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Watersheds are not static: Implications of climate variability and hydrologic dynamics in modeling

Las cuencas no son estacionarias: implicancias de la variabilidad climática y dinámicas hidrológicas en la modelación

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SUMMARY

Demands on the world's freshwater continue to grow as the global population increases, demanding more efficiency in water resources planning and management. Therefore, better confidence and accurate hydrological predictions are needed. Traditionally, many (even most) data-driven hydrological models and hydraulic designs have considered the hydrological behavior of a basin as steady, representing the basin and its hydro-climatic relationships as stable and as long term time-invariant. But currently, a new approach based on hydrologic dynamics where watershed response changes, caused by changes in natural and anthropogenic forcings, are viewed as more adequate and representative of the real hydrological system. This paper discusses the implications of these approaches for modeling and process representation. Finally it is suggested that incorporating the influence of climate change and natural variability into hydrology must be viewed as a priority for water resource planners.

Key words: uncertainty, hydrological stationarity, hydrological dynamics, hydrological modeling.

RESUMEN

La demanda de agua dulce del mundo sigue creciendo a medida que aumenta la población mundial, exigiendo una mayor eficiencia en la planificación y gestión de los recursos hídricos. Por lo tanto, mayor confiabilidad y predicciones hidrológicas precisas resultan necesarias. Tradicionalmente, muchos (sino la mayoría) de los modelos hidrológicos y diseños hidráulicos han considerado el comportamiento hidrológico de una cuenca como estacionario, representando la cuenca y sus relaciones hidro-climáticas como estacionarias e invariantes en el tiempo. Pero en la actualidad, un nuevo enfoque basado en las dinámicas hidrológicas, donde cambios en las respuestas de una cuenca son causados por cambios en los forzantes naturales y antropogénicos, es visto como el más adecuado y representativo de un sistema hidrológico real. En este trabajo se analizan las implicaciones de estos enfoques en el modelado y representación de los procesos hidrológicos. Por último, se propone que incorporar la influencia del cambio climático y de la variabilidad climática natural en la hidrología deba ser considerado como una prioridad para los gestores de recursos hídricos.

Palabras clave: incertidumbre, estacionalidad hidrológica, dinámicas hidrológicas, modelación hidrológica.

INTRODUCTION

Human demands on the world's available freshwater continue to grow as the global population increases, demanding more efficiency in water resources planning and management. Therefore, holistic tools and better confidence and accurate hydrological predictions are needed. Currently, there are many tools, such as data-driven models, to support water resources planning and management. Tools such as conceptual hydrological models have been widely accepted by the hydrological community (Jin *et al.* 2010, Muñoz *et al.* 2011), helping in studies like the understanding of hydrological processes (Fleckenstein *et al.* 2010), water resources availability (Stone *et al.* 2010, Piao *et al.* 2010), climate change impact (Merz *et al.* 2011), land-use change assessments (Liu and Tong 2011), prediction in ungauged basins (Samaniego *et al.* 2010, Wagener and Montanari 2011) and prediction in ungauged climates (Merz *et al.* 2011, Li *et al.* 2012). But the traditional idea of hydrological modeling consisting of stable climate and catchment conditions (*i.e.* a 'stationary world') is falling out of use in favor of incorporating climatic and hydrologic dynamics, *i.e.* how watershed responses change due to changes in natural and anthropogenic forcings. Therefore, disciplines related to water resources management such as forestry, agriculture and hydroelectricity must begin to incorporate these dynamics into their planning and management.

Hydro-climatic dynamics (or shifts) have largely occurred due to natural conditions (*e.g.* the reduction in rainfall over southwestern Western Australia during the late 1960s (Baines and Folland 2007), or the exhibited El Niño frequency and amplitude changes before and after the late 1970s (Yeh *et al.* 2009), due to anthropogenic causes such as the greenhouse effect (Pielke 2005, Kundzewics *et al.* 2008), catchment modifications through river regulation, diversion, extractions, vegetation changes (Peel *et al.* 2010), or due to land use change (Pielke 2005), among other causes. However, models used in hydrological research and water management frequently assume a 'stationary world' (Peel and Blöschl 2011) where the simulated processes (*i.e.* the model) are stationary even when the forcings, in some cases, are not considered as stationary. For example, the hydraulic works design is based on statistical hydrological analyses which commonly (if not always) assume that data can be modeled by a single probability distribution function with temporally fixed parameters (mean, variance, and skewness, among many others). Additionally, this stationary world rationale considers that the response of a watershed to changes in forcings is caused by differences in timing and magnitudes of the response, without considering potential changes within-watershed processes such as the water storage in soil or in fractured rocks.

Due to a combination of natural and anthropogenic causes, many authors (*e.g.* Milly *et al.* 2008, Wagener *et al.* 2010, Merz *et al.* 2011, Coron *et al.* 2012, Steinschneider *et al.* 2012) are already establishing that climatic and hydrologic stationarity no longer serves as the default assumption for water and climatic predictions, and therefore water management, planning and the design of infrastructures should not be based on 'stationary world model' results.

As stated by Wagener *et al.* (2010), 'hydrology requires a paradigm shift in which predictions of system behavior that are beyond the range of previously observed variability become the new norm. To achieve this shift, hydrologists must become both synthesists, observing and analyzing the system as a holistic entity, and analysts, understanding the functioning of individual system components (hydrological processes such as surface, sub-surface and groundwater runoff and storage, infiltration, exfiltration and evapotranspiration, among others), while operating firmly within a well-designed hypothesis-testing framework (Blöschl 2006). This is the basis of the hydrologic dynamics concept, where a basin's processes and hydro-climatic relationships are viewed as time-variant. In this paper, a discussion of the stationary and dynamic hydrological modeling approach, based on model uncertainties and model predictability, is carried out. Moreover, it is suggested that incorporating the influence of climate change and natural variability into modeling must be viewed as a priority for water resource planners.

MODEL UNCERTAINTY

The modeling process has usually been beset by uncertainties in: i) the input data used to drive the model (Donohue *et al.* 2010), ii) the output data used for calibration (*e.g.* streamflow) (McMillan *et al.* 2010), iii) the calibration method and performance measurements adopted (objective functions) (Efstratiadis and Koutsoyiannins 2010), and/or iv) the model structure (Andréassian *et al.* 2009), contributing to model and parameter uncertainty. Therefore, adequate hydrological modeling is necessary to understand and simulate the dominant processes and dynamics that control the hydric balance in a basin, reduce model uncertainty, improve the output and prediction confidence degree, and predict in a realistic manner the future behavior of a basin under changing conditions (Merz *et al.* 2011).

In earth sciences and especially in hydrology, there is a great need to adequately choose and perform conceptual models, reduce their predictive uncertainty, and improve the understanding of hydrological processes, by improving the model structure, ensuring the identifiability of the parameters and/or reducing or limiting the non-uniqueness (equifinality) of model parameters. Only by attempting to resolve the above mentioned issues will the model predictions and related hydraulic designs be better prepared for the real world system. Additionally, model performance relies on measured data, which is also subject to uncertainties (sampling frequencies, sampling locations, representativeness of variables), considering that measured variables are surrogates of hydrological processes. Thus, improving monitoring networks will also contribute to improving hydrological knowledge.

In a conceptual model it is known that different sets of parameters are often distributed within a viable range, and that sometimes, even different conceptualizations of the system (model structure) can give equally good results in terms of predefined objective functions (Wagener *et al.* 2003). This behavior relative to the parameters of a model is defined as equifinality (Beven 2006). The thesis of equifinality aims at highlighting that there are various reasonable (or realistic) representations of a basin that cannot be easily rejected, and therefore must be considered in the estimation of uncertainty associated with the predictions. Put in another way, there are varied parameterizations of a model that can lead to similar statistical results, and therefore just one set of correct parameters (a 'stationary model') cannot be selected (Beven 2006), mainly due to the different response modes of a basin that are not simulated in a 'stationary model'.

STATIONARITY OR DYNAMIC HYDROLOGIC MODELING

Hydrological modeling must be viewed as a tool for water management, planning and analysis. Models are virtual hydrological laboratories where both specific studies and conceptual generalizations are developed to explore and test hypotheses (Kirchner 2006) providing a basis to understand and investigate relationships between climate and water resources (Choia and Deal 2008).

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity, where runoff processes are