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Stochastic watershed models for hydrologic risk management

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ABSTRACT

Over half a century ago, the Harvard Water Program introduced the field of operational or synthetic hydrology providing stochastic streamflow models (SSMs), which could generate ensembles of synthetic streamflow traces useful for hydrologic risk management. The application of SSMs, based on streamflow observations alone, revolutionized water resources planning activities, yet has fallen out of favor due, in part, to their inability to account for the now nearly ubiquitous anthropogenic influences on streamflow. This commentary advances the modern equivalent of SSMs, termed 'stochastic watershed models' (SWMs) useful as input to nearly all modern risk based water resource decision making approaches. SWMs are deterministic watershed models implemented using stochastic meteorological series, model parameters and model errors, to generate ensembles of streamflow traces that represent the variability in possible future streamflows. SWMs combine deterministic watershed models, which are ideally suited to accounting for anthropogenic influences, with recent developments in uncertainty analysis and principles of stochastic simulation.

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1. Introduction

For pedagogic purposes, when introducing a new conceptual approach to planning for the future, it is instructive to consider how we routinely plan our personal finances. Consider the personal problem of planning for retirement to ensure an adequate source of income until death, say 30 years from now. On the one hand, one could plan for retirement assuming that future financial and investment markets will mimic, exactly, the historical market over the past 30 years. Using only historical financial markets would result in an adequate income over the next 30 years with a reliability of just 50%. This result is predicated on stationarity of the past and future market in which case the future 30-year market would generally have an equal probability of delivering higher or lower returns on investment than the historical market. The Monte-Carlo method was introduced to address this issue (see [21]) and is now a pervasive approach to personal retirement planning with proprietary software for personal web-based implementation; it is currently offered by nearly every major financial institution. The Monte-Carlo approach to retirement planning is based on a stochastic representation of the market, enabling evaluation of ones retirement nest egg over hundreds of possible future 30-year markets to ensure that with some reliability (typically in the range of 90–95%) the nest egg will deliver adequate income over that entire planning horizon. Such an approach to managing personal financial risk is more generally defined by the concept of Value-at-Risk [22].

Risk management approaches are now pervasive in the world of finance, and the concept of Value-at-Risk has emerged as the industry standard. By analogy, hydrologic risk management approaches based on Monte-Carlo simulation experiments were introduced in the middle of the twentieth century along with the necessary digital computational resources to enable their application. The creation of the field of 'operational hydrology', or 'stochastic streamflow modeling', introduced by Maass et al. [47], Yevjevich [103], Fiering [19], Matalas [51], Valencia and Schaake [88] and others, revolutionized water resources planning, design and management because it enabled hydrologists to generate what

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they believed (under stationarity assumption) to be representative ensembles of streamflow series over future planning horizons, thus enabling the exploration of consequences of future hydrologic conditions not experienced historically, along with the application of modern risk management approaches [46]. Stochastic Streamflow Models (SSMs) were designed to mimic our historical hydrologic experience, while simultaneously enabling us to recognize the range of statistically possible future hydrologic conditions and the risk of failure associated with water infrastructure. For example, with only a single experience of the 'flood of record' or the 'drought of record', SSMs can provide thousands of possible future hydrologic scenarios, each with its own flood and/or drought of record; such exercises provide a much richer set of hydrologic possibilities with which to evaluate water resource system security. SSMs also enabled hydrologists to generate streamflow traces over planning periods which are either longer or shorter than the arbitrary length of the available historical records upon which they are based. Researchers have also incorporated model parameter uncertainty into generated series to represent the limited precision with which model parameters can be estimated in a stationary world [91,76,77].

Until the arrival of SSMs, reliability based planning for water supply was challenging because hydrologists based their plans on the single n-year drought of record, which under the assumption of stationarity, has a probability of only 50% of being exceeded (or not), in future n-year planning horizons (see [92], for a detailed discussion of this issue). This was analogous to the use of the historical market for planning financial risk prior to the now pervasive use of Monte-Carlo financial risk software described above.

Over time, SSMs have enabled a much richer understanding of the reliability, vulnerability and resilience of future water resource systems [28]. Such computational tools and principles also enabled a more complete integration of uncertainty into water resource decision making and have been in common use by the U.S. Army Corps of Engineers [87] and the U.S. Bureau of Reclamation [43,66,82], and other agencies, worldwide, for over 50 years. SSMs were the prerequisite to modern Risk Based Decision Making (RBDM) approaches. RBDM is a well-established methodology that can enable determination of an appropriate level of investment based on the expected benefits and damages avoided versus the cost of the infrastructure required [58] and is now standard practice by U.S. Federal agencies (see [8]; and [73]; for references). Lempert et al. [45] and others have introduced a robust decision making (RDM) framework for making decisions based on a large number of imperfect forecasts of the future.

Instead of relying on a single probabilistic forecast of the future, RBDM and RDM seek robust strategies that are likely to lead to better outcomes (at least on average) than would result from planning with a single scenario for the future. Both approaches employ computational tools that represent the diversity of reasonable futures. Stakhiv [73] argues that the application of RBDM and RDM approaches depends critically upon a "new family of hydrologic techniques for risk, reliability and uncertainty analysis that could be used for emerging aspects of climate (and other forms of) uncertainty." (Also see [64].) Similarly, in an interagency initiative on water resources management, Brekke et al. [8] argue that "stochastic modeling can be useful for developing climate scenarios that include a wide range of potential hydroclimatic conditions. The expanded variability may allow more robust evaluation of planning alternatives".

Clearly a fundamental requirement for nearly every RBDM simulation study addressing water security, are methods for generating ensembles of streamflow traces which can characterize future hydrologic conditions. Unfortunately, as is described below, most SSMs originally designed for RBDM are no longer adequate because they do not capture changing hydrologic conditions due to anthropogenic influences. Milly et al. [53] argue that "we need to find ways to identify nonstationary probabilistic models of relevant environmental variables and to use those models to optimize water systems. The challenge is daunting."

The following section documents the fragmented state of the art associated with stochastic modeling of nonstationary hydrologic processes which serves as justification for a new approach to the development of nonstationary SSMs advanced here, termed Stochastic Watershed Models (SWMs). SWMs combine advances in deterministic watershed models (DWMs), uncertainty analysis for DWMs and stochastic streamflow modeling, together, to provide a comprehensive set of tools for hydrologic risk management under nonstationary conditions. SWMs are simply deterministic watershed models implemented in a stochastic mode (see [18]) using (possibly nonstationary) stochastic meteorological series for the purpose of generating ensembles of representative streamflow traces that represent the trend and variability in possible future flows as is illustrated in Fig. 1. Interestingly, using DWMs in this manner can also lead to novel insights into existing problems. For example, when ones goal is to calibrate a DWM for the purpose of generating representative streamflow traces, ones view of the role of model error, parameter error and input data errors evolve [39], enabling development of new approaches to model calibration, model hypothesis testing and most importantly improving our ability to ensure future water security.

2. What happened to the field of stochastic streamflow modeling?

Two arguments exist for the apparent demise of SSMs (1) an unrealistic reliance, focus and diversion of attention to purely deterministic approaches in planning frameworks and (2) the inability of traditional SSMs to account for the nonstationary hydrologic behavior now of interest. Koutsoyiannis et al. [38] argue that "Engineering hydrologists understood early that the design of engineering projects based on deterministic approaches would largely be a hopeless task and appreciated the usefulness of probabilistic approaches. Yet, during the last two decades, hydrology, following other geophysical disciplines, changed perspective and invested its hopes in deterministic descriptions and models."

A second argument for the demise of SSMs relates to the inability of nearly all traditional models to capture changes in streamflow regimes resulting from a variety of anthropogenic and climatic influences. This is in spite of our now pervasive understanding that human activity and influence is an integral component of the hydrologic system [52,53,95].

One emerging approach to handle hydrologic change is to adapt stationary SSMs to accommodate hydrologic change. Another approach is to adapt existing DWMs for use as SSMs, which is the central focus of this commentary. A new generation of SSMs termed Stochastic Watershed Models (SWMs) are advanced in this commentary for considering the integrated impacts of changes in climate, land use, water withdrawals, and other factors, within the context of water resource planning for ensuring water security. This section sets the stage for an introduction to a new generation of SSMs for handling nonstationary hydrologic processes, termed Stochastic Watershed Models, by summarizing past efforts to develop SSMs under nonstationary conditions.

2.1. A very brief review of the field of stochastic streamflow modeling

The field of stochastic hydrology began around the same time as digital computational resources became available in the 1960's and may be attributed to numerous hydrologists including, but not limited to Hurst, Fiering, Thomas, Yevjevich, and Beard, who intro-

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