the dimensionality** s.
- **Conclusion**: Comparing the errors of the classical and Monte Carlo methods, we readily obtain that the latter is preferable when the dimensionality $s > 4$.
- **Remark**: For large dimensionality s, e.g. > 20, the classical method is infeasible while the Monte Carlo is always feasible.

The Monte Carlo method is part of routine numerical modelling

- The screen on the right shows how the *Mathematica* software implements various versions of the Monte Carlo method for numerical integration.
- This is not just an additional option within a repertoire of available options; for high-dimensional spaces it is the only possibility.



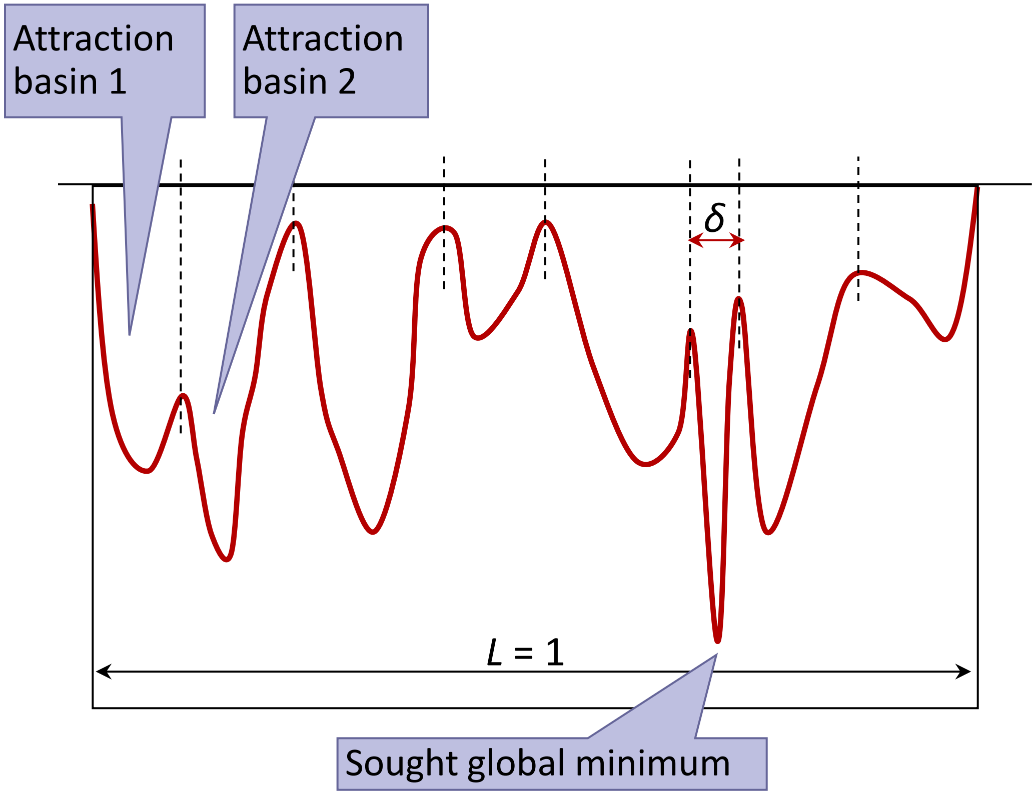
Typical optimization of a scalar function of a scalar variable: deterministic approach



With the chosen $\Delta > \delta$, the global minimum will not be found.

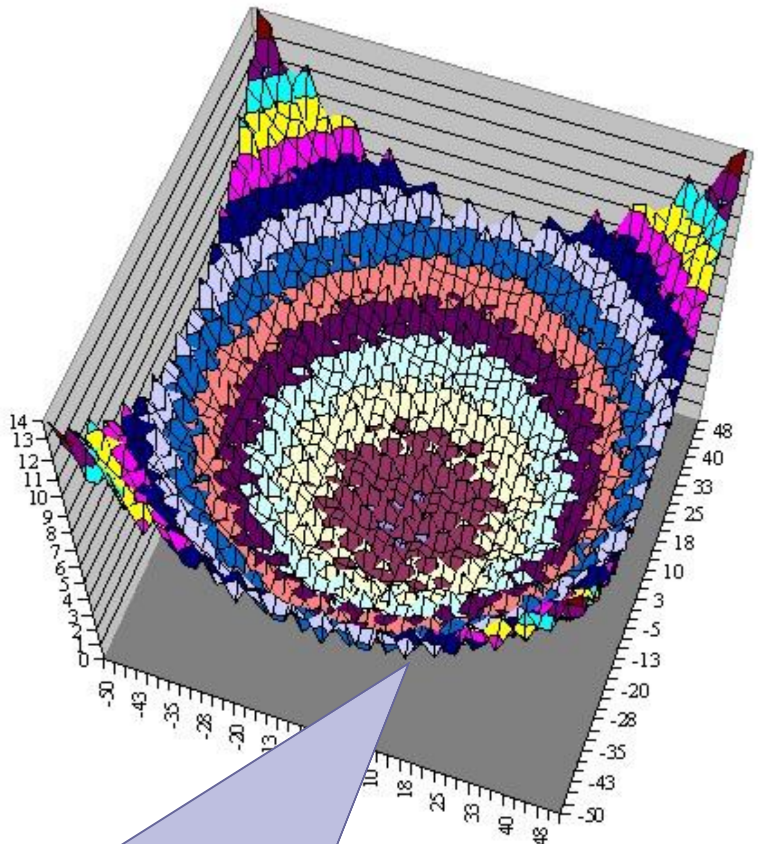
- **Assumption**: We have an effective deterministic local search algorithm (e.g. parabolic interpolation) that, starting from an initial point, will determine the local minimum located in the corresponding attraction basin.
- **Strategy**: We determine the global minimum using a multistart search, starting from a set of N initial points at equidistance Δ along the axis.
- **Conclusion**: We will locate the global minimum if $\Delta \le \delta$.
- Hence, $N_{min} \approx 1/\delta$.

Typical optimization of a scalar function of a scalar variable: stochastic (Monte Carlo) approach



- **Assumption**: The same as in the deterministic approach.
- **Strategy**: We try a number N of initial points chosen at random.
- **Conclusion**: The probability to locate the minimum with one trial is $1/\delta$; the probability to find it starting from N initial points chosen at random is $p_\varepsilon = 1 - (1 - \delta)^N \approx 1 - e^{-\delta N}$
- Hence, even with a few points, there is a possibility (not certainty) to find the minimum.

Optimization of a scalar function of a vector variable

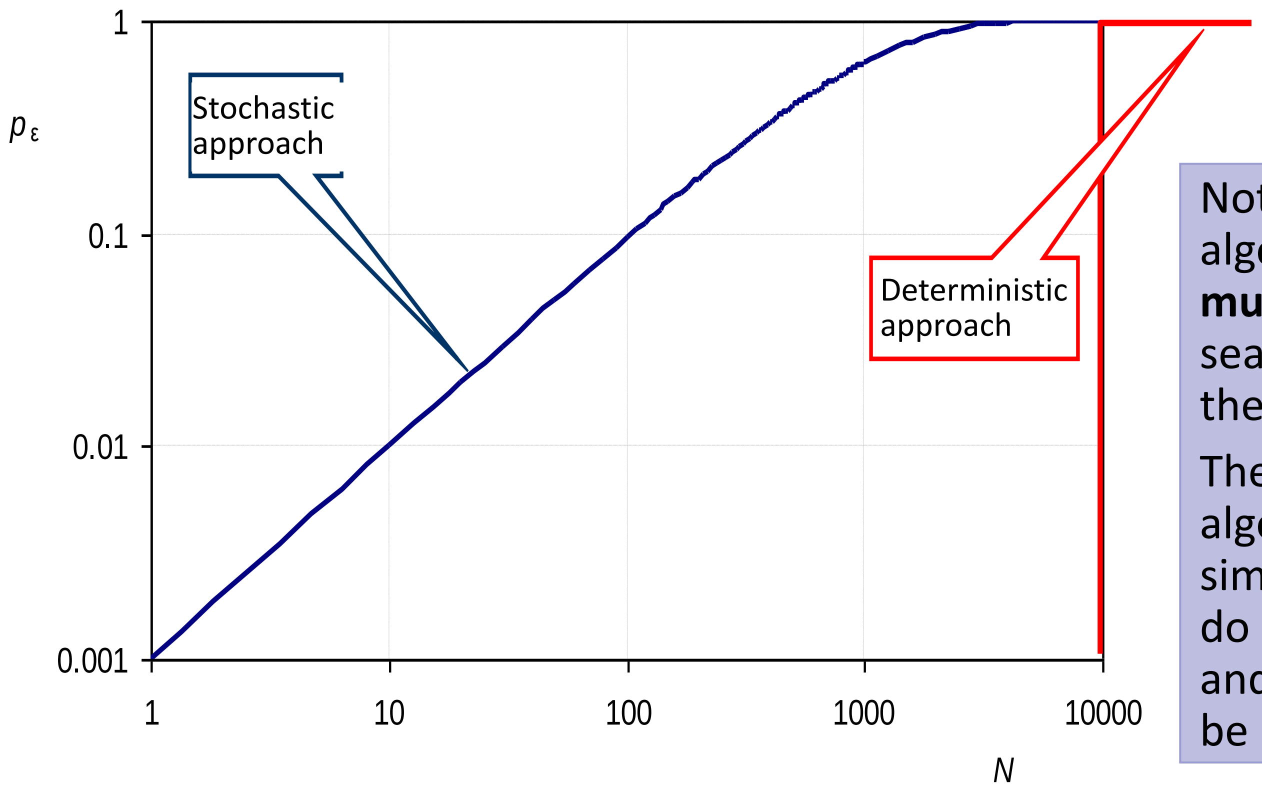


An example: the Griewank function for $n = 2$
$f(x_1, x_2, \ldots, x_n) = (x_1^2 + x_2^2 + \ldots + x_n^2)/400 - \cos(x_1/\sqrt{1}) \cos(x_2/\sqrt{2}) \ldots \cos(x_n/\sqrt{n}) + 1$

- If the attraction basin at a manifold of dimension s (= size of vector variable) has characteristics lengths per dimension $\delta_1, \delta_2, \ldots, \delta_s$, with volume $\alpha = \delta_1\, \delta_2 \ldots \delta_s$, then:
- According to the deterministic approach (initial points at a grid), the global minimum will be found only if $N_{\min} \approx 1/(\min_i \delta_i)^s$.
- According to the Monte Carlo approach, where the initial points are chosen at random, there is always a non-zero probability to find the minimum, equal to $p_\varepsilon = 1 - (1 - \alpha)^N \approx 1 - e^{-\alpha N}$
- Note that δ_i and α are not known a priori.

A comparison of the deterministic and stochastic (Monte Carlo) approaches: a numerical example

- We assume a 2D optimization problem with a hypothetical attraction basin $\alpha = \delta_1\, \delta_2 = (1/10)\,(1/100) = 1/1000$
- Deterministic approach: $N_{min} \approx 1/\,(1/100)^2 = 10\,000$.
- Stochastic (Monte Carlo) approach $p_\varepsilon = 1 - (1 - 1/1000)^N \approx 1 - e^{-N/1000}$.

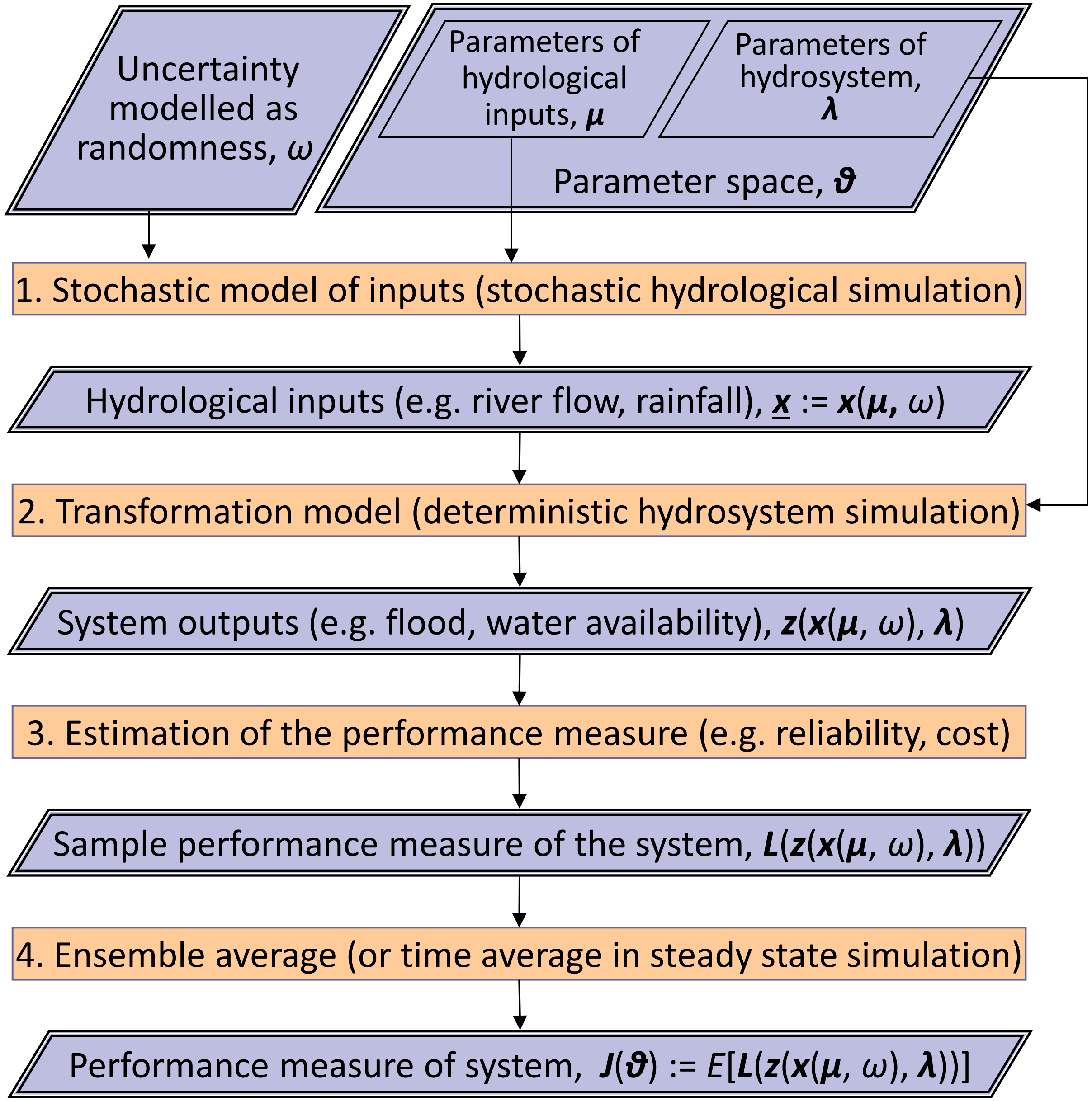


Note: This type of stochastic algorithm is known as a **multistart** algorithm (local search algorithm separate of the global strategy)

There exist other stochastic algorithms (evolutionary, simulated annealing) that do not separate the local and global search and may be more efficient

A general methodological scheme for water management

- Mathematically, water engineering and management problems include two sub-problems:
- An **integration** problem to find the performance measure of the hydrosystem, $J(\boldsymbol{\mu}, \boldsymbol{\lambda}) = E[\boldsymbol{L}(\boldsymbol{z}(\boldsymbol{x}(\boldsymbol{\mu}, \omega), \boldsymbol{\lambda}))]$ Note: expectation means integration.
- A constrained **optimization** problem, in which we seek the hydrosystem operation parameters $\boldsymbol{\lambda}$ that optimize the performance $J(\boldsymbol{\mu}, \boldsymbol{\lambda})$.
- For both sub-problems the Monte Carlo method offers a feasible and consistent solution.



Source: Koutsoyiannis and Economou, 2003

An example in reservoir sizing: (1) “Textbook” methodology (for kindergarten...)

- The problem is stated as follows: If i_t denotes the inflow to a reservoir for time t = 1, 2, …, n, where n is a control horizon, we wish to find the smallest reservoir storage capacity, λ, that sustains a steady state release d.
- Sadly, the textbooks still provide an inconsistent deterministic methodology not differing from the original **Ripple (1883)** ‘mass-curve’ technique.
- Subsequent tabulated versions of the method, e.g. the sequent-peak technique (**Thomas and Burden, 1963)** are equally misleading.
- Other versions of the method that use synthetic, instead of historical, time series (**Schultz, 1976)** do not make any difference, as long as they do not make consistent use of **probability** and the notion or **reliability.**

- **Reliability**, i.e. the probability that the system will perform the required function (Koutsoyiannis, 2005), was introduced by **Hazen (1914).**
- Ironically, while Hazen was American, the Americans did not embrace the notion of reliability.
- It was the Soviet engineering community (**Kritskiy and Menkel, 1935, 1940; Savarenskiy, 1940; Pleshkov, 1939**) which advanced Hazen’s idea.
- For a history of the developments on this problem see **Klemes** (1987).

Reservoir sizing method 2: Linear programming solution (for elementary school...)

- There exists a linear programming formulation (ReVelle, 1999, p. 5), i.e.:

$$
\begin{array}{lll}
\text{minimize} & \lambda & \\
\text{s.t.} & s_t = s_{t-1} + i_t - d - w_t, & t = 1, 2, \ldots, n \\
& s_t \le \lambda, & t = 1, 2, \ldots, n \\
& s_n \ge s_0 & \\
& s_t, w_t, \lambda, d \ge 0, & t = 1, 2, \ldots, n
\end{array}
$$

  where s_t and w_t is the reservoir storage and spill, respectively, at time t.
- While the actual control variable is only one (the reservoir size λ) this formulation uses a number $2n$ of additional control variables, s_t and w_t, as well as a total $3n + 3$ constraints (e.g. for $n = 1000$, we will have 2001 control variables and 3003 constraints); the high dimensionality is not fortunate.
- The tacit assumption is that the future inflows i_t are known.
- This formulation assumes full reliability (a = 100%), which is consistent with the deterministic problem formulation; ReVelle (1999) provides another formulation that can deal with reliability a < 100%, but the logical coherence is questionable (why a < 100% if inflows are deterministic?).
- The method can hardly incorporate nonlinear system components (e.g. leakage or evaporation that are nonlinear functions of storage).

Reservoir sizing 3: Consistent solution (for adults only...)

- The consistent formulation is very simple, elegant and generic:

  minimize $\quad J(\boldsymbol{\mu}, \lambda) = \lambda$

  s.t. $\quad P\{\underline{r}_t = d\} \geq a \qquad$ (alternatively $E[\underline{r}_t]/d \geq a$)

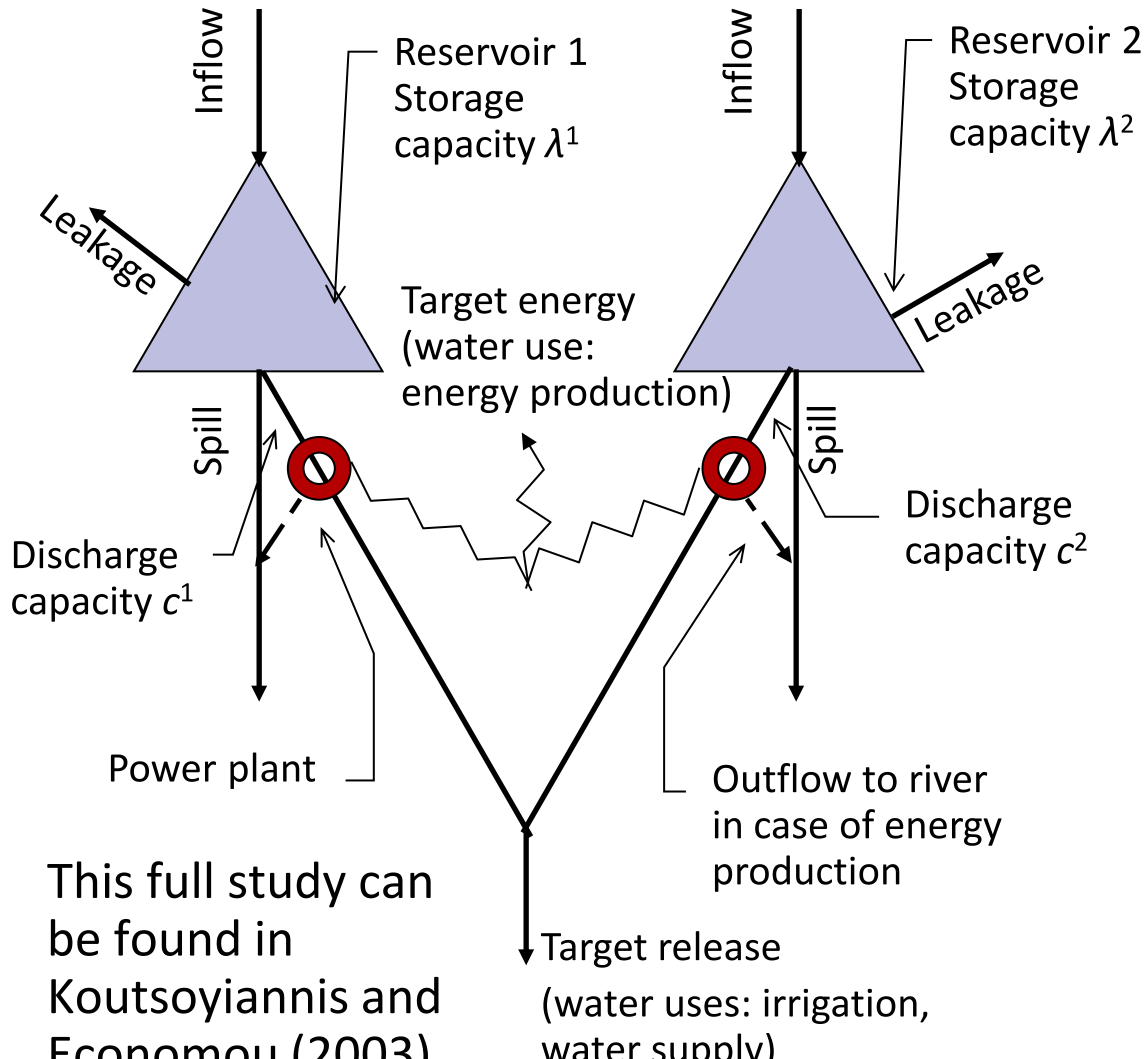
  where λ is the reservoir capacity, $\boldsymbol{\mu}$ is a vector of parameters of hydrological inflows, J is the performance measure to be minimized (here equal to λ), $P\{\ \}$ denotes probability, a is the acceptable reliability and $\underline{r}_t$ and $\underline{s}_t$ are the reservoir release and storage, respectively, at time t, treated as random variables and deterministically related to inflows $\underline{i}_t$ via the system dynamics, i.e.,

  $$\underline{r}_t = \min(d, \underline{s}_{t-1} + \underline{i}_t), \quad \underline{s}_t = \min(\lambda, \max(0, \underline{s}_{t-1} + \underline{i}_t - d))$$

- Here we have only one control variable and one constraint.
- The performance measure depends not on the inputs $\underline{i}_t$ but on the parameters thereof, $\boldsymbol{\mu}$.
- The formulation is highly nonlinear, yet extremely easy to solve (e.g. in a spreadsheet) by Monte Carlo simulation (the integration part refers to the determination of $P\{\underline{r}_t = d\}$ or $E[\underline{r}_t]$).
- Any nonlinear adaptation of dynamics is readily incorporated.

Hypothetical example: System of two reservoirs

- Two reservoirs forming a system that serves a joint objective such as:
- Maximization of release for water supply or irrigation.
- Minimization of cost for water conveyance.
- Maximization of benefit from energy production.



This full study can be found in Koutsoyiannis and Economou (2003)

Hypothetical reservoir system: Study details

- **Tested approach:** The general, doubly Monte-Carlo, methodological scheme.
- **Benchmark procedures:**
  - A high-dimensional perfect foresight method (control variables are the complete series of releases) combined with an evolutionary optimization method.
  - An “equivalent reservoir method”, in which the reservoir system is replaced by one hypothetical reservoir with characteristics merging those of the different reservoirs of the system (it provides an upper bound for the system performance for some of the problems).
- **Simulation scale**: monthly (water supply: 12 months per year; irrigation: 7 months per year).
- **Simulation period**: 16-50 years, depending on the problem examined, so that the total number of control variables in the high dimensional approach be 400 or less (in order for the problem to be tractable using a typical evolutionary solver).

Hypothetical reservoir system: Parsimonious modelling and the PSO approach

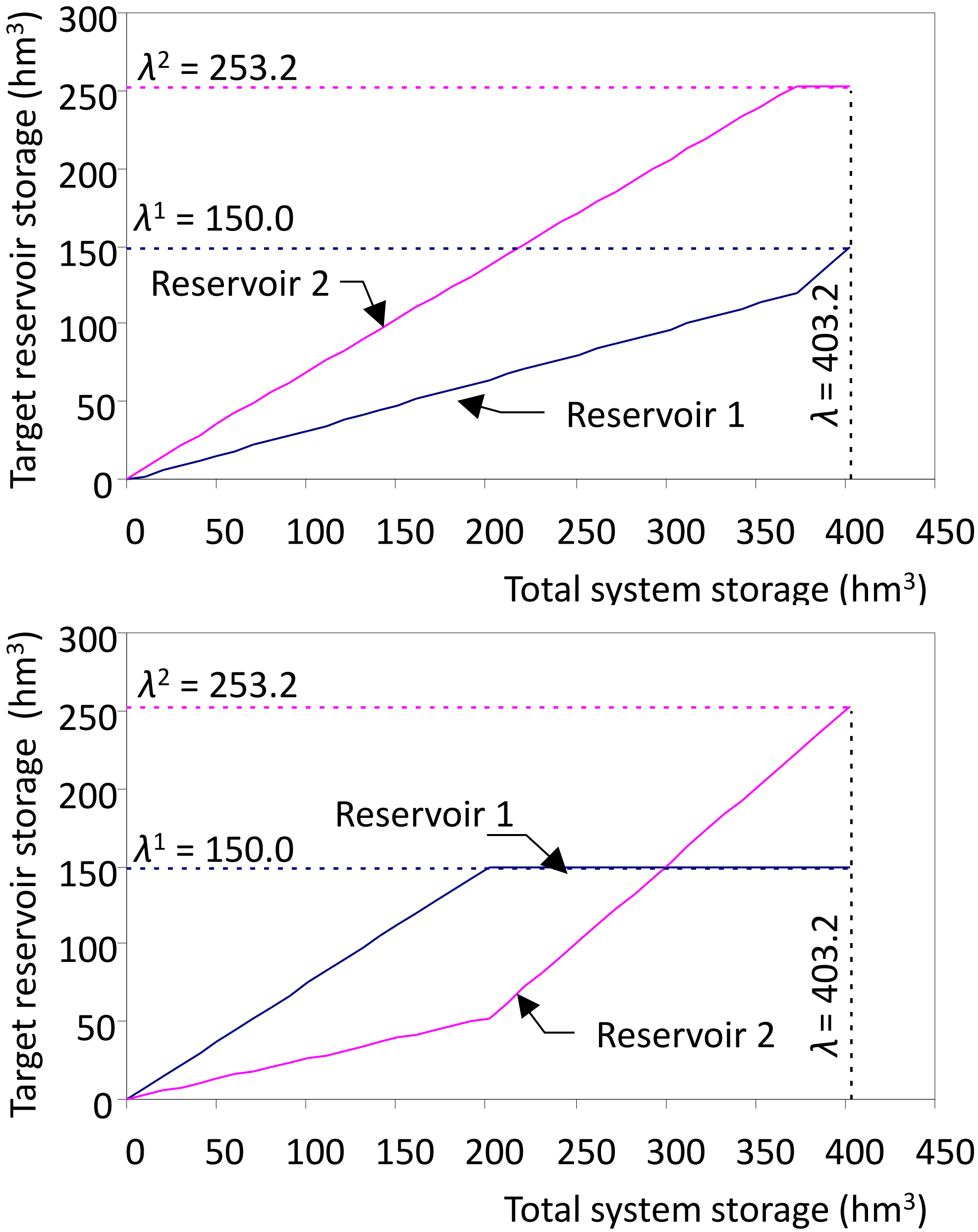
- Referring to a system optimization at a control horizon of 10 years at monthly scale, what is more meaningful result of an optimized system operation e.g. at time step 100 (that is some 8 years from now), for a projected demand of 270 hm^3?
  - **High dimensional approach** (the releases are the control variables): The optimal release from reservoir 1 should be 100 hm^3 and that of reservoir 2 should be 170 hm^3.
  - **Parsimonious approach**: Determine the optimal releases, not now but then, so that the quantities of water stored in each reservoir have some *balance*.
- The latter approach necessitates the use of an operation rule that quantifies what the *balance* is.
- It is reasonable to assume that this quantification should include some parameters, which become the control variables to be determined by the Monte Carlo optimization.
- This gives rise to the so-called **Parameterization-Simulation-Optimization** (PSO) approach.

Hypothetical reservoir system: parameterization

- A simple operation rule can be formulated so as to give the target storage s^j_* of reservoir j as a linear function of the storage capacity of that reservoir, λ^j, and of the system, λ, as well as the total system storage, s, i.e.:

  $$s^j_* = \lambda^j - a^j \lambda + b^j s$$

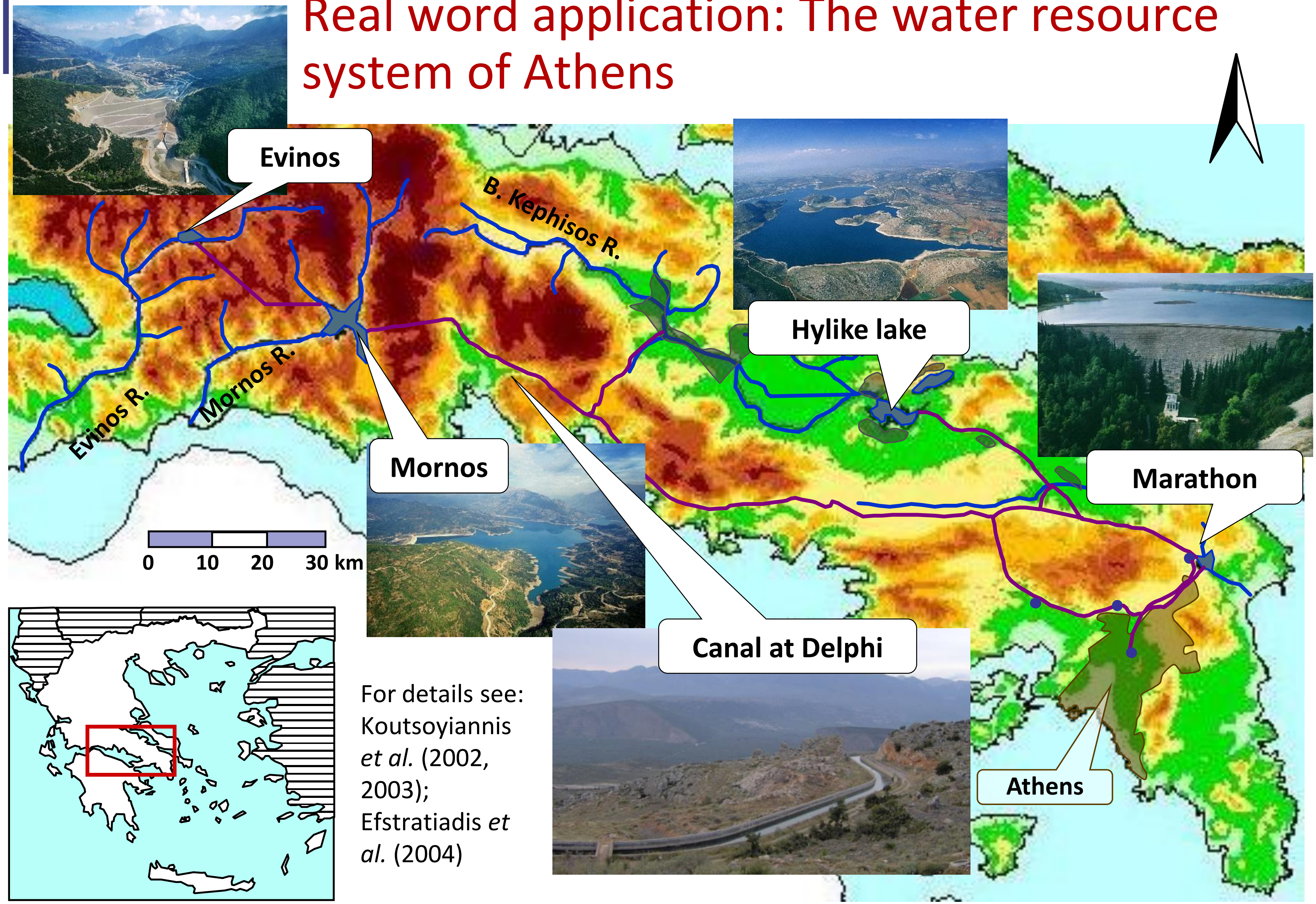
  where a^j and b^j are the parameters to be determined (**2 control variables per reservoir**).
- The linear rule needs some nonlinear adjustments to assure physical consistency (Nalbantis and Koutsoyiannis, 1997).
- The figures exemplify the optimized parametric operating rules for one of the examined problems (upper: rule for the refill period; lower: rule for the drawdown period).



Hypothetical reservoir system: Results from a large family of tests

- **Maximization of reliable release for water supply or irrigation:**
  - The PSO methodology with 5 control variables and zero foresight resulted in practically the same performance as in the perfect foresight method with 351 control variables.
  - Even with 2 control variables the PSO method with zero foresight is very effective as the reduction in performance is only 1.68%.
- **Minimization of cost** (assuming different unit cost to convey water from each reservoir):
  - The results of the PSO with 4 control variables and zero foresight are almost identical to those of the perfect foresight method with 350 variables (irrigation) or 192 variables (water supply).
- **Maximization of benefit from energy production**
  - The reduction in performance of the PSO methodology is no more than 3% with respect to the high dimensional perfect foresight method.
  - Careful inspection showed that the 3% improvement in the high dimensional method is fake as it is associated with the perfect foresight aspect (avoidance of spill by unjustified more intense energy production in earlier months).
- **General conclusion**: The PSO method performs practically as well as benchmark methods, is realistic and has many additional advantages.

Real word application: The water resource system of Athens



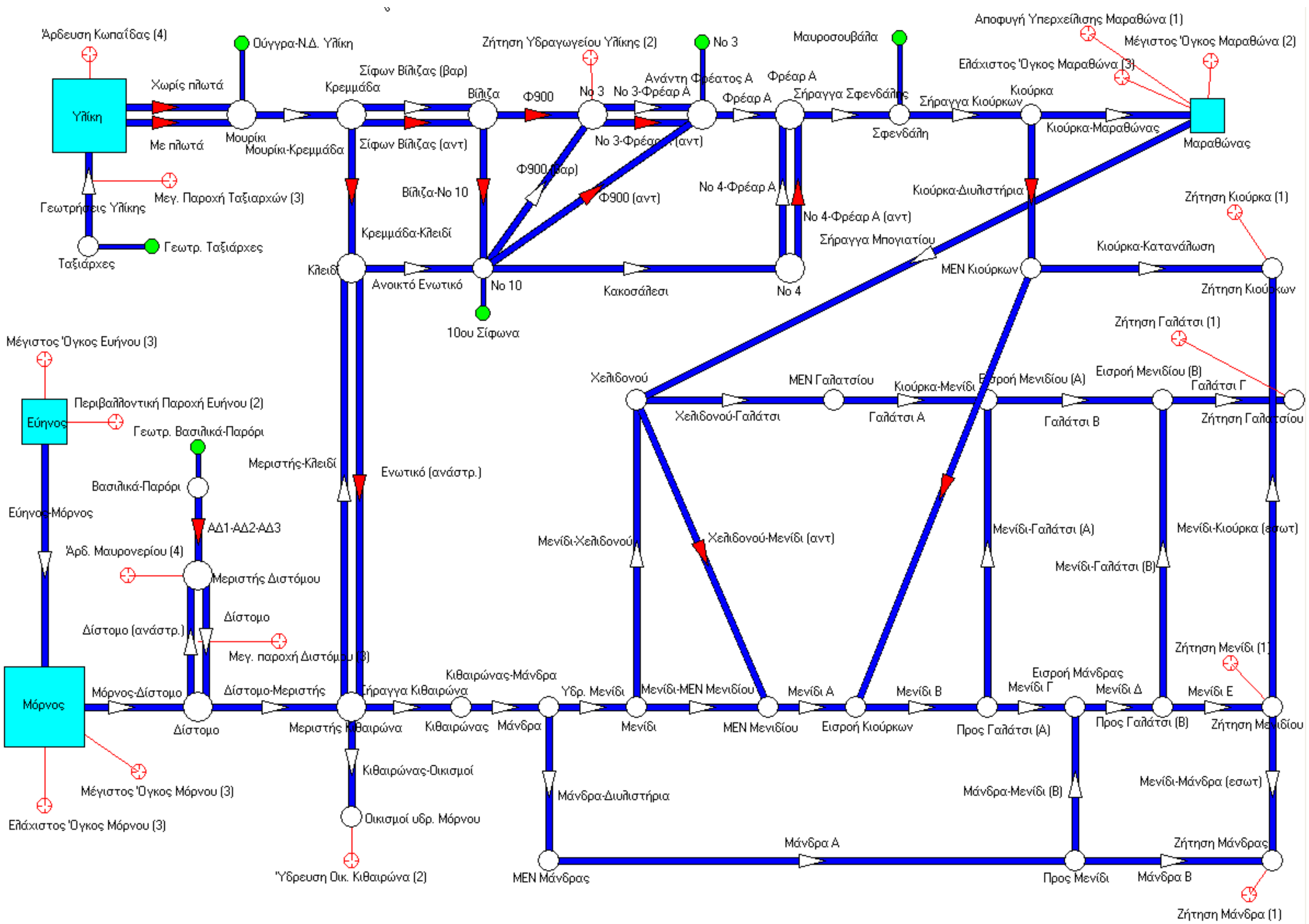
For details see: Koutsoyiannis *et al.* (2002, 2003); Efstratiadis *et al.* (2004)

Real word application: Categories of problems

- Possible objectives:
  - maximum annual reliable release for a certain (acceptable) reliability;
  - minimum total cost for given water demand and reliability.
- Operation mode:
  - Steady state problems for the current hydrosystem.
  - Problems involving time:
    - Availability of water resources in the months to come.
    - Impact of a management practice to the future availability of water resources.
    - Evolution of the operation policy for varying demand.
- Investigation of scenarios:
  - Hydrosystem structure: Impacts of new components (aqueducts, pumping stations etc.).
  - Demand: Feasibility of expansion of domain.
- Adequacy/safety under exceptional events – Required measures:
  - Damages.
  - Special demand occasions (e.g. 2004 Olympic Games).

Real word application: Control variables

We assume a control horizon of 10 years and monthly scale of simulation; the network includes 60 branches.



Number of control variables:

According to a conventional approach:

1 variable/ branch/month × 60 branches × 120 months = 7200.

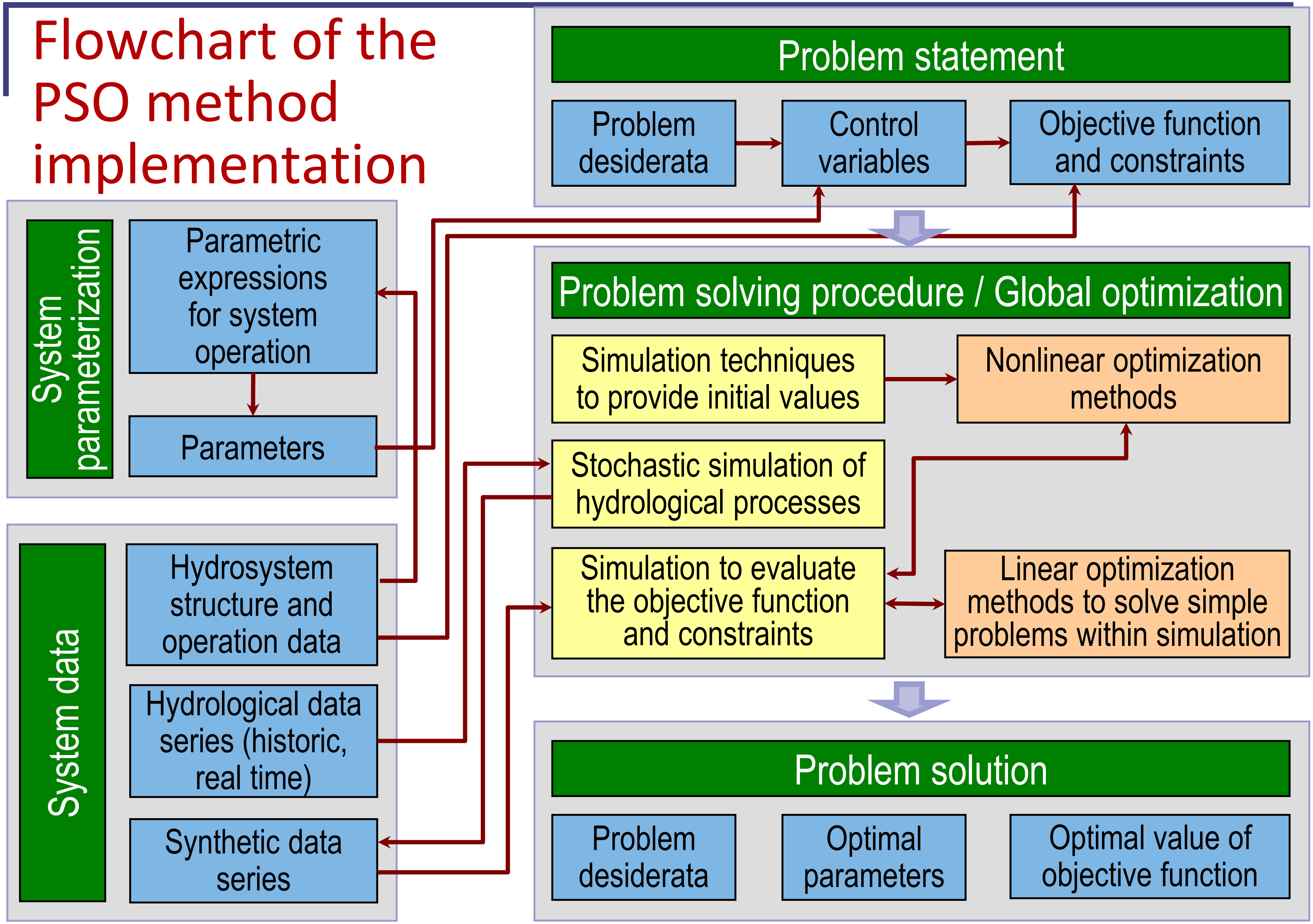
According to the PSO approach:

4 reservoirs × 2 parameters/ reservoir = 8.

Real word application: Simulation and optimization

- Assuming that parameters a_i and b_i of the operation rule are known, the **target releases** from each reservoir will be also known at the beginning of each simulation time step.
- The **actual releases** depend on several attributes of the hydrosystem (physical constraints).
- Their estimation is done using **simulation**.
- Within simulation, an **internal optimization** procedure may be necessary (typically linear, nonparametric).
- Because parameters a_i and b_i are not known, but rather are to be optimized, simulation is driven by an **external optimization** procedure (nonlinear).

Flowchart of the PSO method implementation



Comparison the PSO and classical approaches

Classical approach	Inconsistency	New approach
Input time series are assumed to be known	Water management is made with reference to the future, which is unknown	The **parameters** of a stochastic (Monte Carlo) model of inflows **are known**
Control variables are the controlled water fluxes per time step	This results in inflationary modelling which contravenes the principle of parsimony and is meaningless due to the uncertain future	The **parameterization** approach, in which the control variables are the parameters of operation rules, radically reduces dimensionality
Simplified system representation	Common simplifications (e.g. discretization, avoidance of probabilistic constraints) annuls the optimality of the solutions determined	Faithful system representation and assessment of performance via stochastic (Monte Carlo) **simulation**
Use of simplified optimization methods, such as linear or dynamic programming	Water management problems are highly nonlinear (except some simple sub-problems); dynamic programming is inappropriate	Nonlinear stochastic (Monte Carlo) **optimization**

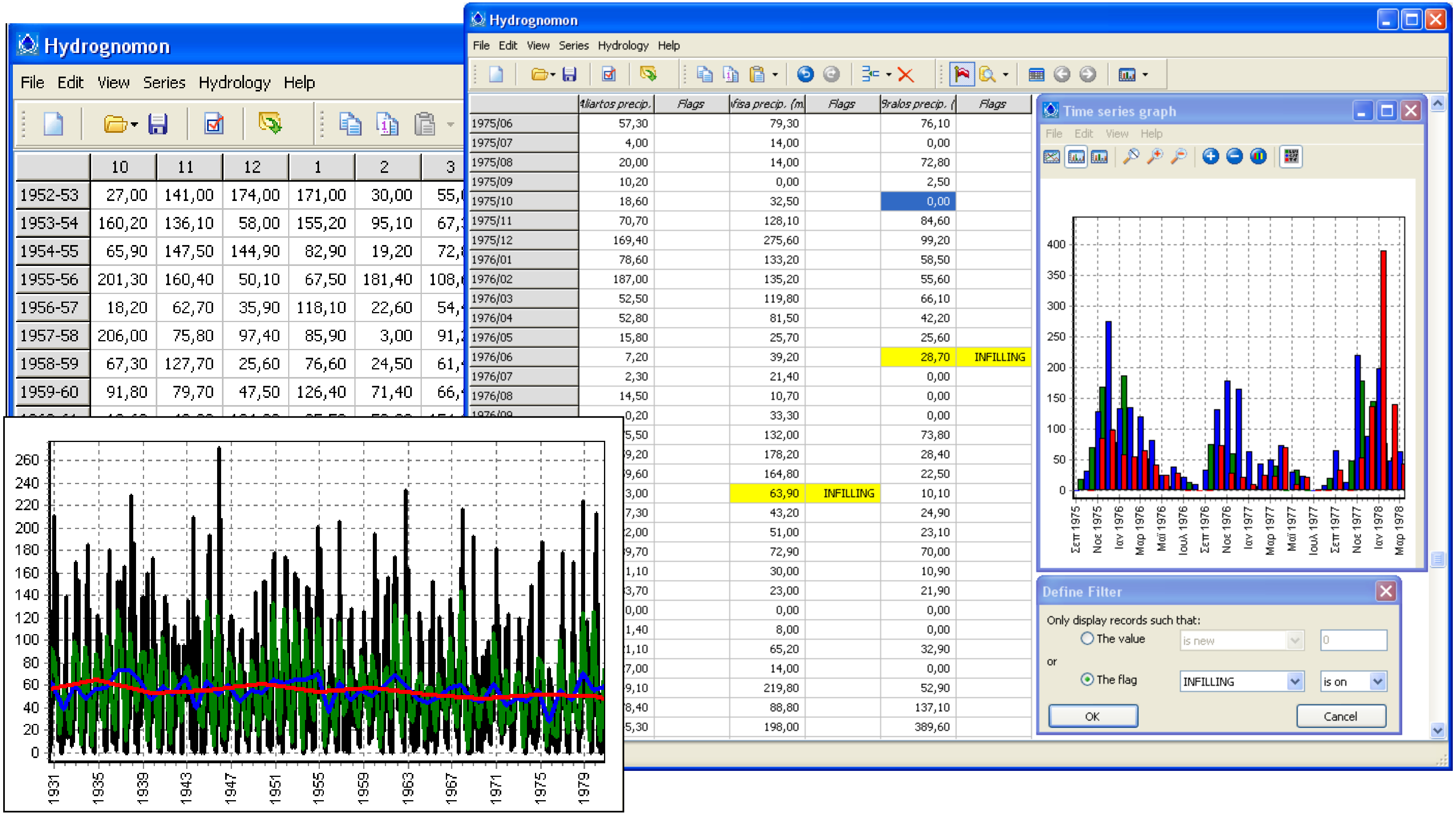
Milestones in the development of the methodology and the software system

Project initiation: 1999.

First master plan of the hydrosystem: Koutsoyiannis *et al.* (2000).

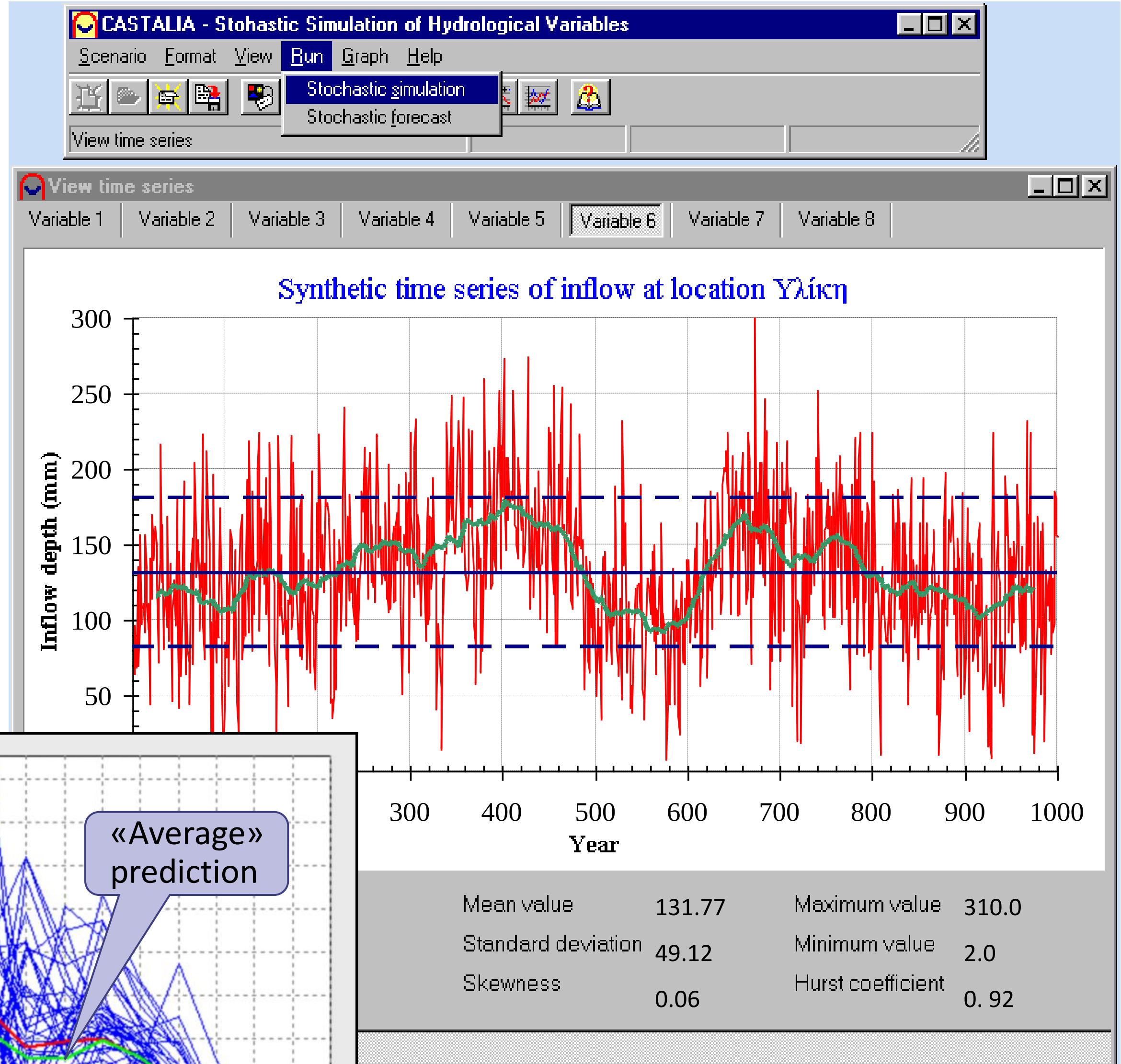
Completion of a decision support tool: Nalbantis *et al.* (2004).

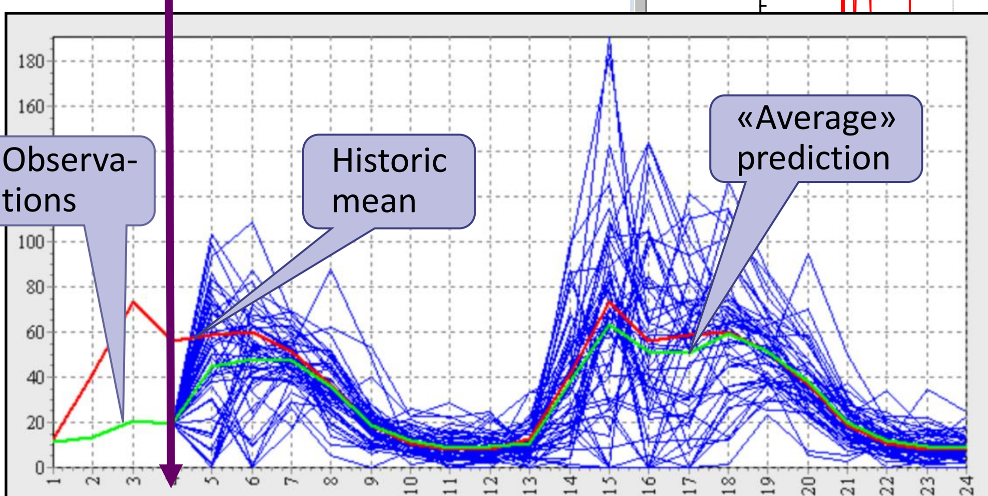
Hydrognomon: Software for the management and processing of hydrological data



All software tools are available online and free; itia.ntua.gr/en/software/

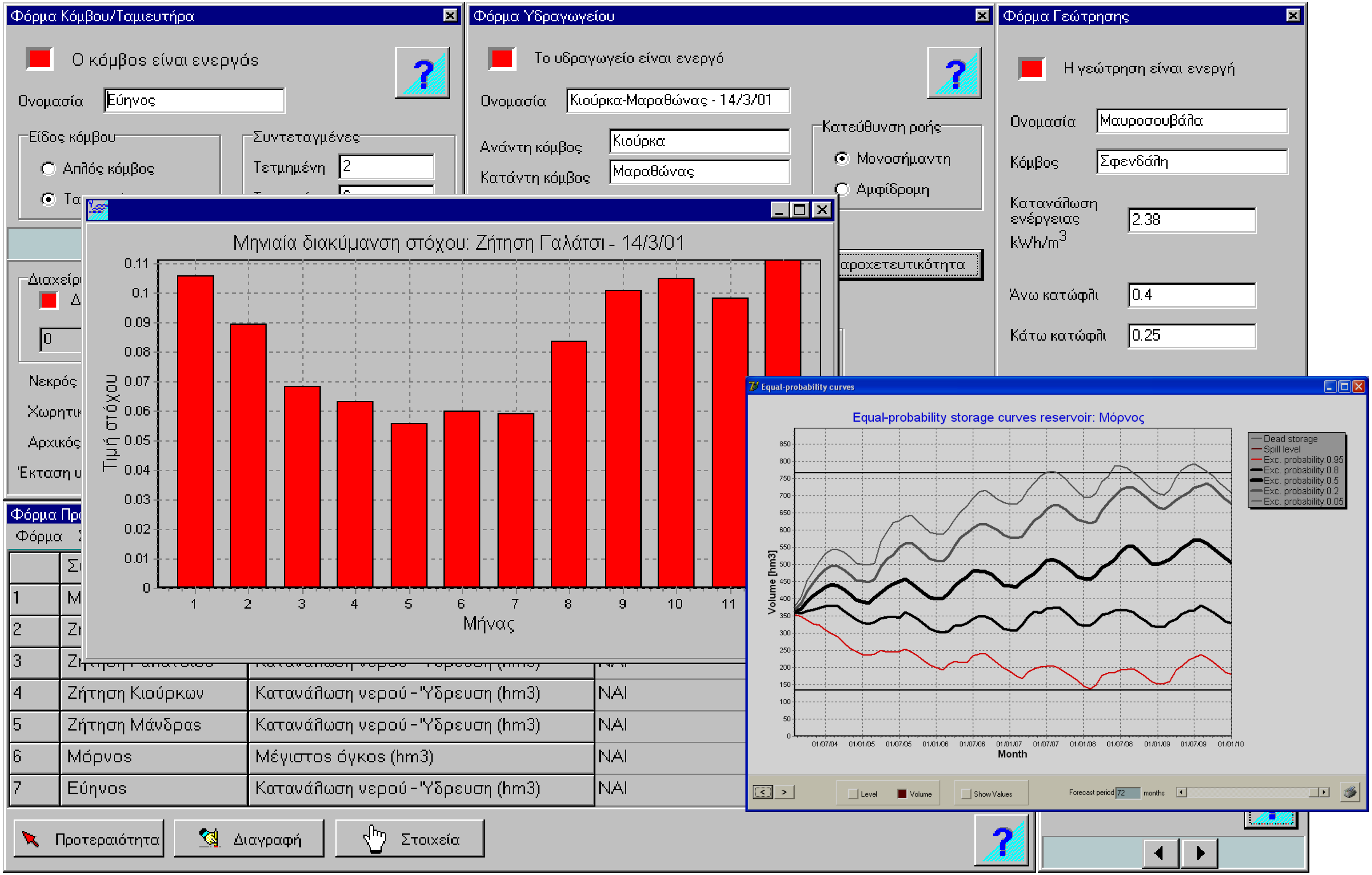
Castalia: Software for the stochastic simulation of hydrological processes





All software tools are available online and free; itia.ntua.gr/en/software/

Hydronomeas: Software for hydrosystem optimization



All software tools are available online and free; itia.ntua.gr/en/software/

Conclusions

- Water infrastructure is necessary in order to address major challenges of the 21st century: Water supply, food security, energy security, protection from natural hazards and environmental recovery.
  - These challenges demand a pragmatic approach based on the specific conditions of each area rather than relying on politico-ideological stereotypes which obscure the real problems.
- Promotion of alleged certainties about the future (e.g. using climate projections based on inadequate climate models) increases the risk.
  - Uncertainty cannot be eliminated but its quantification is possible and can provide a basis for decisions related to planning, design and management of hydrosystems.
- Classical methodologies based on deterministic simulation and optimization approaches are inadequate in water engineering and management.
  - Parsimonious modelling techniques using parameterization of the system operation, combined with stochastic approaches for simulation and optimization, provide effective and easy to apply methodologies for hydrosystems.

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