Modeling and Mitigating Natural Hazards: Stationarity is Immortal!

Alberto Montanari[1] and Demetris Koutsoyiannis[2]

(1) Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna, Italy.

(2) Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Greece.

Abstract

Environmental change is a reason of relevant concern as it is occurring at an unprecedented pace and might increase natural hazards. Moreover, it is deemed to imply a reduced representativity of past experience and data on extreme hydroclimatic events. The latter concern has been epitomized by the statement that "stationarity is dead". Setting up policies for mitigating natural hazards, including those triggered by floods and droughts, is an urgent priority in many countries, which implies practical activities of management, engineering design and construction. These latter necessarily need to be properly informed and therefore the research question on the value of past data is extremely important. We herein argue that there are mechanisms in hydrological systems that are time invariant, which may need to be interpreted through data inference. In particular, hydrological predictions are based on assumptions which should include stationarity, as any hydrological model, including deterministic and non-stationary approaches, is affected by uncertainty and therefore should include a random component that is stationary. Given that an unnecessary resort to non-stationarity may imply a reduction of predictive capabilities, a pragmatic approach, based on the exploitation of past experience and data is a necessary prerequisite for setting up mitigation policies for environmental risk.

Introduction

Facing environmental risk has always been a challenge for societies and is a matter of growing concern today. On the one hand, the increased impacts of extreme events, along with the observation that the environment is changing at an unprecedented pace, highlight that human settlements are more and more exposed to natural hazard and risk. On the other hand, the explanation and attribution of the above increased risk are open research questions in hydrology, and social sciences as well. Consequently, calls are being issued for an improved understanding and interpretation of environmental change [*Montanari et al.*, 2013] and its connection with society, through the study of the two-way interaction between environment and humans [*Sivapalan et al.*, 2012; *Di Baldassarre et al.*, 2013; *Ceola et al.*, 2014; *Koutsoyiannis*, 2013; *Viglione et al.*, 2014; *Montanari et al.*, 2014; *Sivapalan et al*., 2014]. The awareness of the importance of the research themes related to change, in connection with evolving societal systems, recently led the International Association of Hydrological Sciences (IAHS) to focus on these topics during the Scientific Decade 2013-2022, by launching the Panta Rhei research initiative [*Montanari et al*., 2013; *Montanari et al.*, *2014*; www.iahs.info/pantarhei].

Given the urgency of environmental change and environmental risk, a pragmatic and holistic approach is needed to immediately focus on the above research questions. We believe that research activities should identify effective and technically sound solutions, by clarifying to what extent and why the environment is changing and how design variables should be estimated under change. To this end, we need to investigate what useful information is already available, what further information is necessary and what approaches should be considered. Many of the fatalities that occur each year during extreme events could be avoided by setting up simple precautionary actions, yet these are frequently not identified a priori. Research activity is urgently needed to identify critical locations and priorities for mitigation.

A key premise to reach the above goals is to clarify how to best profit from experience, data and information in the face of a rapidly changing environment. There is a widespread perception that the past is no more representative of the future. These beliefs have been epitomized by the statement "stationarity is dead" [*Milly et al*., 2008] which has been lately very popular in the hydrological community, while few have criticized it [*Koutsoyiannis*, 2011; *Lins and Cohn*, 2011; *Matalas*, 2012; *Koutsoyiannis and Montanari*, 2014]. The convincement that stationarity is dead led to claims that paradigm shifts should be pursued in hydrology to elaborate new philosophies and methods [*Milly et al*., 2008]. The shift would be towards methods that are driven by deterministic models and future forcing scenarios that would replace the assumption of stationarity. These would be elaborated upon an improved understanding and modeling of the underlying processes. We believe that this is not necessarily the most efficient way to draw predictions and therefore we aim to discuss the above premise in the context of hydrological modeling and engineering design in a changing environment. We elaborate on this issue here below, by focusing on the specific case of environmental risks related to water and hydrology.

Defining the problem

The practical problem is simple to state: how to efficiently identify and plan mitigation policies for natural disasters caused by hydroclimatic extremes, through environmental planning and engineering design. Engineers traditionally tackled this challenge by observing the phenomena, making predictions (mostly of statistical type) on likely future occurrences and finally designing mitigation actions. Examples of these latter are catchment management, construction of flood retention reservoirs, river engineering works and non-structural measures [*Thampapillai and Musgrave*, 1985; *Kundzewicz*, 2002]. Engineers were always aware of uncertainty, which may also be amplified by environmental changes, and therefore developed appropriate methodologies to quantify it and used safety factors in the design process [*Beven*, 2013].

Today, instances of failure of mitigation policies and protecting structures that were set up a long time ago are often interpreted as a sign that the traditional design methods are inefficient to face current risks. Therefore, new modeling approaches are invoked [*Schaefli et al.*, 2011]. Are they really necessary? Or is the pursuit of new approaches just a manifestation of departure from scientific and engineering thinking, combined with the radical reduction of investment in engineering infrastructure [*Koutsoyiannis*, 2014]?

Approaches for environmental modeling

Models are essential to better understand hydrological systems and to design mitigation actions for hydrological risk. Design is always carried out by using models, sometimes implicitly. For instance, the estimation of the peak river flow for an assigned return period is carried out by using models of various types. Identifying the appropriate model is a crucial step in engineering design [*Laio et al.*, 2009].

A multitude of approaches have been proposed for environmental modeling. Such models typically refer to the transformation of inputs of a system to outputs. They can be broadly divided in two classes (see Figure 1): deterministic and non-deterministic (statistical or stochastic) models. We believe it is important to clarify the advantages and drawbacks of such categories when dealing with change.

In a deterministic formulation the system output is uniquely determined by the input. Namely, input data are precisely associated to the model response and therefore uncertainty in the model structure is not directly taken into account. The popularity of deterministic approaches leading to deterministic predictions has considerably been increased in recent times. Two factors may have contributed to such popularity. First, the ever increasing power of computers, which can provide, in reasonable time, numerical solutions of dynamical systems (typically described by differential or difference equations), led many to develop the belief that natural systems can be modeled fully deterministically and with precision, once a sufficient level of detail (reflected in spatio-temporal resolution) is achieved in system description [*Koutsoyiannis et al.*, 2009]. Second, the culture developed within climate change exploration and spread in many disciplines including hydrology, led many to deem future scenarios obtained with deterministic models as credible predictions of the distant future.

The argument behind such reasoning is that assuming (a) perfect knowledge of the considered hydrological system, which enables a complete and precise description, (b) perfect knowledge of initial and boundary conditions, (c) perfect information to identify precise model parameters and feed a model with input data, then a deterministic model of the system would allow to make perfect predictions of the outputs for whatever lead time (up to centuries), thus providing an ideal solution to any type of problem. With such a model, change would not be a matter of concern anymore, as in a perfectly described system any shifting regime could be precisely modeled and predicted. Indeed, deterministic models allow one to account for causality with mechanistic solutions and therefore provide a valuable opportunity. However, we note that deterministic hydrological models need to be calibrated and therefore their use will never eliminate the need to make statistical inference from historical information. More importantly, one should note that in hydrology deterministic predictions are inevitably affected by several uncertainties due to imperfect geometric description of the control volume, inexact initial and boundary conditions [*Koutsoyiannis*, 2010], limited and often erroneous observability of the hydrological and meteorological variables [*Beven and Westerberg*, 2011; *Di Baldassare and Montanari*, 2009; *Montanari and Di Baldassarre*, 2012], imperfect model structure [*Beven*, 2012; *Gupta et al*., 2012], imperfect parameters and, as far as the future is concerned, unknown inputs. In such a situation, predictions can still be elaborated and can still be useful, but randomness and uncertainty need to be taken into account [*Vogel*, 1999]. The presence of randomness is the reason why engineering hydrology frequently relied on non-deterministic models and in particular statistical approaches. The use of statistics was induced by understanding, rather than ignorance, of the underlying processes [*Yevjevich*, 1974]. For instance, when the considered phenomena is described by a model with a high degree of non-linearity, a deterministic prediction is not possible even when the system is fully understood, while a stochastic prediction may allow one to draw probability distributions of future occurrences. In fact, for any perfect deterministic system, including linear models with some uncertain components, statistical predictions are the only viable ones for long time horizons [*Koutsoyiannis*, 2010]. In view of the above reasoning we conclude that using a stochastic approach, with a physical basis, is needed in hydrology.

No matter what approach is used, the modeling strategy to obtain design variables is based on the identification of invariant properties of the investigated phenomena to devise the model structure and inform the prediction. In the case of deterministic modeling these invariant properties may be, for instance, quantities like mass, momentum, angular momentum, energy and others [*Koutsoyiannis*, 2011]. In stochastic modeling of complex systems the preservation of only these invariant quantities does not suffice as a model basis and therefore some statistical properties of the studied stochastic process are computed by using past data and are assumed to be time invariant, provided that such assumptions are consistent with the data and the process understanding. The assumption that the above statistics are time invariant is called "stationarity" [*Kolmogorov*, 1931; *Khintchine*, 1934; see also *Koutsoyiannis and Montanari*, 2014].

Now, an important question today is: should a physically-based stochastic approach rely on the hypothesis of stationarity, even in the presence of change? Would this assumption be still reliable and useful? And, if not, what alternative assumption should one use? Is non-stationarity a useful way forward to deal with technical problems? Is the past still representative of the future? Can historical data inform engineering design and mitigation policies for natural hazards?

Stationarity

To address the above research questions, it is necessary to clarify the meaning and technical implications of stationarity and the meaning of the related statement that the past is representative of the future (or not).

Theory of Stationarity

We mentioned above that stationarity is an assumption introduced when making inference and prediction. In rigorous terms and according to the original definition [*Khintchine*, 1934; *Kolmogorov*, 1938], a stochastic process $\boldsymbol{X}(t)$ is stationary if and only if

$$F(x_{t_1}, x_{t_2}, \ldots, x_{t_n}) = F(x_{t_1+\tau}, x_{t_2+\tau}, \ldots, x_{t_n+\tau}), \forall\, n, t_1, t_2, \ldots, t_n, \tau \tag{1}$$

where $F(\ )$ denotes the joint probability distribution function. Given that $F(\ )$ does not change with a time shift τ, it follows that the statistics of a stationary stochastic process do not change in time (for more details see *Kolmogorov* [1931, 1938], *Khintchine* [1934] and *Koutsoyiannis and Montanari* [2014]). It is important to note that the definition implies that the process is stochastic and does not imply that the state of the process itself does not change. Actually, a stationary process, as was introduced in the works of Kolmogorov and Khintchine, undergoes change, but its statistics are conserved in time. Therefore, change does not imply non-stationarity and stationarity does not imply at all unchanging process state.

In view of the above definition, one can conclude that non-stationarity necessarily implies that some of the process statistics are time varying.

Stationarity and non-stationary models

When interpreting with mathematical models environmental processes non-stationarity may be justified and therefore a non-stationary model may be applied. However, this will never be perfect and therefore it will lead to residuals that will necessarily be treated as stationary if a good fit of change is obtained. Therefore, the use of a non-stationary model does not allow one to get rid of stationarity: namely, the modeling of change, in any case, must be based on the identification of invariant statistical properties and observed data are the necessary means to attain this goal.

A first implication of the use of a non-stationary model is that additional parameters are needed. If non-stationarity is properly described, the non-stationary model will lead to less biased simulation of future conditions, but the variance of the estimates will increase, for the above mentioned increased number of parameters. Therefore, one should evaluate whether the reduction of bias is worth the increased variance. Indeed, the selection of a non-stationary rather than stationary approach should be framed as a standard model selection problem where one selects the best model, namely, the one that produces the best design variables in terms of bias and variance of the estimates. Better estimates imply a more successful design not only in terms of reliability and durability of the proposed solutions, but also in terms of their cost effectiveness and therefore economical feasibility. The above mentioned increased variance of the estimates provided by a non-stationary model, due to a larger number of parameters, may imply an increase of the economic costs of the proposed solutions, therefore reducing their feasibility. Non-stationarity is just an option and not a universal solution to modelling environmental change. We maintain that engineers and technicians need to adopt the most reliable approach in view of the available information.

A second implication of the use of a non-stationary model is that its statistics necessarily are a deterministic function of time [*Koutsoyiannis*, 2011; *Koutsoyiannis and Montanari*, 2014]. The term "deterministic" is extremely important here, as it underlines that the use of a non-stationary approach, particularly in engineering design, must be based on the identification of a deterministic relationship identified by logics, mathematics or physics and also verified by the data, to explain the change in time of some statistics of the process (see Figure 1). In absence of such deterministic attribution, one cannot introduce any assumption of non-stationarity and therefore a non-stationary model cannot be set up. We realize that this latter statement is crucial for delivering our message efficiently and therefore would like to clarify it further.

In fact, our assertion above may be questioned by one who is convinced that a process is non-stationary because its statistics may change in time according to a random process. However, this is not possible, as process statistics are deterministic variables (typically unknown constants) by definition and the model would be ill-defined or even meaningless if they were assumed to be random. For instance, take the mean value of a generic, real-valued, random variable which is defined as

$$\mathrm{E}[X(t)] = \int_a^b x p(x;t)\mathrm{d}x \tag{2}$$

where $p(x;t)$ is the probability density of the outcome $x(t)$ from the random variable $X(t)$ at time t and $[a, b]$ is the interval of real values over which X is defined. Given that a stochastic process is a collection of random variables, each representing all possible values of the process at a given time step, the process itself will be characterized by an assigned mean value at each time t. According to eq. (1), the mean of the process $\mathrm{E}[X(t)]$ will be given as a deterministic function of time, taking identical values if the process is stationary ($\mathrm{E}[X(t)] = \mathrm{E}[X]$). The case in which statistics may randomly vary is therefore excluded. Let us provide an example, by referring to a Gaussian white noise $X(t)$ with mean μ_X and standard deviation σ_X. Now, let us assume that μ_X is replaced by another Gaussian white noise $Z(t)$ with mean μ_Z and standard deviation σ_Z, therefore assuming that the mean of $X(t)$ is random. Then, another Gaussian process $Y(t)$ is obtained, with $\mu_Y = \mu_Z$ and standard deviation $\sigma_Y = (\sigma_X^2 + \sigma_Z^2)^{0.5}$. Therefore, the statistics of $Y(t)$ are deterministic constants and not random variables and thus $Y(t)$ is stationary.

One may say that prior information may allow one to know that the statistics of the process are changing (and/or will change) and therefore the process is non-stationary, but the shape of the change may still be unknown; therefore the process is non-stationary even though one is not allowed to assume any deterministic relationship explaining the progress of statistics in time. Such statement would also be incorrect. In fact, the above situation would imply that one is not allowed to set up any non-stationary model to explain an evolution that is unknown and therefore the use of the concept of non-stationarity is not possible. Changes in the statistics of the process which are unpredictable (or unknown) result in a stationary approach – not a non-stationary one.

The above need for a deterministic relationship to explain the progress in time of the process statistics, in order to claim non-stationarity, is extremely important because it emphasizes that a proper justification is needed for using a non-stationary model in technical applications. There are indeed cases where the use of a non-stationary description is justified. If we knew the evolution in time of hydrological characteristics and parameters (in addition to hydrological observations, we may have information about how the percent of urban area changed in time, for instance), then we can build a non-stationary model, where the available information allows one to reduce the bias of the predictions. One should note that, even in the latter case, the non-stationary model will anyway include a random component that is stationary. In contrast, if we see a changing behaviour but we do not have any quantitative information, then particular care should be used if we decide to set up a non-stationary model that would be based on information that may be unreliable. For instance, it is frequent practice in environmental modeling to estimate the above deterministic changes of the process statistics by using "projections" of future environmental and climatic conditions that are obtained by applying models (for instance climatic models; see *Milly et al*. [2008]). Reliability of these projections is a necessary condition for obtaining less biased estimates, and therefore better defined mitigation policies for environmental risks. If projections are not reliable, not only the variance of the estimates will increase; their bias will increase as well and therefore non-stationary models may turn out to be less efficient with respect to their stationary counterpart. In order to properly inform model selection, the uncertainty of the above projections needs to be carefully evaluated. If projections are highly uncertain, a stationary model may well turn out to be the best solution for technical problem solving.

While non-stationarity necessarily needs to be described by a deterministic change of process statistics, it is important to emphasize that the introduction of a deterministic component in a stochastic process, to take into account the knowledge of the underlying phenomenon, does not necessarily imply that the resulting random process is non-stationary. For instance, accounting for seasonality through a deterministic description leads to a cyclostationary process, which in aggregate scales is stationary.

Implications of stationarity in engineering design

The above discussion brings to the following conclusions that we believe are extremely important in engineering design. (1) Stationarity is a concept that applies to stochastic processes and the assumption of non-stationarity needs to be supported by a deterministic description of the process statistics along time (Figure 1). (2) Any deterministic change of the process statistics is superimposed on a random component (unexplained variability) that is necessarily stationary. Namely, any random process – no matter if stationary or not – necessarily includes a stationary component, and therefore any future prediction needs to ultimately rely on the assumption of stationarity of that random part. (3) If a deterministic description of the process statistics along time, applicable to future times, is not available, which implies that non-stationarity is impossible to define, the only way for making predictions is through the assumption of stationarity. (4) The selection of a non-stationary model, rather than a stationary one, must be supported by a proper model selection analysis, as non-stationary models may turn out to be a less efficient solution in view of their increased uncertainty. A reduced robustness of the design variables is certainly something that engineers want to avoid when dealing with natural hazards. The latter considerations justify why engineers often rely on the assumption of stationarity.

Therefore we can conclude that stationarity is still a necessary concept in engineering design. Unfortunately, several different meanings are attributed to the term “stationarity” in modern hydrology (as explained by *Koutsoyiannis* [2011] and *Thompson et al*. [2013]). We believe that redefining concepts that are largely used in practice brings the risk to induce misconceptions. In the specific case of environmental risk mitigation, claiming that stationarity should be abandoned would imply that mitigation policies are not properly identified. Therefore, we believe it is appropriate to refer to the original definition of stationarity as proposed by *Kolmogorov* [1931,1938] and *Khintchine* [1934].

Dealing with change

The above summary of the situation clarifies how hydrological change can be defined and quantified [see also *Ceola et al*., 2014]. If one sticks to a deterministic representation, change is defined through the study of the process behavior. If a physically-based stochastic representation is used, which we believe is the appropriate solution, two ways forward can be identified: (1) if the natural process is modelled as stationary, change is quantified by relying on the hypothesis of stationarity, studying past patterns, gaining a knowledge of the process allowing to include the known physical basis, and making statistical inference and predictions; (2) if non-stationarity is justified, change is dealt with in the same way as for stationary processes but deterministic relationships are introduced for its statistical properties instead of assuming them constant, by investigating past patterns and exploiting information for the future, provided that such information is deemed reliable. In any case, the analysis of the past, through data, is an essential step to elaborate predictions, together with the analysis of any other hydrological information and assessment of the applicability of deterministic relationships for the future statistics.

Is environmental change non-stationary? Is stationarity dead?

The above considerations make clear that environmental change can be (in our opinion should be) modeled as a physically-based stochastic process, which in general can be stationary and only in justified cases non-stationary, and observations and information are key elements for a successful prediction. In fact, in view of the considerations that we developed so far in this paper, we are convinced that the question of whether change should be modeled within a stationary or non-stationary setting should be viewed in the frame of its relevance in solving practical problems. Of course modeling solutions depend on the nature of the process, but stationarity and non-stationarity are just two different options for building a physically-based stochastic model. In model building it is quite important to identify behaviors and parameters by analyzing past patterns using evidence provided by observations. But most important of all is to provide reliable and effective solutions to the real world problems; otherwise the debate about stationarity becomes a discussion on just semantics. In the case of mitigation of natural hazards, solving practical problems implies the design of management policies and engineering structures that need to be based on the estimation of design variables and their uncertainty, which is strictly related to economical feasibility of solutions.

After the above discourse, we have no doubt to conclude that stationarity cannot be dead: it is a modeling convenience that allows one to make reliable predictions for engineering design rather than a real world entity. Modeling concepts will only die if they are useless. We are convinced that the stationarity concept is quite useful because it highlights the fact that, whatever deterministic controls and mechanisms are identified and whatever progress is made in deterministic modeling, there will always be unexplainable variability in any system for which a probabilistic description assuming stationarity is needed. We believe that both exact predictability (particularly for distant times) and inference without data are impossible while only (physically-based) stochastic modeling offers a pragmatic solution. In this respect, it is not paradoxical to conclude that stationarity is immortal, as immortal is the need for statistical descriptions and the need to seek robust solutions to practical problems.

Concluding remarks

To conclude with some practical considerations, we first emphasize once again the importance of data. Data, and therefore the observation of the past, are the key to reach a better understanding of change, to improve our knowledge of hydrological processes and to make predictions for the future. The information available to hydrologists is tremendously increasing and therefore a concerted effort is needed by the hydrologic community to: (a) propose initiatives to support data accessibility and data sharing, (b) formulate advanced methods for integrating several sources of different information, (c) identify critical data gaps and (d) advance monitoring means. These should be high priorities for researchers working on hydrological change and environmental risk.

Second, we are convinced that a perfect deterministic description of hydrological systems will never be possible [*Koutsoyiannis*, 2010; *Montanari and Koutsoyiannis*, 2012; *Montanari and Koutosyiannis*, 2014; *Ceola et al.*, 2014] and therefore a physically-based stochastic description, based on the analysis of past patterns (and possibly non-stationary but always allowing a transformation that would lead to stationarity, i.e. invariance in time of statistical properties of some transformation of the process of interest), is the way forward to gain an improved understanding and seek efficient solutions to deal with environmental risk. This is also the concept and the approach that is used in other disciplines like seismology and volcanology [*Vere-Jones et al.*, 2005; *Mader et al.*, 2006].

In discussions about stationarity or non-stationarity we should bear in mind that this is a research question, which has practical consequences with respect to the use of available information in the design of structures and management policies. For the latter, a holistic and practical approach should be adopted. There is no need to rethink hydrology from scratch, nor to promote paradigm shifts or to build new sciences: practical problems solving should be based on finding the best way to profit from experience, to profit from new information and computational means. For the purpose of deepening our knowledge of hydrological processes, it is necessary to recognize their random character while improving prediction models. We propose to look at the future with an optimistic perspective of the opportunities that randomness offers. We do not need to seek an impossible determinism to cope with natural hazards: we just need forward looking and pragmatic ideas to profit from ever improving knowledge and information.

Post scriptum – Statistics versus process understanding

We believe that there is a widespread misconception in the hydrologic community, related to the use of process-based versus statistical models. The prevailing view is that process-based deterministic models are deductive means that take advantage of the available knowledge of the process dynamics, while statistical models are inductive and therefore are useful when the above knowledge is limited. We believe that this view is inconsistent. In complex hydrological systems, both deterministic and stochastic models are necessarily inductive (as they rely on fitting on data), while any deductive component in a deterministic model can be conveyed also in a stochastic model [*Montanari and Koutsoyiannis,* 2012]. The actual difference between deterministic and statistical models is just that the former establish a precise relationship between input (including initial and boundary conditions) and output (including systems state), while the latter examines the probabilities of events (or time evolution thereof) by admitting that randomness, and therefore uncertainty, is inescapable. A statistical or stochastic model is just not deterministic: it can be physically-based, it can represent spatial and time variability and can take full advantage of the knowledge of the system. Because of this, stochastic models with an increasing content of physical reasoning have been gaining increasing attention over the last decades. In order to identify the appropriate model to use, one should simply decide whether one wants to represent the inherent randomness affecting hydrological processes, and whether or not one wants to take uncertainty into account. There is no doubt that process-based models are the most appropriate solution for solving many water related problems, but we do not see any reason not to formulate them in a stochastic context. In our opinion, stochastic-process-based models are the way forward to bridge the gap between physically-based models without statistics and statistical models without physics. There has been a lot of applications in hydrology that clarified the potential of stochastic process-based models (see, for instance, *Montanari and Koutsoyiannis* (2012); *Langousis et al*. (2008); *Langousis and Veneziano* (2009a; 2009b)).

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References

Beven, K., and I. Westerberg (2011), On red herrings and real herrings: disinformation and information in hydrological inference, *Hydrol. Process.*, *25*, 1676-1680, doi: 10.1002/hyp.7963.

Beven, K. (2013), So how much of your error is epistemic? Lessons from Japan and Italy. *Hydrol. Process.*, *27*, 1677–1680, doi: 10.1002/hyp.9648.

Beven, K. (2012), Causal models as multiple working hypotheses about environmental processes, *Comptes Rendus Geoscience*, *344*, 77-88, doi: 10.1016/j.crte.2012.01.005.

Ceola, S., A. Montanari, and D. Koutsoyiannis (2014), Towards a theoretical framework for integrated modelling of hydrological and societal change, *WIREs Water*, 1, 427-438, doi:

10.1002/wat2.1038

Di Baldassarre, G., and A. Montanari (2009), Uncertainty in river discharge observations: a quantitative analysis, *Hydrol*. *Earth Syst. Sci*., *13*, 913-921, doi:10.5194/hess-13-913-2009.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, J.L. Salinas, and G. Blöschl (2013), Socio-hydrology: conceptualising human-flood interactions, *Hydrol. Earth Syst. Sci*., *17*, 3295-3303, doi:10.5194/hess-17-3295-2013, 2013.

Gupta, H.V., M.P. Clark, J.A. Vrugt, G. Abramowitz, and M. Ye (2012), Towards a comprehensive assessment of model structural adequacy, *Water Resour. Res.*, *48*, W08301, doi:10.1029/2011WR011044.

Khintchine, A. (1934), Korrelationstheorie der stationären stochastischen Prozesse, *Mathematische Annalen*, 109, 604–615.

Kolmogorov, A.N. (1931), Uber die analytischen Methoden in der Wahrscheinlichkcitsrechnung, *Math. Ann*. *104*, 415-458 (English translation: On analytical methods in probability theory, In: Kolmogorov, A.N., 1992. Selected Works of A.N. Kolmogorov - Volume 2, Probability Theory and Mathematical Statistics A. N. Shiryayev, ed., Kluwer, Dordrecht, The Netherlands, pp. 62-108).

Kolmogorov, A.N., 1938, A simplified proof of the Birkhoff-Khinchin ergodic theorem, Uspekhi Mat. Nauk 5, 52-56. (English edition: Kolmogorov, A.N., 1991, Selected Works of A. N. Kolmogorov - Volume 1, Mathematics and Mechanics, Tikhomirov, V. M. ed., Kluwer, Dordrecht, The Netherlands, pp. 271-276).

Koutsoyiannis, D. (2011), Hurst-Kolmogorov dynamics and uncertainty, *Journal of the American Water Resources Association*, 47, 481–495, doi: 10.1111/j.1752-1688.2011.00543.x.

Koutsoyiannis, D. (2010), HESS Opinions: “A random walk on water”, *Hydrol. and Earth Sys. Sci.*, *14*, 585–601, doi:10.5194/hess-14-585-2010.

Koutsoyiannis, D. (2013), Hydrology and Change, *Hydrological Sciences Journal*, 58, 1177–1197, doi: 10.1080/02626667.2013.804626

Koutsoyiannis, D. (2014), Reconciling hydrology with engineering, *Hydrology Research*, 45, 2–22, doi:10.2166/nh.2013.092.

Koutsoyiannis, D., C. Makropoulos, A. Langousis, S. Baki, A. Efstratiadis, A. Christofides, G. Karavokiros, and N. Mamassis (2009), HESS opinions: “Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability”, *Hydrol. and Earth Sys. Sci.*, *13*, 247–257, doi:10.5194/hess-13-247-2009

Koutsoyiannis, D., and A. Montanari (2014), Negligent killing of scientific concepts: the stationarity case, *Hydrological Sciences Journal*, doi:10.1080/02626667.2014.959959.

Kundzewicz, Z.W. (2002), Non-structural flood protection and sustainability, in: Simonovic, S.P. (ed.), *Non-Structural Measures for Water Management Problems*, Proceedings of the International Workshop, London, Ontario, Canada, 18-20 October 2001, IHP-V Technical Documents in Hydrology No. 56, UNESCO, Paris, pp. 8-27.

Laio, F., G. Di Baldassarre, and A. Montanari, Model selection techniques for the frequency analysis of hydrological extremes, *Water Resour. Res.*, *45*, doi:10.1029/2007WR006666, 2009.

Langousis, A. and D. Veneziano (2009a), Theoretical Model of Rainfall in Tropical Cyclones for the Assessment of Long-term Risk, *J. Geophys. Res.*, 114, D02106, doi:10.1029/2008JD010080.

Langousis, A. and D. Veneziano (2009b), Long-term Rainfall Risk from Tropical Cyclones in Coastal Areas, *Water. Resour. Res.*, 45, W11430, doi:10.1029/2008WR007624.

Langousis, A., D. Veneziano, and S. Chen (2008), Boundary Layer Model for Moving Tropical Cyclones, In: Hurricanes and Climate Change, Edts. J. Elsner and T. Jagger, Springer, NY, doi: 10.1007/978-0-387-09410-6, pp. 265-286.

Lins, H.F., and T.A. Cohn (2011), Stationarity: Wanted Dead or Alive?, *Journal of the American Water Resources Association*, *47*, 475-480, doi: 10.1111/j.1 752-1688.2011.00542.x 688.2011.00542.x.

Mackey, M.C. (1992), *Time's Arrow: The Origins of Thermodynamic Behavior*, Dover, Mineola, NY, USA, 175 pp.

Mader, H. M., S. G. Cole, C. B. Connor and L. J. Connor (eds) (2006), *Statistics in Volcanology*, Special Publications of IAVCEI 1, Geological Society of London, London, UK.

Matalas, N.C., (2012), Comment on the Announced Death of Stationarity, *Journal of Water Resources Planning and Management*, 138, 311-312, doi: 10.1061/(ASCE)WR.1943-5452.0000215.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer (2008), Stationarity is dead: whither water management?, Science, 319, 573-574, doi: 10.1126/science.1151915

Montanari, A., and D. Koutsoyiannis (2012), A blueprint for process-based modeling of uncertain hydrological systems, *Water Resour. Res.*, *48*, W09555, doi:10.1029/2011WR011412.

Montanari, A., and D. Koutsoyiannis (2014), Reply to comment by Grey Nearing on “A blueprint for process-based modeling of uncertain hydrological systems,” Water Resour. Res., 50, 6264–6268, doi:10.1002/2013WR014987.

Montanari, A., S. Ceola, and E. Baratti (2014), Panta Rhei: an evolving scientific decade with a focus on water systems, in: Castellarin, A., Ceola S., Toth, E. and A. Montanari (eds), *Evolving Water Resources Systems: Understanding, Predicting and Managing Water–Society Interactions*, IAHS Publ.364, Wallingford, UK, 560pp.

Montanari, A., and G. Di Baldassarre (2013), Data errors and hydrological modelling: The role of model structure to propagate observation uncertainty, *Advances in Water Resources*, *51*, 498-504, doi: 10.1016/j.advwatres.2012.09.007.

Montanari, A., et al. (2013), “Panta Rhei – Everything Flows”, Change in Hydrology and Society – The IAHS Scientific Decade 2013-2022, *Hydrological Sciences Journal*, 58, 1256–1275, doi: 10.1080/02626667.2013.809088.

Schaefli, B., C.J. Harman, M. Sivapalan, and S.J. Schymanski (2011), HESS Opinions: "Hydrologic predictions in a changing environment: behavioral modelling", *Hydrol. Earth Syst. Sci.*, *15*, 635-646, doi:10.5194/hess-15-635-2011, 2011.

Sivapalan, M., M. Konar, V. Srinivasan, A. Chhatre, A. Wutich, C. A. Scott, J. L. Wescoat, and I. Rodríguez-Iturbe (2014), Socio-hydrology: Use-inspired water sustainability science for the Anthropocene, *Earth's Future*, 2, doi:10.1002/2013EF000164.

Sivapalan, M., H.H.G. Savenije, and G. Blöschl (2012), Sociohydrology: A new science of people and water, *Hydrological Processes*, *26*, 1270–1276, doi:10.1002/hyp.8426.

Thampapillai, D. J., and W. F. Musgrave (1985), Flood Damage Mitigation: A Review of Structural and Nonstructural Measures and Alternative Decision Frameworks, *Water Resour. Res.*, 21(4), 411–424, doi:10.1029/WR021i004p00411.

Thompson, S. E., M. Sivapalan, C.J. Harman, V. Srinivasan, M.R Hipsey, P. Reed, A. Montanari, and G. Blöschl (2013), Developing predictive insight into changing water systems: use-inspired hydrologic science for the Anthropocene, *Hydrol. Earth Syst. Sci.*, *17*, 5013-5039, doi:10.5194/hess-17-5013-2013, 2013.

Vere-Jones, D., Y. Ben-Zion, and R. Zúñiga (2005), Statistical Seismology, *Pure and Applied Geophysics*, 162, 1023-1026, doi: 10.1007/s00024-004-2659-2.

Viglione, A., G. Di Baldassarre, L. Brandimarte, L. Kuil, G. Carr, J.L. Salinas, A. Scolobig, and G. Blöschl (2014), Insights from socio-hydrology modelling on dealing with flood risk – Roles of collective memory, risk-taking attitude and trust, *Journal of Hydrology*, 2014, http://dx.doi.org/10.1016/j.jhydrol.2014.01.018.

Vogel., R. (1999), Stochastic and Deterministic World Views, *Journal of Water Resources Planning and Management*, 125, pp. 311-313, doi: 10.1061/(ASCE)0733-9496(1999)125:6(311)).

Yevjevich, V., Determinism and stochasticity in hydrology, *J. of Hydrol.*, 22, 225-238, 1974.

FIGURE CAPTIONS

Model type	Studied properties	Stationary case	Nonstationary case
Deterministic	Evolution in time of system states without reference to statistical properties	Not applicable	Not applicable
Non-deterministic (statistical/stochastic)	Evolution in time of probabilities of systems states or statistical properties thereof	Probabilities and statistical properties are assumed constant in time	Probabilities and statistical properties are changing according to deterministic functions of time

Figure 1. Classification of modeling approaches, studied properties and behaviors in the stationary and non-stationary case.