# Mathematical Physics And Complex Analysis: Collection Of Survey Papers 4 I.e. 4th On The 50th Annive

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The 50th Anniversary of Water Resources Research

**Physically based modeling in catchment hydrology at 50: Survey and outlook**

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Key Points:
- Five decades of research on process-based hydrological modeling are reviewed
- Main themes are physical and mathematical consistency, rigorous numerics, and integrated models
- Research challenges discussed include model coupling, data assimilation, and subgrid variability

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**Abstract** Integrated, process-based numerical models in hydrology are rapidly evolving, spurred by novel theories in mathematical physics, advances in computational methods, insights from laboratory and field experiments, and the need to better understand and predict the potential impacts of population, land use, and climate change on our water resources. At the catchment scale, these simulation models are commonly based on conservation principles for surface and subsurface water flow and solute transport (e.g., the Richards, shallow water, and advection-dispersion equations), and they require robust numerical techniques for their resolution. Traditional (and still open) challenges in developing reliable and efficient models are associated with heterogeneity and variability in parameters and state variables; nonlinearities and scale effects in process dynamics; and complex or poorly known boundary conditions and initial system states. As catchment modeling enters a highly interdisciplinary era, new challenges arise from the need to maintain physical and numerical consistency in the description of multiple processes that interact over a range of scales and across different compartments of an overall system. This paper first gives an historical overview (past 50 years) of some of the key developments in physically based hydrological modeling, emphasizing how the interplay between theory, experiments, and modeling has contributed to advancing the state of the art. The second part of the paper examines some outstanding problems in integrated catchment modeling from the perspective of recent developments in mathematical and computational science.

## 1. Introduction

The advent of numerical modeling in hydrology coincides roughly with the birth of *Water Resources Research* (WRR). The first years of the journal document a rapid transition from electric analog and physical models to mathematical models. Early simulation studies in both subsurface [e.g., *Freeze and Witherspoon*, 1966] and surface [e.g., *Woolhiser and Liggett*, 1967] hydrology were to have a great influence on research directions in hydrology over the next half-century. To commemorate the 50th anniversary of WRR and to signal its contributions to process-based modeling in hydrology, we look back at developments in experimental, theoretical, and computational hydrology that have shaped the current state of the art in physically based catchment hydrological models (section 2), and we provide an outlook on current challenges and trends in the ongoing effort to cast these models into a rigorous and robust mathematical, physical, and numerical framework (section 3).

The roughly chronological survey allows us to trace significant advances and to mark the emergence of specialized subfields such as stochastic hydrology, parameter estimation, topographic analysis, and data assimilation. Our focus is mainly on flow processes, reflecting the traditional, central problem of rainfall-runoff partitioning in catchment hydrology, although relevant developments in solute transport will also be included. Numerical modeling of solute mass transfer and transport phenomena has been guided more by problems of soil and groundwater contamination and remediation, but in recent decades solute transport has played an increasingly prominent role in catchment hydrology, as it is essential for interpreting isotope tracer studies, for addressing travel time issues, and for incorporating geochemical and ecological phenomena in interdisciplinary models. An additional focus of the paper is on integrated surface/subsurface hydrological models (ISSHMs), as this is an area of much recent research and provides a platform for discussing developments in physically based interdisciplinary modeling, which extend beyond water flow and solute transport at the catchment scale toward multiphysics or Earth system models at much larger scales. In section 2, we review mainly WRR papers, but important contributions from other sources are also covered,





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