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**Research proposal (Part B1)**

# WATer pathways towards the non-deterministic future of renewable enERGY

# WATERGY

**Cover Page:**

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- Host institution: National Technical University of Athens
- Proposal title: WATer pathways towards the non-deterministic future of renewable enERGY
- Proposal short name: WATERGY
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Since 1990 extensive funds have been spent on research in climate change. Although Earth Sciences, including climatology and hydrology, have benefited significantly, progress has proved incommensurate with the effort and funds, perhaps because these disciplines were perceived as "tools" subservient to the needs of the climate change agenda rather than autonomous sciences. At the same time, research was misleadingly focused more on the "symptom", i.e. the emission of GHGs, than on the "illness", i.e. the unsustainability of fossil fuel-based energy production. Unless energy saving and use of renewable resources become the norm, there is a real risk of severe socioeconomic crisis in the not-too-distant future. We propose a framework for drastic paradigm change, in which water plays a central role, due to its unique link to all forms of renewable energy, from production (hydro, wave) to storage (for time-varying wind and solar sources), to biofuel production (irrigation). The expanded role of water should be considered in parallel to its other uses, domestic, agricultural and industrial. Hydrology, the science of water on Earth, must move towards this new paradigm by radically rethinking its fundamentals, which are unjustifiably trapped in the 19th-century myths of deterministic theories and the zeal to eliminate uncertainty. Guidance is offered by modern statistical and quantum physics, which reveal the intrinsic character of uncertainty/entropy in nature, thus advancing towards a new understanding and modelling of physical processes, which is central to the effective use of renewable energy and water resources. Our target is to deconstruct pervasive myths in the areas of hydrology and climate and propose a new consistent approach. We will further explore the impact of this new approach on renewable energy and water resources planning and management, and unravel its implications towards a real (in lieu of the current euphemistic) sustainable development.

**Section 1:** *The Principal Investigator*

**1a Scientific Leadership Profile**

I am professor in *Hydrology and Analysis of Hydrosystems* and Head of the *Department of Water Resources and Environmental Engineering* of the National Technical University of Athens. I have created and maintained continuously for almost 25 years, the research team *Itia* (Greek for willow tree – not an acronym), currently comprised of 18, highly qualified, research and academic staff. Past members of the team exceed 30, not counting more than 80 students conducting their graduate and postgraduate theses. Five present or past members of Itia are now academic staff, and two other are postdoctoral researchers. Itia is an open team with collaborators from all continents and has its own *open access* digital library which contains our papers, reports, books, educational notes, software, etc., as well as project data and information (itia.ntua.gr).The mentoring attitude of Itia and the PI has been well known internationally, as testified by the numerous requests for scientific advice by students and young scientists worldwide, as well as by the short course (lectured by the PI) for young researchers organized in the European Geosciences Union General Assembly 2010 (meetingorganizer.copernicus.org/EGU2010/session/3172).

My relationship with the international scientific community was built around my research publications in peer-reviewed journals. My current scientific publishing record (detailed in Itia's digital library) comprises 544 works; 84 of them are publications in peer-reviewed scientific journals, in all of which except two I am the only author or a senior author. The bibliometric data for my publications, which give an indication of the impact of my studies, are shown in the following table (as of 2011-01-31):

| Source | # registered publications | # cited publications | # citations | H-index |
|---|---|---|---|---|
| Google Scholar | 323 | 175 | 1801 | 24 |
| Web of Science/Cited Ref. Search | 136 | 136 | 973 | 19 |
| Web of Science/Standard Search | 65 | 57 | 808 | 19 |
| Scopus | 83 | 69 | 992 | 20 |
| Scopus, excl. self-citations | 83 | 66 | 766 | 16 |
| Itia's data base, excl. self-citations | 544 | 139 | 1210 | 20 |

About 55% of these citations were received in the last three years, i.e. after the submission of my previous unsuccessful proposal to ERC (see section 1b). Bibliometric data highly depend on the scientific discipline and therefore have a relative (in comparison to peers) rather than absolute value. Data for comparison within the field of hydrology have been analyzed by Koutsoyiannis and Kundzewicz (2007) based on the citation records of 27 laureates of the International Hydrological Prize; the average h-index, among the laureates, in the last decade is ~10, which shows that my own metrics given in the table above are high. Some of the citations to my work originate from other disciplines, including mathematics, physics, astronomy, operations research, economics and archaeology. Diffusion of my works is exemplified by Google searches by such keywords as 'statistical hydrology', 'statistical climatology', 'ancient Greece engineering', 'Hurst phenomenon', 'fractional Gaussian noise', 'climate models credibility', 'rainfall disaggregation', which bring up several of my works as hits (rank 1-5) among tens of thousands to million entries.

My contribution to the scientific community is also reflected in my 433 reviews and/or editing of articles submitted to 41 different scientific journals. Since 1998, all my reviews are eponymous and since 2004 I am actively promoting the idea of eponymous reviewing. In recognition, I have been appointed as Co-Editor of *Hydrological Sciences Journal*; member of the editorial board of *Hydrology and Earth System Sciences*; and formerly of *Journal of Hydrology* and *Water Resources Research*. All journals I served are top journals in the field of hydrology and water resources, with highest impact factors.

Furthermore, I have been awarded the *Henry Darcy Medal* 2009 by the European Geosciences Union (EGU) for outstanding contributions to the study of hydrometeorological variability and to water resources management. I have been chairman of the *Sub-Division on Precipitation & Climate* of the *Division on Hydrological Sciences* of the EGU (2006-2010). I am Union Plenary Speaker of the IUGG 2011 (Melbourne, Australia) and have been an invited speaker in 22 conferences and workshops. I have contributed in the organization of 49 scientific conferences and workshops.

The ground-breaking character of my research is summarized in the EGU statement for my awarding (www.egu.eu/awards-medals/awards-and-medals/award/henry-darcy/demetris-koutsoyiannis.html): "... *Koutsoyiannis has focused his career on strengthening the foundations of stochastic hydrology, often by courageously tearing down flawed ideas and rebuilding sections of the discipline anew*."

**1b Curriculum Vitae**

| | |
|---|---|
| Name: | Demetris Koutsoyiannis |
| Nationality; Birth info: | Greek; Village of Mesounta, Epirus, Greece, 27 April 1955 |
| Professional Certification: | Civil Engineer (1978), Dr. Engineer (1988) |
| Employment: | Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens (NTUA) |
| Position: | Professor, Hydrology and Analysis of Hydrosystems (since 2008) |
| Other national positions: | Professor of hydraulics in the Hellenic Army's Postgraduate School of Technical Education of Officers Engineers (2007-10)<br>Board of Directors of the Organization for the Management and Restoration of the Kephisos River and its Tributaries (2003-10) |
| International positions: | Co-Editor, *Hydrological Sciences Journal* (since 2009; Deputy Editor since 2006; Associate Editor in 2003-06)<br>Editor, *Hydrology and Earth System Sciences* (since 2007)<br>Associate Editor, *Water Resources Research* (2007-09) and *Journal of Hydrology* (2000-08)<br>Chair, *Precipitation and Climate* of *Hydrological Sciences Division* in the *European Geosciences Union* (2006-10) |
| Academic visitor: | Imperial College, London (1999-2000), Hydrologic Research Center, San Diego (2005), Georgia Tech (2005-06), University of Bologna (2006), University of Rome "Sapienza" (2008). |

My birthplace, a small village in Epirus, where I lived in a traditional agrarian state, up to the age of 12 (1955-1967) and completed the elementary school, offered me important knowledge that I would lack had I been born in a city, and that is the compass of my work even to this day. Being constantly in touch with water, abundant in Epirus, helped me understand *hydraulic and hydrological behaviours*. I realized the importance of *water quality* by the fact that not all of this abundant water was good to drink. In fact, as a child I had an everyday duty to bring drinking water from the nearest (1 km) spring to my house. As my family run a traditional water mill, I had the chance to actively engage *hydropower* and understand the energy transformation from potential to kinetic and production of work. I also acquired an experiential feeling of what today we would call *sustainable use of resources*: full recycling of material sources (zero waste production), and minimal use of energy in agriculture and transportation (animal power), heating (wood) and lighting (oil—no electricity).

From the years of my study in the high school in Athens (10th public Gymnasium of Athens, 1967-1973) I learned the value of adapting to new environments and of taking responsibility for my actions (because I lived on my own since 1970). This allowed me to unfold and develop my skills, and achieve top performance in school. One of the most remarkable things of this period was the contrast between, on one hand, reason, ethical virtues, freedom, democracy, participation, that were taught in school based on classical Greek texts and, on the other hand, the irrationality of a tough military dictatorship in power in Greece at the time, which, unfortunately, relied on the tolerance of a scared public majority.

In my first month (Nov. 1973) in the university (School of Civil Engineering, NTUA, 1973-78) I participated in the uprising against the dictatorship. After three days of occupation of the university quarters, I found myself opposite to a tank that invaded the university to suppress the uprising. This was a valuable lesson on the importance and worthiness of overcoming fears and resisting against irrationality—and that such a struggle can be effective as this uprising was the first step to overthrow Greece's dictatorship a few months later. Thus, I continued my studies in a free university. I received state scholarships for top performance throughout the years of my university studies. I followed the hydraulic engineering option (which I found natural due to my early familiarity with water and its flow) and received my Diploma in 1978, graduating top of my class among more than 300 students, with 3 university and state awards for high achievements.

I then started my career in engineering as a consultant for private constructions as well as in hydrological, structural and surveying engineering projects. I was a founding member of three engineering companies (Polytechnike Co., METER Ltd, BIOMETER Ltd) but left them five years later to dedicate myself to academia, which I had never left since I maintained a part time employment as a research assistant even during my years in industry. On the other hand, I never lost touch with industry and I still participate as a consultant in hydrologic and water resources engineering projects. I participated in more than 60 engineering studies, 12 of which on hydrologic design of dams throughout Greece (for hydropower, water supply and irrigation)—notably two concern the Athens and the Acheloos-Thessaly hydrosystems, the most important ones of Greece.

I studied for my PhD in the same School (1983-88; advisor Th. Xanthopoulos, later Rector of NTUA and Vice Minister for Public Works). While working on my thesis ("*A disaggregation model of point rainfall*") I studied probability and stochastic processes and realized their power in better understanding natural behaviours and constructing mathematical models of natural processes. I also gained expertise in computer programming. My PhD work continued uninterrupted throughout my 25-month military service (seaman in the Hellenic Navy, 1984-86) and I received my PhD in 1988.

My academic employment includes my positions as lecturer (1990-95), assistant professor (1995-2003), associate professor (2003-2008) and then professor in the Department of Water Resources and Environmental Engineering of NTUA. I have taught undergraduate courses in *Engineering hydrology*, *Stochastic methods in water resources*, *Urban hydraulic works* and *Sediment transport*, and postgraduate courses in *Hydrometeorology*, *Advanced hydrology*, *Water resource systems optimization* and *Water resource management*. I have supervised 87 diploma and postgraduate theses and 9 doctoral theses.

I have gained a reputation in the water sector in Greece as someone who is able to solve real-world problems using advanced scientific methods. My reputation is also enhanced by my numerous former students, who have appreciated the effort and time I invest diffusing knowledge and in creating and keeping my courses up to date. This reputation encouraged generous funding from Greek authorities, including the *General Secretariat of Research and Technology – GSRT* (Hydroscope: Creation of a National Databank for Hydrological and Meteorological Information, 1992-93, 1.60 M€; Odysseus: Integrated Management of Hydrosystems in Conjunction with an Advanced Information System, 2003-06, 0.81 M€; Deukalion – Assessment of flood flows in Greece under conditions of hydroclimatic variability: Development of physically-established conceptual-probabilistic framework and computational tools, 2011-13, 0.145 M€—my only current grant), the *Ministry of Environment, Planning and Public Works – MEPPW* (Evaluation of Management of the Water Resources of Sterea Hellas, Phases 1,2,3, 1990-2000, 1.18 M€) and the *Water Supply and Sewerage Company of Athens – EYDAP* (Modernization of the Supervision and Management of the Water Resource System of Athens, 1999-2003, 0.71 M€). I also undertook a number of smaller projects from these or other authorities, some of which, despite their small budget, were scientifically stimulating (e.g., *Support on the Compilation of the National Programme for Water Resources Management and Preservation*, *MEPPW*, 2007-08, 0.05 M€). These projects (17, amounting to a total budget of 3.44 M€, not including 28 projects in which I participated with a role other than project leader) aimed to solve demanding real-life problems (e.g. the management of the Athens water supply system in view of the Athens 2004 Olympics) and produce operational software tools. All projects were concluded successfully and their practical objectives were fulfilled. At the same time, I was able to perform scientific generalization, extension, abstract representation and ground-breaking in-depth penetration, and produce high quality research papers motivated by practical problems. Several of these papers study fundamental scientific questions and include elements beyond the state of the art (section 1c), even though they were outcomes of applied research projects or in some cases results of unfunded research and independent academic activity.

Most of these national projects (those by GSRT and EYDAP) were co-funded by the EU. Earlier, I had an experience with EU research in an EPOCH project (*AFORISM, A comprehensive forecasting system for flood risk mitigation and control*, 1991-94), of which I was the key investigator for the Greek team (budget 0.08 M€). At the international level, I also participated in two UK projects (in collaboration with Imperial College and University College London, 1999-2001), in two projects in the USA (in collaboration with the Hydrologic Research Center and Georgia Tech, 2005-06), and in a Greek-Ethiopian expedition project. Other EU related research activities are my participation in a COST action and in an INTERREG-CADSES project. I have participated in several research proposals to the EU, some of which passed the evaluation criteria but were not funded. In my opinion, my research profile and academic and publishing track record should have justified more support from EU research funds. It appeared to me that ERC's aims, placing "scientific excellence as the sole criterion for funding" irrespective of research area to support "investigator-driven" "frontier research" made an ideal (and up to recently missing) funding body for my research work. However, my 2008 application to the programme IDEAS (my proposal no 228060 with acronym CHEWtheCUDandRISE) was not funded and my appeal to redress was not approved.

In scientific review processes, rejection is a very likely outcome for novel and innovative research (cf. Miller, 2007). I am very familiar with rejections, because a key focus of my work has always been to debunk well-established myths that hinder science. According to my experience, persistence (combined with an optimistic and humourist attitude) is a powerful antidote to rejections. Also, most often, time rewards pioneering ideas eventually. Therefore, I am submitting a revision of that proposal.

## 1c 10-Year-Track-Record

My research and publications in the last ten years fall in the following ten categories (not including a separate category related to the ethics of the scientific community and its evaluation systems, in which I have devoted a major effort and publications). In each category, I list below a sample of two publications (a parenthesis at the end gives the number of the citations by other authors). I also summarize the questions addressed and provide a remark on the novelty of research. This synopsis was deliberately based on journal publications, which more accurately reflect my research achievements. Due to space limitations, I am not providing details of other activities. Information on my entire publication record and citations, invited presentations, organisation of international conferences, international honours and awards, and memberships to editorials boards of international journals is included in sections 1a and 1b.

**I. Nature of hydrological and geophysical processes**

1. Koutsoyiannis, D., Uncertainty, entropy, scaling and hydrological stochastics, 1, Marginal distributional properties of hydrological processes and state scaling, *Hydrol. Sci. J.*, 50(3), 381–404, 2005. (21)
2. Koutsoyiannis, D., Hurst-Kolmogorov dynamics as a result of extremal entropy production, *Physica A: Statistical Mechanics and its Applications*, doi:10.1016/j.physa.2010.12.035 2011. (-)

*Questions addressed*: Why hydroclimatic and other geophysical and technological processes exhibit peculiar behaviours, such as long-term persistence, fluctuations on large scales, clustering, state and time scaling, and heavy distribution tails?

*Remark*: This research, highlighting entropy as a driving force of natural processes and suggesting that maximum entropy, i.e. maximum uncertainty, can explain observed large-scale behaviours, is novel, innovative and ground breaking. These results, answering fundamental (type “why”) questions, are challenging mainstream research and there are no similar publications in literature.

**II. Climate stochastics**

3. Koutsoyiannis, D., Climate change, the Hurst phenomenon, and hydrological statistics, *Hydrol. Sci. J.*, 48(1), 3-24, 2003. (51)
4. Koutsoyiannis, D., A. Efstratiadis, N. Mamassis, and A. Christofides, On the credibility of climate predictions, *Hydrol. Sci. J.*, 53 (4), 671–684, 2008. (28)

*Questions addressed*: Are notorious future climate projections reliable and do they provide grounds to assess impacts in hydrological processes? What is the relationship of climate with stochastics?

*Remark*: These works show that mainstream climate research is fundamentally flawed due to misrepresentation of the notion of climate (whose definition relies on stochastics) and suggest remedies.

**III. Hurst-Kolmogorov dynamics and scaling**

5. Koutsoyiannis, D., The Hurst phenomenon and fractional Gaussian noise made easy, *Hydrol. Sci. J.*, 47(4), 573-595, 2002. (43)
6. Koutsoyiannis, D., Nonstationarity versus scaling in hydrology, *J. Hydrol.*, 324, 239-254, 2006. (39)

*Questions addressed*: What are the main characteristics and implications of the Hurst-Kolmogorov stochastic dynamics (also known as the Hurst phenomenon, Joseph effect, scaling behaviour, long-term persistence, multi-scale fluctuation, long-range dependence, long memory)?

*Remark*: The research suggests that the Hurst phenomenon is not a puzzle, as regarded for half a century, but a regular natural behaviour, manifesting multi-scale fluctuation and highlighting domination of uncertainty in nature.

**IV. Hydrological extremes**

7. Koutsoyiannis, D., Statistics of extremes and estimation of extreme rainfall, 1, Theoretical investigation, *Hydrol. Sci. J.*, 49(4), 575-590, 2004. (44)
8. Di Baldassarre, G., A. Montanari, H. F. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Blöschl, Flood fatalities in Africa: from diagnosis to mitigation, *Geophys. Res. Lett.*, 37, L22402, doi:10.1029/2010GL045467, 2010. (-)

*Questions addressed*: How can we effectively and consistently describe the behaviour of extreme rainfall and flood? Are hydrological practices for estimation of extremes correct? Are extremes increasing?

*Remark*: The research shows that the prevailing hydrological methodologies and views of extremes underestimate extremes significantly, and are inappropriate and misleading.

**V. Deterministic vs. stochastic description of hydrological processes**

9. Koutsoyiannis, D., On the quest for chaotic attractors in hydrological processes, *Hydrol. Sci. J.*, 51(6), 1065-1091, 2006. (7)
10. Koutsoyiannis, D., H. Yao & A. Georgakakos, Medium-range flow prediction for the Nile: a comparison of stochastic and deterministic methods, *Hydrol. Sci. J.*, 53(1), 142-164, 2008. (8)

*Questions addressed*: Do hydrological processes reveal deterministic chaos? Do they exhibit deterministic trends? Or can they be better modelled as stochastic processes?

*Remark*: The research reveals that numerous recent studies that have detected chaotic deterministic behaviour in hydrological processes with low-dimensional attractors are flawed; it locates the errors made and suggests that stochastic descriptions are more effective and provide better forecasts.

**VI. Stochastic modelling of hydroclimatic processes**

11. Koutsoyiannis, D., and A. Montanari, Statistical analysis of hydroclimatic time series: Uncertainty and insights, *Water Resour. Res.* 43 (5), W05429, doi:10.1029/2006WR005592, 2007. (30)
12. Koutsoyiannis, D., A random walk on water, *Hydrol. Earth Syst. Sci.*, 14, 585–601, 2010. (4)

*Questions addressed*: How can we build stochastic models of hydroclimatic processes effectively describing the natural behaviours and peculiarities? How can we quantify uncertainty?

*Remark*: The research highlights the intrinsic character of uncertainty in hydroclimatic processes and proposes novel formalism for statistical and stochastic description and simulation, much more parsimonious, general and powerful than the common ARMA models.

**VII. Scales and disaggregation**

13. Koutsoyiannis, D., Coupling stochastic models of different time scales, *Water Resour. Res.*, 37(2), 379-392, 2001. (24)
14. Koutsoyiannis, D. & C. Onof, Rainfall disaggregation using adjusting procedures on a Poisson cluster model, *J. Hydrol.*, 246, 109-122, 2001. (40)

*Questions addressed*: How can we disaggregate hydrological data? How can we couple stochastic models of different time scales?

*Remark*: The research proposes a novel and theoretically consistent methodology for disaggregation of data from coarser to finer time scales, radically different from existing ones, and applies it in the most demanding problems such as rainfall disaggregation on fine time scales.

**VIII. Hydrosystems modelling and management**

15. Koutsoyiannis, D., & A. Economou, Evaluation of the parameterization-simulation-optimization approach for the control of reservoir systems, *Water Resour. Res.*, 39(6), 1170, 1-17, 2003. (20)
16. Koutsoyiannis, D., A. Efstratiadis, and G. Karavokiros, A decision support tool for the management of multi-reservoir systems, *J. American Water Resour. Assoc.*, 38 (4), 945–958, 2002. (15)

*Questions addressed*: How can we effectively model and manage large hydrosystems? Can we combine simulation and optimization techniques? How many decision variables do we need in the management of a large hydrosystem? How can we perform global optimization of hydrosystems?

*Remark*: The research proposes a radically novel approach for hydrosystem management, which is parsimonious in decision variables (parameterization), and combines Monte Carlo simulation and global nonlinear optimization, replacing existing oversimplifying linear or dynamic programming methods.

**IX. The role of water and its relationship with energy, development and sustainability**

17. Koutsoyiannis, D., C. Makropoulos, A. Langousis, S. Baki, A. Efstratiadis, A. Christofides, G. Karavokiros, and N. Mamassis, Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability, *Hydrol. Earth Syst. Sci.*, 13, 247–257, 2009. (7)
18. Koutsoyiannis, D., Scale of water resources development and sustainability: Small is beautiful, large is great, *Hydrol. Sci. J.*, 2011 (accepted with minor revisions) (-)

*Questions addressed*: What are the threats and challenges related to the future of water resources? How is water related to energy and climate? What is the proper scale of water resource development?

*Remark*: Several political and ideological agendas have obscured the causes of water related problems and point to wrong solutions. This research attempts to reveal real causes of problems and propose pragmatic solutions.

**X. Ancient technologies and water management practices**

19. Angelakis, A. N., D. Koutsoyiannis & G. Tchobanoglous, Urban wastewater and stormwater technologies in ancient Greece, *Water Res.*, 39(1), 210-220, 2005. (30)
20. Koutsoyiannis, D., N. Zarkadoulas, A. N. Angelakis & G. Tchobanoglous, Urban water management in Ancient Greece: Legacies and lessons, *J. Water Resour. Plan. Manag.*, 134(1), 45-54, 2008. (11)

*Questions addressed*: How recent are the modern technologies and management practices in water supply, wastewater, and agricultural water use?

*Remark*: This research shows that the most important breakthroughs in hydraulic technology, water management and sanitation have been achieved as early as 2000-4000 years ago in Ancient Greece and earlier civilizations.

## 1d. Extended Synopsis

**Note:** This proposal is based on an older one submitted for the ERC Advanced Grant in February 2008 (Koutsoyiannis *et al.*, 2008). Although that proposal was not funded, some of its ideas were published (e.g. Koutsoyiannis *et al.*, 2009; see also note in Section 2a) or further worked on. This proposal is a revision of its predecessor, with its main points being essentially the same. In this revision we have considered the review comments. We have also considered the new developments in the field, which affirm the correctness, usefulness and ground-breaking character of our research orientation, as well as the necessity of applying the framework we propose.

*Αἰών παῖς ἐστι παίζων πεσσεύων* (Ηράκλειτος)
*Time is a child playing, throwing dice* (Heraclitus; ca. 540-480 BC)

### Introduction

One of the consequences of the explosive population growth in the 20th century and the related intense use of fossil fuels was the emission of carbon dioxide and other greenhouse gases into the atmosphere, which may have an effect on climate. While many have claimed that this effect has been already detected or is "more likely than not" (IPCC, 2001, 2007), others have argued that such detections are a result of misuse of statistics and that existing data analysed with correct statistics do not support such conclusions (Cohn and Lins, 2005; Koutsoyiannis & Montanari, 2007). It is puzzling how the ambiguous and still debatable concept of "*climate change*" has dominated the scientific vocabulary over the more defendable terms of *"environmental change"* and *"demographic change"*. The unfortunate implication of the domination of this term on scientific thought is that carbon dioxide emissions, a by-product ("symptom") of unsustainable energy policies and practices, have been given a tremendous research priority. Science and technology are currently focusing on the study and remedy of a "symptom" of a major "illness", instead of on the "illness" itself and its causes.

Since 1990, funds running to billions of euro per year are being spent worldwide in trying to deterministically project climate, understand its impacts and resolve possible vulnerabilities based on these projections. This deterministic approach to climate need not be surprising in view of the equally deterministic thinking that has thus far governed the crucial (and arguably more central to the environmental change debate) issue of energy production. Fossil fuels gave us the luxury of a controllable and deterministically manageable energy production, with the flip of a switch. However, their use is unsustainable and short-lived. Industry and economic growth are intimately connected to energy production and within the current paradigm, ultimately bound by the quantity of (limited) fossil fuels. There is hence a growing realization that the use of renewable energy sources needs to be drastically increased to avoid severe socioeconomic crisis in the not-too-distant future. However, although technology has increased the efficiency and lowered the cost of renewable sources of usable energy, a drastic change from fossil fuels to renewable sources is still difficult to implement: Renewable sources of energy, such as wind and solar, are highly variable, and their efficient use implies an energy management paradigm that recognizes and exploits the intrinsic uncertainty of natural processes. The radically different nature of renewables as compared to fossil fuels calls for a paradigm shift in energy technology and management, which embraces uncertainty as a dominant natural behaviour and converts it into an element boosting, rather than hindering, sustainable development and evolution. Besides, nature itself provides many hints that randomness, chaos and uncertainty are necessary prerequisites for evolution.

Rather than attempting to eliminate uncertainty, as has hitherto been the state-of-the-art in climate and hydrology research, we propose here to perform ground-breaking research that will *develop a consistent mathematical and methodological framework for the description and management of randomness and uncertainty in natural systems behaviour and will investigate its implication for integrated management of renewable and, hence, variable resources with an emphasis on the role of water in sustainable energy production and management under uncertainty*.

Managing uncertain resources requires regulation through storage. For example, exploitation of wind and solar energy, which are highly variable, dependent on atmospheric conditions (wind speed, sunshine), irregularly varying and unavailable at the time of demand, should be necessarily combined with technologies for energy storage. In their state of the art review, Crabtree & Lewis (2007) classify the cost-effective storage of electricity well beyond any present technology and more recently Kerr (2010) states in the *Science* Magazine "*Engineers haven't yet developed energy storage devices suitable for storing solar and wind power*". Nonetheless, we claim that, at least for electricity production applications, the proven method of pumped storage (pumping of water to an upstream location consuming available energy, to be retrieved later as hydropower) is an efficient method, representing the best available technology since: (1) it does not emit any by-products to the environment, (2) it is cost efficient, with efficiency ratios exceeding 90% (in large scale projects) and (3) hydroelectric energy production does not consume water (only converts its dynamic energy), and thus can be combined with other water uses: domestic, agricultural and industrial. To this extent, a technological paradigm where natural elements such as water, wind and sunshine are the sources of energy, with water in an additional integrative and regulating role, becomes plausible and desirable. Hydrology, the science of water on the Earth, and its interface with atmospheric sciences and energy technologies, have thus a prominent role to play in this new paradigm.

**Towards a novel mathematical framework to quantify uncertainty in nature (Activities A & B)**

Engineering hydrologists understood from early on that the design of engineering projects based on deterministic projections is a hopeless task and appreciated the usefulness of probabilistic approaches. However, during the last two decades hydrology changed perspective and invested its hopes in deterministic descriptions and models, harmonizing itself with a more general trend in geophysical disciplines and particularly in climatology. The trend towards the so-called "physically based models" signifies this change of perspective. The concept behind these models is that modern computational means would allow the full description of the physics of the hydrological cycle using mechanistic model structures and "first principles" such as Newton's laws and their particular formulations in fluid mechanics (i.e. Navier-Stokes equations). From the first steps of these modelling attempts, it was argued that there are fundamental problems in their application for practical prediction in hydrology, which result from limitations of the model equations relative to a heterogeneous reality; see e.g. Beven (1989). Nonetheless, the aspiration of achieving pure deterministic modelling still dominates. We argue that this is not feasible (see Koutsoyiannis, 2010) and that research targets to reduce predictive uncertainty within a deterministic context are misleading.

This direction in hydrology reflects a general philosophical and scientific view in which determinism is almighty and uncertainty is a subjective element that could be, in principle, eliminated with better understanding of mechanisms that are regarded to follow a "sharp" causality. This general view fails to recognize the radical advances in physics and mathematics of the twentieth century such as: (a) dynamical systems theory, which shows that uncertainty can emerge even from pure, simple and completely known deterministic (chaotic) dynamics and, hence, cannot be eliminated; (b) quantum theory, which emphasizes the intrinsic character of uncertainty and the necessity of a probabilistic description of nature; (c) statistical physics, which use the purely probabilistic concept of entropy (which is nothing other than a quantified measure of uncertainty defined within the probability theory) to explain fundamental physical laws (notably the Second Law of Thermodynamics), thus leading to a new understanding of natural behaviours and to powerful predictions of macroscopic phenomena; (d) mathematical logic, and particularly Gödel's incompleteness theorem, which challenged the almightiness of deduction (inference by mathematical proof) paving thus the road to inductive inference from data; (e) numerical mathematics, where developments 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; and (f) evolutionary biology, which emphasizes the importance of randomness (e.g. in selection and mutation procedures and in environmental changes) as a driver of evolution.

Our initial research activities intend to:

*Deconstruct myths* currently prevailing in hydroclimatic research (*Activity A*), by demonstrating that:

1) climate and the impacts of climate change cannot be deterministically predicted;
2) deterministic approaches may be obstacles in hydrological sciences and water resources technologies; and
3) classical statistics and stochastics are insufficient to describe complex hydroclimatic processes.

Develop a *new hydroclimatic theory* (*Activity B*), which recognizes the intrinsic character of uncertainty in natural processes and builds upon it, using the advances in physics and mathematics of the twentieth century. This activity includes:

1) the study of entropy as a concept for understanding and quantifying uncertainty with respect to hydro-climatic processes and as a driving mechanism of these processes;
2) the study of the nature of geophysical processes based on observed long time series, with particular emphasis on extremes and time dependence structure; and
3) the streamlining of a stochastic theory of hydroclimatic processes.

Activities A and B will provide the foundations for scientific progress, including rigorous definitions of concepts and useful interpretations of behaviours. Currently the emphasis has been given on the construction of algorithms and models and the concepts themselves have been left unclear. Therefore the proposed scientific framework, which will provide clear definitions of concepts, is a breakthrough that will boost future research. The notion of entropy and the principle of maximum entropy as a tool for logical inference (Jaynes, 2003), understanding of natural phenomena (Stowe, 2007) and effective modelling thereof, can be implemented to hydroclimatic systems (Koutsoyiannis, 2005a,b, 2011) to provide a sound theoretical basis for hydroclimatology, which is currently missing.

**Knowledge discovery from past information on water, climate, energy and socio-economic development (Activity C)**

According to Isaiah Berlin (1991), history is the only reliable teacher: "*She will never tell us the opposite of the truth*". A rigorous analysis of the past is thus an unsurpassable tool for science to formulate and test scientific hypotheses and avoid misconceptions. Recent advances in dynamical systems and chaos have highlighted the importance of quantified historical information for prediction: the method of analogues has proved efficient in analysing, learning and predicting from similar system states in the recorded past.

To assist the deconstruction of myths and strengthen the development of a consistent and concrete theory for hydroclimatic processes, our *Activity C* focuses on organizing historical information on climate, water, energy, their interconnections and their relationship to socioeconomic development. Specifically, we plan to:

1) process documented historical and paleoclimatic (proxy data) information as a means of (a) understanding historical climatic changes, (b) constructing quantified time series for statistical analysis; and (c) testing the theory constructed in Activity B.
2) relate past socio-economic development with (a) the extent of the climatic variation at specific locations, (b) the prevailing practices in society related to resources use (water consumption, exploitation of solar and wind energy), and (c) the ability of different societies to manage natural sources (construction of works, management practices, etc.) in an unstable environment; and
3) investigate the different conditions and models of energy use in developed and developing countries, with respect to interactions with population growth, agriculture and food production, transportation, water use and lifestyle.

Activity C will provide invaluable insights on both historical factors relevant to the understanding of future uncertainty and the interplay between resource consumption, energy and sustainable development.

**Coupling water, renewable energy and sustainability (Activity D)**

The new approach towards understanding, analysis and modelling of water and climate, developed in activities A and B and supported by the historical evidence and socio-economic implications examined in activity C, will give rise to a new framework for describing, quantifying and ultimately managing renewable water and energy resources. *Activity D* focuses on developing comprehensive tools for long-term water-energy management both at local and global scales. Specifically, we intend to:

1) quantify the interdependencies between water availability and climatic conditions required for efficient long-term exploitation of renewable energy resources (including, hydropower, wind, solar, wave and bio-fuels);
2) understand and model the variability of renewable water-energy resources, using the new hydro-climatic knowledge and models from activities A and B;
3) develop methods and tools for long-term, strategic planning for the integrated exploitation of renewable water-energy resources; and
4) integrate hydrometeorological models for short term prediction of wind and sunshine and link their results to the management of renewable energy production.

The above research will explore the key role of water in sustainable energy management and develop strategic planning and real time management methodologies for exploitation of renewable energies.

**Proof of concept (Activity E)**

The potential of the developed theoretical and technological framework for renewable energy management will be tested in real-world conditions (*Activity E*). A unique large-scale hydrosystem extended in two major river basins interconnected through diversion projects will be explored. Importantly, the chosen sensitive socio-economic area lacks fossil fuels and is strongly dependent on external energy sources, despite its substantial hydropower potential. Hence, its sustainable development requires drastic change of the present over-consumptive socio-economical model and the development of local renewable energy resources. In this, it presents an ideal case, highly transferable to other areas of the EU and the world.

The proposed case study, which will test the applicability of the developed framework and also investigate the sustainable development potential of the study area, includes:

1) analysis of the current energy use and management;

2) investigation of the potential of sustainable energy development;
3) development of future energy scenarios;
4) long-term simulations for the development of a strategic renewable energy plan;
5) short-term simulations to demonstrate the reliability and robustness of the proposed plan; and
6) investigation of the transferability of lessons learned from the case study to other cases around the world.

**An open knowledge approach (Activity F)**

Science requires verifiability and falsifiability, which, in turn, imply ease of access to all underlying information. To enable the scientific community to reproduce experiments and the public to monitor the progress of publicly funded research, our final *Activity F* aims at:

1) organizing all hydrometeorological and energy data using an advanced open source database system;
2) storing the developed open-source application software on a publicly available repository; and
3) developing a project-oriented web site that will provide news and documentation and point to all sources of relevant information.

The spirit of openness and the idea that true open access and discussion is the best way for scientific research, will allow the scientific community to verify (or even challenge) our findings and, hence, advance research in multiple directions yielding further results.

**Structure, outcomes and indicators of progress**

The technological means to efficiently transform renewable sources into usable energy largely exist already and significant improvements are expected in the near future in specific technologies (e.g. conversion of solar energy), which are the subject of ongoing research in the EU and globally. But the shift from finite (fossil fuels) to renewable resources requires more than specialized technologies. It requires a global (conceptual, scientific, technological and economical) paradigm shift towards integrated management of energy production and use under uncertainty. This type of uncertainty is yet unknown to “classical” modes of energy production. We propose to contribute to the establishment of this new paradigm and the formulation of its theoretical and methodological basis, in a research programme which includes six activities, A to F, as described above and summarized in the following schematic:

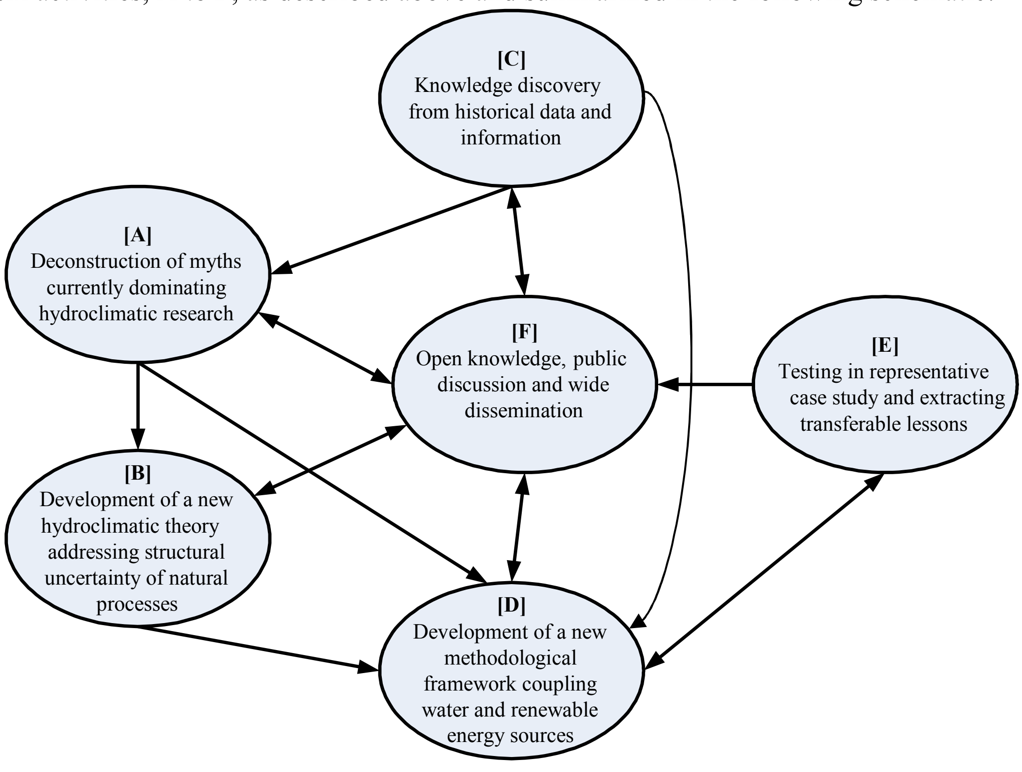


**Figure 1** Schematic of programme structure

The research will be conducted in the National Technical University of Athens by the Itia research team, currently consisting of 18 scientists, lead by D. Koutsoyiannis. Four new researchers with complementary expertise will be added to Itia to support the needs of this work. The team will be complemented by short, targeted visits by key experts as well as by longer visits (during sabbatical leaves) of five prominent European scientists, who currently work in other European countries and the USA.

The research programme will be tightly connected to *educational processes*, through the involvement of postgraduate students in research activities and workshops, the elaboration of PhD, MSc and diploma theses, and the adaption of relevant postgraduate courses to encompass knowledge produced within the programme.

*Outcomes* of this research are envisaged to include:

1. a rigorous scientific analysis, with philosophical connotation, of the dominant myths on natural processes and their cross-disciplinary implications, leading to their deconstruction;
2. an extensive (open access) historical knowledge base related to climate, water and energy use;
3. a new scientific framework for understanding natural behaviours recognizing their inherent uncertainty;
4. an entropic-stochastic theory of uncertainty and risk;
5. a novel tested methodology for modelling hydroclimatic processes;
6. a new methodological approach for the sustainable coupling of water and renewable energy;
7. a proof of concept of integrated renewable resource management in the form of a case study;
8. a set of recommendations and transferable lessons learned, as a basis for innovative applications;
9. a structuring of knowledge gained, for incorporation into educational processes.

We anticipate the following *measurable indicators* of progress of the *research* and its links with *education*:

- 35+ publications in peer-reviewed journals, in the form of research and opinion papers, and commentaries;
- 50+ presentations in widely respected international conferences;
- 1 book on Hydroclimatic Stochastics and 2 monographs on Sustainable Water and Energy;
- an *open access* database with long-term hydroclimatic information and energy data;
- a toolkit with software implementation of all models developed, provided as *open source*;
- a content management system with all information related to the project, including a weblog;
- 5 workshops designed to bring together experts on relevant fields to foster further discussion;
- 8 short visits and 5 long visits of international experts;
- 5 PhD and 15+ MSc and diploma theses produced within the research programme;
- 2 postgraduate-level courses (hydrometeorology, stochastic water resources technology) on an e-learning platform, adapted to encompass knowledge produced within the research programme.

### Commitment to the project

The principal investigator normally spends 100% of his time in Greece, an EU country. Even in the case of sabbatical or other leave, his presence in Greece will be more than 80% of his time. He currently has undertaken only one other research project, which has a small budget and will end in 2013, and which is primarily conducted by other members of the team under his coordination. Since this proposal reflects his main interests and research, he will devote 50% of his working time to the project.

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