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Toward a theoretical framework for integrated modeling of hydrological change

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Abstract

In an attempt to provide a unified scheme for the simulation of changing behaviours of hydrological systems, a theoretical framework for stationary and non-stationary modelling is presented. The main triggers for hydrological change are reviewed, their impact on the long term properties of the inherent system are analysed and theoretical solutions are proposed for their representation. Model calibration is also discussed along with the impact of hydrological change on simulation uncertainty. Non-stationarity and its simulation are examined as well. We propose a stochastic approach which is general, and allows a comprehensive treatment of uncertainty. The proposed framework is relevant to integrated modelling of hydrology and human impacts and therefore fits into the concepts of "Panta Rhei", the scientific decade 2013-2022 promoted by the International Association of Hydrological Sciences.

INTRODUCTION

Hydrological change is one of the most important research issues in modern hydrology. Hydrology and change are tightly connected[1]. This is manifested, among other things, in the fact that many aphorisms (including Heraclitus's 'Panta Rhei') use the notion of the flow or the river to refer to change. In this respect, the term 'hydrological change' may look as a pleonasm. However, in the last decade the term has been used initially to describe climatically induced changes in hydrology[2], in the frame of assessing impacts of hypothetical (projected) 'climate change'. Here we use 'hydrological change' in a broader meaning to highlight the changing aspects of hydrological processes, either resulting by natural variability (intrinsic and therefore not-human induced variability of natural processes) or human induced (anthropogenic influences, particularly due to catchment modifications). Hydrological change is thus a shift in the regime of selected hydrological processes and/or the behaviour of the related control volume and/or boundary conditions. Hydrological change may be manifested through a variation in catchment and/or aquifer conditions, which imply an alteration of the related hydrological variables. Shifts are not necessarily permanent: they may be due to the presence of long term fluctuations, whose time scale should be sufficiently extended, therefore excluding short term variations like those induced by seasonality. Hydrological change may also result from the expansion of the timescales of interest for decision making problems, which imply a focus on long term properties of the considered system.

The emergence of unprecedented patterns in water-related environmental processes has been reported in several recent contributions[3-6], thus pointing out how relevant changes are affecting the fundamental hydrological dynamics[7]. The impact of hydrological change on natural hazards, and consequently on the related risks affecting human settlements and activities, mainly catalyses the interest of researchers. Indeed, water plays a central role for societal systems and therefore any change affecting water security, and water related risks in general, is a matter of concern for society[1,8].

However, hydrological change is still "a well known unknown"[9]. On the one hand, humans are well aware that environmental systems are continuously changing and unrepeatable[10-12]. It is well known that natural variability is multifaceted and may induce the occurrence of continuously evolving situations. Indeed, if one looks at the morphology and land cover of catchments it is evident that they evolved through a series of unprecedented events. The unrepeatability of hydrological processes is related to water flow[9], which inevitably changes its surroundings by the associated transfer of mass and energy (e.g. by erosion and deposition).

On the other hand, natural variability and the associated change are poorly known. The analysis of distinctive features and time scales of hydrological change together with the assessment of human impacts on environmental change and risks are still open research challenges. Indeed, fundamental questions remain unsolved such as "To what extent humans may affect the global water cycle?"[13] and "How to model the interactions and feedbacks between natural systems and society?"[14-16]. Furthermore, it is not clear to date how hydrological change can be interpreted and modelled. This lack of clarity is inducing relevant misconceptions, like for instance the widespread belief that change is a synonym for non-stationarity which implies that non-stationary approaches are needed to predict the impact of change. As a matter of fact, a systematic theoretical framework for dealing with hydrological change is still lacking.

The awareness of the above research challenges is the reason why the International Association of Hydrological Sciences has decided to focus on "Change in Hydrology and Society" during the scientific decade 2013-2022, by launching the "Panta Rhei" research initiative[9]. A consultation with the scientific community, through a blog and face-to-face discussions, which were often held during scientific meetings of the most important international geophysical and hydrological societies, defined the subject of the scientific decade. To address the challenges of societal and environmental change and deepen the knowledge of in-between hydrological systems, "Panta Rhei" aims to promote frontier scientific research with a joint effort of the worldwide hydrologic community. The activity of "Panta Rhei" is being structured in research themes to address selected research questions, and will be carried out by single working groups. More details can be found in the "Panta Rhei" Science Plan (available at http://www.iahs.info/pantarhei).

The purpose of this paper is to summarise ideas for the development of a theoretical framework to support the interpretation and modelling of hydrological change, therefore contributing to the "Panta Rhei" research targets. To this aim, we present here an overview of the foremost available approaches to deal with hydrological change, to better clarify how to (i) comprehend the changing behaviour of hydrological systems, (ii) improve our capability to support hydrological design, and finally (iii) contribute to address the urgent societal issues related to water and environmental risks.

PHYSICAL REASONS FOR HYDROLOGICAL CHANGE, PERCEPTIONS AND PARADOXES

As stated in the Introduction, there is increasing awareness that environmental processes are in a continuous state of change. However, the occurrence or even the communication emphasis in recent times of seemingly unusual events has reinforced the concern that hydrological systems may be undergoing unprecedented changes. Another relevant aspect to consider is related to the possibility that the above changes are human induced, in view of the massive development that modern society experienced in many regions of the world in the last decades. Indeed, the physical considerations that may justify an unprecedented change are multifaceted.

A possible physical motivation for hydrological change that attracts the interest of researchers is climate change[5,8,17-28]. There is no doubt that climate has ever been changing, as suggested by paleoclimate proxies which show that the climate has never been static[29]. Climate change is certainly a potential driver of hydrological change, but the interaction between climate and hydrology is very complex and attempts to simulate it through climatic models did not provide satisfactory results[30-33]. As a consequence, intense research activity has been triggered to correct the climate model results, giving rise to the so-called downscaling methods[34].

There are other obvious changes that affect the hydrological regime, including increased irrigation demand, land use transformation and agricultural practices (e.g. use of fertilizers and pesticides), pollution of streams and aquifers as a result of urban activities, and perturbations of the natural water balance through overexploitation of groundwater, resulting in a dramatic lowering of water tables and, in coastal areas, salt water intrusion[17,35,36]. In other words, direct human influence on hydrological change may prevail over the more indirect climate change effects, as highlighted by several extreme events mainly caused by urbanisation of flood prone areas[37], river training and increased imperviousness of catchments.

Unfortunately the information and knowledge of hydrological processes is limited. Systematic hydrological measurements only started in the eighteenth century and therefore it is not easy to assess whether recent hydrological events can be classified as unprecedented. An important exception is represented by the Nilometer data set, which contains information of annual minimum and maximum water lever of the Nile for over eight centuries[38]. While the Nilometer water levels do not enable reconstruction of the hydrological processes in the huge Nile basin, they provide precious information about the decadal and centennial changes in hydrological behaviour. Indeed they show that the occurrence of extreme (maximum and minimum) water levels changes dramatically through decades and centuries[1].

We may thus infer that catastrophic events and their grouping in time are likely not unprecedented. What certainly is unprecedented is the drastic improvement in the last decades of the communication means that make the dissemination of information on catastrophic events much easier. The enhanced availability of both monitoring activities and information may lead to a biased perception that extreme events became less rare. Indeed, the frequency of monitored events is not coincident with the actual frequency of events. In this respect, a sociological element that leads to biased interpretation of flood trends has been recently noted[18]: a recent large flood in a catchment often triggers a study on the flood history of that catchment which will naturally find there was a large flood at the end of the record. What is actually needed is the simultaneous analysis of many catchments in a large region[39], which will help to reduce the chances of these self-fulfilling prophesies. In addition, the perceived increase of the frequency of extreme hydrological events may be also associated to the enhanced exposure and vulnerability of human settlements and activities in the last decades[37] (see Sidebar - Flood events as an indicator of hydrological change). As a consequence, the same natural event may lead to a greater damage (and attention) nowadays rather than decades ago.

The discussion on the possible causes for hydrological change is not a purely scientific debate, but actually it is instrumental in identifying solutions and priorities. The economical resources for developing regional and global programmes to contrast the negative effects of hydrological change are limited and therefore a careful policy evaluation and development is needed. Today there is a widespread belief that reducing the CO_2 emissions is a first priority for environmental protection and recovery. This has been a long and multifaceted discussion. Nevertheless, we appeal to scientists and the public opinion not to underestimate the priority of other actions that might be more effective in reducing the exposure of societies to environmental hazards, like for instance improving catchment and water resources management, relocating residents in flood prone areas and using engineering means for flood and drought control.

Hydrological change should become a first societal priority, whose assessment should be based on information exploitation and monitoring strategies. In particular, hydrological observations play a key role[17] as a necessary pre-requisite to inform environmental protection and mitigation policies for environmental risk.

TOWARDS A THEORY OF HYDROLOGICAL CHANGE

A theoretical framework for modelling hydrological change

To simulate a generic, time dependent hydrological variable $X(t)$, referring to time t, hydrological models are widely employed. Following a deterministic approach, and assuming that the model parameter vector $\boldsymbol{\Theta}$ is not varying in time, the model can be written as

$$X(t) = S(\boldsymbol{\Theta}, \boldsymbol{I}(t)) \tag{1}$$

where S is the deterministic model structure with parameter vector $\boldsymbol{\Theta}$ and $\boldsymbol{I}(t)$ is the input data vector, which may eventually include initial and boundary conditions. A deterministic formulation implies that the model S establishes a one-to-one relationship between the input data vector $\boldsymbol{I}(t)$ and the hydrological variable $X(t)$. Namely, the same input data is associated to the same hydrological response and therefore uncertainty is not directly taken into account. Conversely, if one adopts a stochastic formulation, the model can be written as adapted from[40]:

$$f_X(X) = K f_{\boldsymbol{\Theta},\boldsymbol{I}}(\boldsymbol{\Theta},\boldsymbol{I})\Big|_{X=S(\boldsymbol{\Theta},\boldsymbol{I})} \tag{2}$$

where X, $\boldsymbol{\Theta}$ and $\boldsymbol{I}$ are now represented as random variables (in particular X and $\boldsymbol{I}$ are components of stochastic processes and the notation implies that $\boldsymbol{\Theta}$ and $\boldsymbol{I}$ are both vectors), f indicates a probability density function and K is a stochastic operator that transforms the density function $f_{\boldsymbol{\Theta},\boldsymbol{I}}$ to the density f_X. The right-hand part is evaluated at $X = S(\boldsymbol{\Theta}, \boldsymbol{I})$ thus introducing the dependence on the deterministic model S. According to this formulation, the hydrological time series is now a realisation of the stochastic process X and f is always a (joint or marginal) density that represents the (multidimensional or one-dimensional) probability of occurrence of the considered random variables. A specific form of (2) for some assumptions has been recently outlined[40,41].

The stochastic formulation (2) defines a relationship between probability distributions rather than a deterministic relationship of input and output variables, as in (1). The given input data $\boldsymbol{I}$ may be associated to several realisations of $X(t)$, therefore taking uncertainty into account in the input-output relationship. From a practical viewpoint, (2) is typically evaluated by Monte Carlo simulations, thus necessitating a shift from one to several hydrological model runs for the same values of inputs and parameters.

The deterministic formulation is a particular case of the stochastic one. In fact, (1) can be interpreted as a realisation of the stochastic process (2) when an assigned pair $\boldsymbol{\Theta}$ and $\boldsymbol{I}$ is picked up from the probability density function $f_{\boldsymbol{\Theta},\boldsymbol{I}}(\boldsymbol{\Theta},\boldsymbol{I})$ and the stochastic operator K is such that $K f_{\boldsymbol{\Theta},\boldsymbol{I}}$ is a Dirac δ function resulting in $f_X(X) = \delta(X - S(\boldsymbol{\Theta}, \boldsymbol{I}))$. Aiming at an integrated modelling of uncertainty and at a more general analysis, in what follows we will adopt and refer to the stochastic formulation expressed by (2), which is more appropriate for modelling change. In fact, the above one-to-one correspondence between input and output data that applies for the deterministic formulation does not apply anymore in the stochastic setting, where the one-to-one correspondence is established between probability distributions. Therefore, the stochastic approach allows a more flexible description of variability and long term fluctuations by exploiting the random properties of the considered system.

Equation (2) allows its variables to be varying or constant in time. In what follows we will always assume that inputs $\boldsymbol{I}$ are changing in time. However, their probability distribution $f_{\boldsymbol{\Theta},\boldsymbol{I}}(\boldsymbol{\Theta},\boldsymbol{I})$ may not necessarily be time varying. Likewise, the parameters $\boldsymbol{\Theta}$, the deterministic transformation S and the operator K can either be constant or changing in time, as detailed below.

When $f_{\boldsymbol{\Theta},\boldsymbol{I}}$, $\boldsymbol{\Theta}$, S and K do not change in time, stochastic variations may still make the hydrological model (2) capable of simulating changes in the regime of the hydrological variable $X(t)$, therefore reproducing relevant instances of hydrological change. In fact, the presence of persistence in the system, which is exploited by the stochastic formulation, implies that external shocks, like a flood, may produce long lasting impacts that result in a long term fluctuation, or may indicate a shift to a new regime characterized by the occurrence of a cluster of floods. However, one may argue that the most interesting occurrences of change are related to permanent shifts (namely, changes in the considered variable that do not spontaneously revert to the previous state) and not to long term fluctuations, and therefore time varying formulations are more relevant. On the one hand we may in principle agree that possible permanent shifts are interesting but, on the other hand, we note that for the sake of obtaining reliable and useful predictions one should keep the model as simple as possible. Therefore time variability of items in (2) should be introduced according to what data, evidence and understanding of physical processes suggest. The target of modelling is to make inferences and future predictions, eventually based on past data. The more items assumed time varying, the less possible inference becomes.

Stationarity versus non-stationarity

Stationarity is a concept first defined in stochastics[42,43]: a stochastic process is called stationary if the joint probability distribution of random variables corresponding to different times, and consequently their statistical properties, do not change in time. Conversely, when the joint probability distributions are time varying, the stochastic process is non-stationary, which implies that the statistics of the considered stochastic process are deterministic functions of time[10,11]. The identification of a deterministic relationship that explains the change in time of some process statistics is necessary for claiming non-stationarity. The notion of non-stationarity versus stationarity has been mentioned in many recent contributions when dealing with hydrological change[12,15,44], even though the definition of stationarity may have been misused[45,46]. We believe, however, that it is important to adhere to the correct definitions of concepts rather than revise them. Stationarity has been used for decades by engineers in several fields, with relevant implications for design and planning activities and, thereby, for society. Given that practitioners have been well aware that stationarity is a concept that refers to statistical approaches currently employed for the estimation of design variables, the classical statistical definition of stationarity should always be used, to avoid misconceptions that may negatively impact on the safety of engineering design and on the environmental risk.

Therefore, in the context of the present paper we focus on the above classical definition of stationarity[42,43] from which one can conclude that model (2) with time varying inputs and outputs will be stationary if $f_{\boldsymbol{\Theta},\boldsymbol{I}}$, $\boldsymbol{\Theta}$, S and K are not varying in time. However, in view of the above premises on time variability, model (2) with all these items constant may still represent relevant occurrences of hydrological change. Thus stationarity is fully compatible with changes (i.e. long term climatic change) and long term persistence. The latter may be manifested through, e.g. the Hurst effect[1,47] which may induce the presence of long term fluctuations (often called multidecadal cycles or oscillations) in a stationary process. For instance, the recent global warming can be explained by means of a stationary stochastic process affected by long term persistence[17,48]. Therefore, two relevant implications arise: (i) stationarity can be successfully used to model certain instances of hydrological change and (ii) particular care should be taken when asserting that stochastic processes are non-stationary, even in the presence of human impact. As noticed before, to claim non-stationarity a deterministic relationship must be always defined for some process statistics.

A non-stationary stochastic formulation for hydrological models

Human induced changes in the environment, such as urbanization (or permanent land use change) and construction of dams, certainly justify an approach in which non-stationarity is assumed. If the change is abrupt and clearly located in time (e.g. in a dam construction) then piece-wise stationary modelling (e.g. one model configuration before the dam construction and one after) would be a simple and readily applicable solution. The case of gradual changes (i.e. slow changes along time) is more difficult to handle. This would require to consider an explicit time-dependence for at least one of the items in the stochastic model (2). We can thus distinguish among the following cases (see Fig. 1):

1. Non-stationary inputs $\boldsymbol{I}(t)$: their marginal probability density function is an explicit function of time $f_I(\boldsymbol{I},t)$, which translates into a time-dependent joint density with $\boldsymbol{\Theta}$, $f_{\Theta,I}(\boldsymbol{\Theta},\boldsymbol{I},t)$.

2. Time varying parameters $\boldsymbol{\Theta}(t)$: in the stochastic framework presented here the parameters are regarded as random variables and thus they have a probability density $f_\Theta(\boldsymbol{\Theta})$. In the case of non-stationarity, the marginal density is an explicit function of time, $f_\Theta(\boldsymbol{\Theta},t)$, and again its joint density with inputs $\boldsymbol{I}$ will also be a function of time, $f_{\Theta,I}(\boldsymbol{\Theta},\boldsymbol{I},t)$.

3. Time varying relationships between inputs and parameters: the joint density $f_{\Theta,I}(\boldsymbol{\Theta},\boldsymbol{I},t)$ is a function of time, while the marginal densities $f_I(\boldsymbol{I})$ and $f_\Theta(\boldsymbol{\Theta})$ are not time-dependent.

4. Time varying model structure $S(\boldsymbol{\Theta},\boldsymbol{I},t)$: this applies as a result of changes in the dynamics of the physical processes.

5. Time varying stochastic operator $K(t)$: the change in time of K can be expressed indirectly as a function of the deterministic model output, either assuming a constant model S (so that $K(t) = K(S(\boldsymbol{\Theta},\boldsymbol{I}))$, where the dependence on time is introduced through the changing $\boldsymbol{I}(t)$[40], or even a model S changing in time (so that $K(t) = K(S(\boldsymbol{\Theta},\boldsymbol{I},t))$.

6. Combinations of the above.

In conclusion, if any of the above items is an explicit function of time the resulting model would classify as non-stationary. However, when changes in time are not substantial compared to the variability of the inputs or the involved uncertainty, then a fully stationary setting is preferable because, as we already mentioned, it better supports inference and prediction. A similar reasoning applies when the effects of changes in time are annihilated during the rainfall-runoff transformation. A trivial example may be given by referring to river flow modelling through lumped models. Given that these models are not sensitive to changes in time of rainfall spatial variability, any attempt to account for the latter would end up with reduced reliability of the predictions. Accounting for non-stationarity implies an increased model complexity whose appropriateness should be carefully evaluated.

Recognising non-stationarity

We clarified above that stationarity refers to models and not to real processes and therefore the question that is dealt with in this Section should be formulated as follows: "How to assess whether a non-stationary approach is a proper model for a given set of observations of a natural process?" The literature proposed several data analysis methods to support the above identification procedure, either parametric[49] or non-parametric such as the run test[50]. The outcome from these tests depends on the null hypothesis and therefore to justify a non-stationarity approach is never an easy task, which becomes more complicated if an extended set of observations is not available.

The approach we promote here is to first collect extended information on the considered processes. Non-stationarity should be justified by physical evidence, which in some cases is clear, like for instance in the presence of heavy and relevant human impacts. The evidence should drive the identification of the deterministic change of the process statistics. Data analysis to support the assessment of non-stationarity must be used carefully, as usually the outcome is highly uncertain and the results heavily depend on the null hypothesis. When one is doubtful on the appropriateness of a non-stationary model, then we advise the modeller to prefer a stationary approach, in view of its reduced uncertainty and improved predictability, unless the advantage of the non-stationary formulation is clear with respect to the scope of the analysis. If a non-stationary approach is chosen, a minimum requirement would be to justify it through a split-sample approach[51], so that the deterministic function describing non-stationarity is identified on one part (e.g. half) of the data set and then validated on the other part (where both parts should belong to the period affected by the change).

Ultimately, we suggest to base model selection on a comparative assessment of the results, including their uncertainty, to identify the most convenient and safest option to move forward. Hydrological models are often used for an applied purpose and therefore modelling solutions should be identified with a practical approach. Even when models are used for pure research purposes, a comparative assessment is extremely useful for hypothesis testing and gaining an improved interpretation of the physical systems. In our experience stationarity often provides the most convincing results and the most reliable predictions.

Summary of modelling solutions for hydrological change

The theoretical introduction here outlined has clarified how to model hydrological change and, in particular how to represent diverse occurrences of hydrological change by means of a single general stochastic formulation, given by model (2). However, hydrological change may be practically induced by various different physical factors which translate into several and specific modelling solutions. Therefore, it is important to summarise how to recognise the different instances of hydrological change, therefore setting the basis for a model identification procedure.

The first question for the modeller (Q1) is whether hydrological change is inducing a temporal deterministic change of the statistics of the involved hydrological variables (namely, whether some of these variables are to be modelled as non-stationary processes, see Fig. 1). A positive answer to Q1 implies that the above deterministic relationship is identified (and not just assumed to exist or deemed to be random). Whereas if the answer is negative, the classical solutions for hydrological modelling, which identify the related stationary hydrological model, can be used, perhaps with more sophisticated modelling assumptions (e.g. assuming long-term persistence). A blueprint for stochastic modelling of uncertain hydrological systems has been recently presented[40], which basically relies on a multiple simulation approach that uses several different realisations for stochastic input data, stochastic parameters and stochastic model structure.

In the case of a positive answer to Q1, a second question (Q2) arises next as whether non-stationarity is induced by non-stationary input, changing parameters (due to changes in catchment behaviours, soil storage, soil properties, river roughness, hydraulic conductivity, etc.), time-varying relationship between input and parameters, or time-varying process dynamics, which translates in a time-varying model structure. In this respect, two important remarks should be framed: (i) a physical explanation should be provided to justify non-stationarity in physical processes; (ii) the model uncertainty in any of the non-stationary cases will also be time varying and will generally increase, because the modelling framework becomes more complex, while the available information encapsulated in the data set is the same for all modelling options. We mentioned that this fact should be carefully considered when evaluating the opportunity to account or not for time-varying behaviours. Each hypothesis need to be tested by comparing model results and their uncertainty, therefore implying that uncertainty has a relevant role in the interpretation and modelling of hydrological change.

When non-stationarity is clearly recognised, the corresponding deterministic relationship for the statistics of hydrological variables should be identified. Therefore the stochastic expressions for $f_{\boldsymbol{\Theta},\boldsymbol{I}}(\boldsymbol{\Theta},\boldsymbol{I},t)$ and $Kf_{\boldsymbol{\Theta},\boldsymbol{I}}(\boldsymbol{\Theta},\boldsymbol{I},t)$ should be defined[40].

Model calibration and objective functions

In hydrology, and especially in the presence of hydrological change, model calibration is of fundamental relevance. In fact, time variable parameters may inflate the estimation variance and therefore parameter uncertainty. When a stochastic formulation (Equation (2)) is adopted, an optimisation algorithm for parameter calibration should be used in order to estimate the entire probability distribution of the model parameters and not simply their expected value. An opportunity is given by the DREAM algorithm[52,53]. DREAM is a global optimization algorithm that makes use of population evolution like in evolutionary algorithms together with a selection rule to assess whether a candidate parameter set is to be retained. The sample of retained sets after convergence can be used to infer the probability distribution of model parameters. However, it should be noted that DREAM is computationally intensive and therefore its use may be problematic in some circumstances.

A relevant challenge is the identification of non-stationarity in the model parameters and the identification of a deterministic relationship to explain their change in time. As we mentioned when discussing the challenge of recognizing non-stationarity, our proposed approach needs to acquire much information as possible on the system. We believe that the adoption of a non-stationary approach should be always supported by physical evidence, that may potentially suggest how parameters may vary in time. For instance, several models include parameters that quantify the water storage capacity in the catchment, which may vary after heavy urbanisation. In such a case, one could assume that the change in time of the considered parameter is explained by a deterministic parametric law. The structure of such relationship could be linear or non-linear, depending on the available information. Finally, a comparative assessment of the results and their uncertainty should lead to the identification of the most feasible approach.

Whatever estimation methods and algorithms are used, an objective function needs to be selected for parameter calibration. Several options can be found in the scientific literature. Among them we may recall likelihood functions whose statistical basis is supposed to lead to a consistent parameter estimation[54-57]. As a matter of fact, there is an increasing preference of likelihood functions to "ad hoc" objective functions or to the classical quadratic solutions that are frequently employed in hydrology (e.g. Nash-Sutcliffe efficiency, least squares, etc.).

Even though a statistically based estimation procedure has the advantage to infer distributional properties (like consistency and asymptotic normality), it is constrained by assumptions and hypotheses hardly satisfied when dealing with Nature, in particular in the presence of hydrological change. If the hypotheses are not fully met, the statistical properties of the estimator do not hold and therefore the advantage of using a likelihood function for parameter estimation may vanish. In this case, the use of an alternative, perhaps not statistically based, objective function should be considered, particularly if it provides a more robust estimation in view of the scope of the analysis.

To estimate the probability distribution of the model parameters, one should also note that hydrological models are never perfect[58]. Therefore, true values of parameters strictly speaking do not exist and the probability distributions of model parameters intimately depend on model calibration. We may thus conclude that it is unavoidable to use imperfect estimators in hydrology and therefore their use should be always motivated on a practical basis. Namely, one should prove that the underlying approximations and unsatisfied assumptions can be tolerated for the sake of reaching the purpose of the analysis, no matter if a likelihood function is used or not[40].

A final point, which is important to discuss is the key role that parameter calibration plays in hydrological modelling. In the recent past several research attempts have been made to devise calibration-free approaches. Reducing calibration requirements has also been one of the targets of the PUB (Predictions in Ungauged Basins) research initiative[59,60]. In fact, the increased awareness of hydrological change raised the concern that data collected in the past may be not representative of current conditions and therefore calibrated models could be unable to predict change. We believe that this view is narrowing the opportunities that hydrological modelling offers for the solution of current research and applied challenges. We already expressed our opinion that uncertainty is unavoidable in hydrology and hydrological change makes uncertainty even more relevant. The presence of uncertainty implies the need for a stochastic approach and therefore the need for calibration. It will never be possible to measure the parameters of hydrological models. When data are not available, calibration could be performed by basing on expert knowledge. However, calibration based on data observations is always preferable. Past data and information are very useful to predict change, as they offer the opportunity to decipher its dynamics.

Identifying the feedbacks with societal systems

The discussion presented here has emphasized that deterministic relationships may be necessary to identify the dependence on time of (the statistics of) model input, parameters and structure for effectively modelling hydrological change. Deterministic relationships recognizing hydrological change should emerge as a fact that is scientifically explainable and testable and should not arise from either perception or belief. If one assumes that something is changing in the environment, then it is necessary to support such an assumption with data and with a clear evidence of what is changing and how. We would like to issue a call for bringing scientific evidence and data upfront, and the above need to identify sufficient evidence of changing behaviours is an opportunity to this end.

There is no doubt that many instances of hydrological change are induced by human impact and therefore the joint study and modelling of hydrology and related human actions is an essential prerequisite to formulate hypotheses and to better understand the dynamics of the complex interactions between humans and water[9,61]. The connection between water and humans has been formerly modelled as a one-way interaction, therefore neglecting the human impact on environmental systems. Indeed, hydrology mainly worked on pristine catchments, in order to improve the knowledge of undisturbed systems. Recently, the human impact became progressively evident. As a consequence, modern hydrology should move forward the study of human-impacted catchments and the related two-way interaction between society and water[62]. The analysis of human modifications on natural systems as well as societal dynamics may thus provide support to the identification of the deterministic relationships for hydrological change. These may be expressed, for instance, as functions describing the increase of urbanization and water withdrawal, which may translate into relationships explaining the change in time of model parameters and/or external forcings. The aforementioned feedbacks can be taken into account by either (i) adopting one of the six time-varying modelling solutions identified above (see Fig. 1), or (ii) using the piece-wise stationary modelling stated before and even a stationary model, when feedbacks are not changing in time.

Interdisciplinarity is a necessary requirement for obtaining an improved interpretation of the links between hydrology and society. However, interdisciplinarity must be focused on the purpose of the analysis. Practical hydrological problems are decision making problems, whose optimal solutions should synthesize the contribution of the different disciplines. A potential drawback related to interdisciplinarity may be recognized, namely, the risk of being affected by the biased view of the discipline or even seeking the benefit of the discipline instead of the benefit for society (which corresponds to an efficient identification of the problem solution). Such a risk is enhanced with the increasing number of involved disciplines. The role of sister disciplines should be to provide support to the main discipline related to the specific problem: for hydrology, the role of social sciences is to contribute to the interpretation of the social dynamics to promote an efficient identification of solutions to decision making problems that are markedly technical.

The intimate relationship between humans and water has a very long history: however, there is no doubt that it recently evolved at an unprecedented pace. Focused research and a forward looking perspective are needed to set the basis for planning the future for water and society.

CONCLUSION

The future of water and society is intimately related to hydrological change, which is the result of natural variability and human impacts, either planned (e.g. for enhancing exploitation and utility of water) or resulting as side effects of multiple activities (e.g. urbanization). Natural variability and human impacts interact according to dynamics that are not fully understood, yet they are crucial for the mitigation of water-related risks and environmental planning. For this reason, hydrological change is a topical research issue today, and it is the subject of "Panta Rhei", the scientific decade 2013-2022 of the International Association of Hydrological Sciences. Hydrological change is a challenging research topic, that is rooted in the history and tradition of hydrology but, at the same time, calls for a reorganization of the way in which hydrology is studied, taught and applied. It is a challenge that requires a forward looking interdisciplinary approach to address problems that can only be solved through community efforts at all levels. The hydrological community is setting the basis to tackle the related research questions through a corporative approach and an improved global accessibility to scientific research.

This paper aims to clarify and systematise the theoretical background to model hydrological change. We promote a stochastic approach because it is general, comprehensive and it allows an integrated treatment of uncertainty, which we believe is a fundamental property of hydrological systems and tightly related to change. The study of the past, through recorded data as well as historical information related to hydrology, is the key to comprehend hydrological change. Data are an essential prerequisite to improve prediction models through a more refined interpretation and modelling of hydrological systems.

The opportunity for research in hydrology is enormously increasing therefore offering new perspectives and tools[63,64]. There is no doubt that hydrological change should be faced by promoting a change of research in hydrology: we are convinced that we do not need any major paradigm shift, but rather an improved focus on monitoring techniques and exploitation of information for improving the physical basis of hydrological models within a stochastic representation. This latter is necessary to take into full account the unavoidable inherent randomness of the water cycle.

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Sidebar title: Flood events as an indicator of hydrological change

Recent flood events are often reported to be relevant evidences of hydrological change. Indeed, the damages caused by floods are steadily increasing in many countries but the triggers are not yet clearly identified and may include societal development and the associated increased urbanisation and extension of impervious areas, changes of the river network geometry and catchment alteration. From 1980 to 2012 the world-wide occurrence of flood events significantly increased from nearly 40 events per year to almost 130, with a peak of 175 events in 2006[28,65]. Recent catastrophic flooding may be recalled here: for example, the Central Europe floods in summer 2010, the Queensland floods (Australia) in December 2010-January 2011, and the recent Sardinia flood (Italy), last November 2013. Floods are the first cause of fatalities and economic losses among natural disasters all over the world (Fig. 2). Globally, in 2011 nearly 135 million people were affected by floods and their total damage amounted to almost 70 billion USD. The recent flooding event in Sardinia, for instance, caused 17 deaths and an estimated value of nearly 890 million USD of damages[66]. Given that hydrological change may play a relevant role in the formation of the flood flows, an improved representation of its effects is necessary to locate the areas where priority should be given for the mitigation of the flood risk, as recommended by several international policies for flood risk mitigation.

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Figures

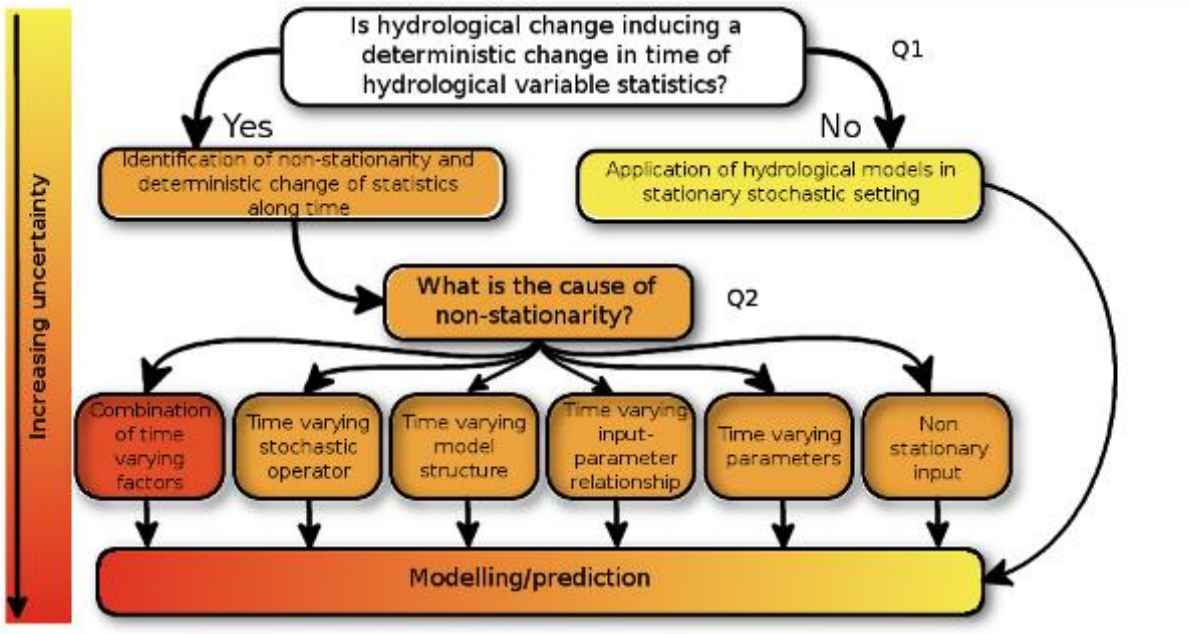

Figure 1. Sketch of modelling solutions for hydrological change.

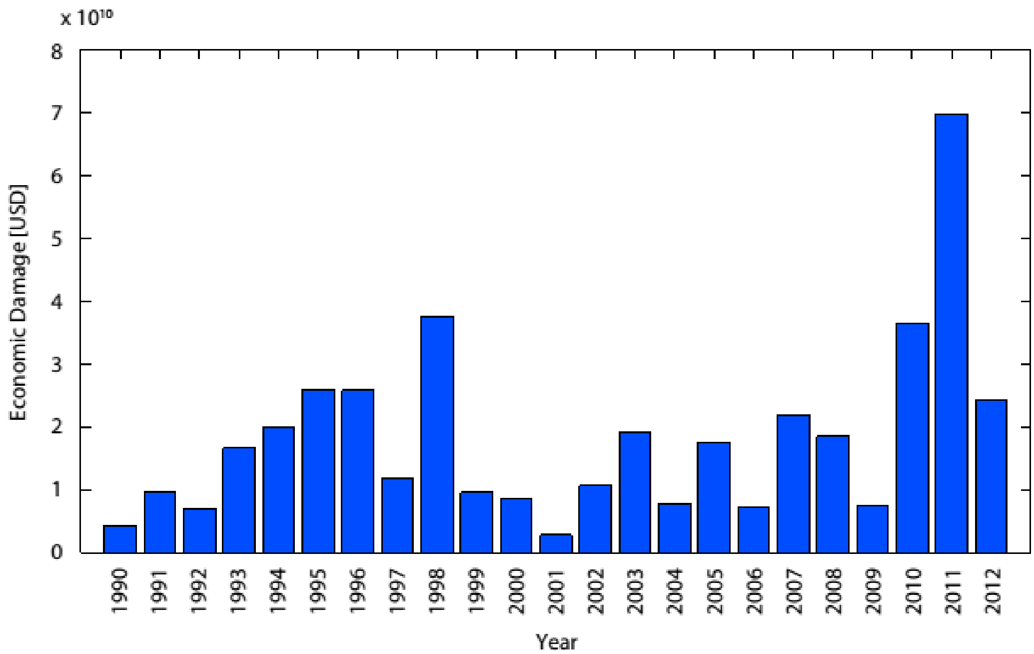

Figure 2. Temporal trend of flood related economic damages at the global scale (Source: EM-DAT[65]).