water

MDPI

Editorial

Watershed Hydrology: Scientific Advances and Environmental Assessments

Xuan Yu [1] and Christopher J. Duffy [2,*]

[1] Department of Geological Sciences, University of Delaware, Newark, DE 19716, USA; xuan@udel.edu
[2] Department of Civil and Environmental Engineering, Penn State University, University Park, PA 16802, USA
* Correspondence: cxd11@psu.edu; Tel.: +1-814-863-4384

Received: 9 February 2018; Accepted: 6 March 2018; Published: 8 March 2018

Abstract: The watershed is a fundamental concept in hydrology and is the basis for understanding hydrologic processes and for the planning and management of water resources. Storage and movement of water at a watershed scale is complicated due to the coupled processes which act over multiple spatial and temporal scales. In addition, climate change and human activities increase the complexity of these processes driving hydrologic change. Scientific advances in the field of watershed hydrology is now making use of the latest methods and technologies to achieve responsible management of water resources to meet the needs of rising populations and the protection of important ecosystems. The selected papers cover a wide range of issues that are relevant to watershed hydrology and have motivated model development, application, parameterization, uncertainty estimation, environment assessment, and management. Continued technological advances grounded in modern environmental science are necessary to meet these challenges. This will require a greater emphasis on disciplinary collaboration and integrated approaches to problem solving founded on science-driven innovations in technology, socio-economics, and public policy.

Keywords: watershed; catchment; models; climate change; ecosystem; management

1. Introduction

As water moves on, above, and below the Earth's surface, it forms the hydrologic cycle (i.e., hydrosphere), which lies between the atmosphere and the lithosphere and across the biosphere. Watershed is defined as the basic land unit for the hydrologic cycle description and resource management, because the water divide can be obtained from widely available topographic data and streamflow can be measured at the outlets [1]. Refining observations and modeling watershed hydrologic states and fluxes are the main components required to help improve the understanding of hydrologic processes and provide management support.

A modern approach to modeling watershed processes studies known coupled processes operating over a range of spatial and temporal scales. These processes include precipitation, overland flow, evapotranspiration, unsaturated flow, and groundwater flow, which describe the movement of water and simultaneous exchange between the various hydrological compartments, e.g., land surface, soil or vadose zone, and the underlying aquifers (i.e., phreatic zone). At the watershed scale, the hydrologic cycle also interacts with atmospheric processes, land surface, ecological processes, geological processes, and the pervasive effects of human activity. Therefore, the development of watershed models has been a strong objective of hydrologists [2,3] and remains challenging where gaps in our understanding of hydrologic processes and model capability are limited by data computational challenges [4].

Watershed analysis and models are important tools for environmental assessment, management, and conservation. In the United States, the Environmental Protection Agency, Army Corps of Engineers, and US Geological Survey provide repositories for tested watershed models for federal, state, and local water-resources planning, which have been applied on the national- and basin scales for water quality assessment (e.g., [5,6]). These model results have been widely applied for environmental management (e.g., best management practices (BMPs, [7]) and low impact development (LID, [8])). Technological advances in cyberinfrastructure have enabled the integrative hydrologic model and data development. A variety of watershed models have been archived or hosted by universities (e.g., The Pennsylvania State University (PIHM, http://www.pihm.psu.edu/), Texas A&M University (Hydrologic Modeling Inventory Website, http://hydrologicmodels.tamu.edu/)), research centers (e.g., Helmholtz Centre for Environmental Research (The Mesoscale Hydrologic Model, http://www.ufz.de/mhm/)), environmental companies (e.g., Aquanty (https://www.aquanty.com/hydrogeosphere), MIKE Powered by DHI (https://www.mikepoweredbydhi.com/products)), professional communities (e.g., CSDMS (Community surface dynamics modeling system, https://csdms.colorado.edu/wiki/Hydrological_Models/), CUAHSI (The Consortium of Universities for the Advancement of Hydrologic Science, Inc., https://www.cuahsi.org/data-models/)), and computer code repositories (e.g., ParFlow (https://github.com/parflow/parflow), UW Hydro (Computational Hydrology, http://uw-hydro.github.io/), GEOtop (GEOtop 2.x; http://geotopmodel.github.io/geotop/), RHESSys (The Regional Hydro-Ecologic Simulation System, https://github.com/RHESSys/RHESSys/)) to support broad applications in environmental management.

The main objective of the Special Issue is to assemble contributions of watershed models including model developments and environmental applications, which documents and inspires future directions in watershed hydrology.

2. Overview of This Special Issue

This Special Issue consists of 13 papers that cover diverse aspects of watershed hydrology. We summarize the articles using two main themes: (i) watershed models to advance scientific understanding of processes, parameters, and uncertainty; and (ii) model applications for environmental assessment, management, and conservation.

2.1. Advancing Process-Based Models in Watershed Hydrology

Begou et al. [9] conducted a sensitivity analysis and uncertainty estimation to compare the performance of catchment and sub-catchment calibration. The Soil and Water Assessment Tool (SWAT) was applied at Bani River, the major tributary of the Upper Niger River, Africa, and then calibrated using the Generalized Likelihood Uncertainty Estimation (GLUE) approach. The authors found that global parameter sets calibration was able to predict monthly and daily discharge with acceptable predictive uncertainty, which ensures transferability of the model parameters to ungauged sub-basins.

Cornelissen et al. [10] used the physics-based hydrological model HydroGeoSphere to test the role of distributed parameters in modeling hydrological processes. They investigated the sensitivity of discharge, water balance, and evapotranspiration patterns to spatial heterogeneity in land use, potential evapotranspiration, and precipitation. The results suggested that precipitation was the most sensitive input data set for discharge simulation, while spatially distributed land use parameterization had a much larger effect on evapotranspiration components and its pattern.

Son et al. [11] examined the impacts of fine-scale topography on ecohydrological processes by a spatially distributed model Regional Hydro-Ecological Simulation System (RHESSys). The results showed that the modeled streamflow was sensitive to digital elevation model (DEM) resolution, and coarser resolution models overestimated the climatic sensitivity of evapotranspiration and net primary productivity. These findings suggested that it is reliable to use at least 10-m DEM to simulate ecohydrological responses to climate change.

Muma et al. [12] modeled a coupled surface–subsurface flow process on an agricultural watershed. They applied a physics-based 3D hydrologic model CATHY (acronym for CATchment Hydrology) at Bras d'Henri River Watershed in Canada. Based on the calibrated model, subsurface drainage was found to increased baseflow and total flows, and decreased peak flows. In addition, the model can be applied to estimate the impacts on surface water quality of different agricultural practices.

Stern et al. [13] simulated streamflow and sediment transport using the Hydrological Simulation Program—Fortran (HSPF). The study area was a snow-dominated watershed contributing to the San Francisco Bay. The total sediment load has decreased by 50% during the last 50 years due to many reasons. The HSPF simulation matched the observed historical sediment reduction and highlighted the importance of climate as a main driving factor for sediment supply in this watershed. In particular, large storms associated with high peak flows are the most important driver of sediment transport.

Garee et al. [14] applied the SWAT model with a temperature index and elevation band algorithm in a glacier dominated watershed. The study area is one of the main sources of the Indus River, and upstream of Tarbela Dam, one of the largest dams in the world. The authors found that the combined effect of increased precipitation and warmer temperatures will increase streamflow by 10.63–43.70% by the year 2060. The projecting climate change impacts on the watershed will guide water resources management plans and dam construction and operation.

Li et al. [15] developed a stream network length estimation method based on flow recession dynamics. In headwater catchments, stream network length varies as the catchment wets and dries, both seasonally and in response to individual precipitation events, and direct observations of active stream network length (ASNL) is difficult. Based on flow recession rates, aquifer depth, and aquifer breath, the ASNL was estimated and agreed with GIS analysis results. This novel approach will bring more attention from both hydrologists and geomorphologists on stream network length estimation.

2.2. *Application of Watershed Models for Environmental Assessment*

Peng et al. [16] evaluated different soil water conservation methods on ecohydrological processes by RHESSys. The Loess Plateau is known for its highly erodible soil and fragile ecosystem. A variety of soil and water conservation methods have been applied since the 1950s, and a clear decline of streamflow has been observed. However, both climate change and water use could contribute to streamflow decreases as well. This study added modules of in-stream routing and reservoir operation to existing version of RHESSys, and evaluated soil and water conservation impacts on streamflow decline. The results suggested 78% of total impact on streamflow reduce is due to engineering construction of soil and water conservation.

Zhang et al. [17] combined several watershed analysis methods to evaluate the hydrologic impacts of dam construction. The study area was the Jiulong River Watershed (JRW), a medium-sized coastal watershed in Southeast China, which suffered from intensive human activities with over 13,500 hydraulic engineering facilities including over 120 small or medium dams along the mainstream and major tributaries. Flow duration curve analysis, hydrologic alteration, ranges of variability, and environmental flow were calculated to assess the impacts on daily and monthly streamflow regime. The approach is valuable for environmental impact assessment of dam construction.

Tang et al. [18] developed a flood frequency method to understand impacts of climate change on coastal watersheds. Many coastal areas are experiencing intensified flooding due to the combined impacts of the floods from the upstream watershed and the rising high tidal levels induced by sea-level rise (SLR). These climate change aspects have led to non-stationarity (i.e., trends) in flood records. The authors selected Pearl River Delta in South China due to its high density of river network and high frequency of extreme tides introduced by typhoons or storm surges. They combined a time-varying moments model and a hydrodynamic network model to estimate flood levels at 22 stations and found that when the non-stationarity was ignored, error up to 18% was found in the 100-year inflow floods and up to 14% in the 100-year tidal level.

Yu et al. [19] presented temporal variability of annual precipitation across a watershed to identify the spatial pattern of flood and drought frequency. The study area was the Huaihe River Basin with an area of 259,700 km^2, which typically suffered from both drought and flood hazards. The study found that the spatial distribution of precipitation varied remarkably, although a slight increasing trend could be observed over the entire basin, which provides important guidance for the water resources management in Huaihe River.

Li et al. [20] developed a classification method to assess catchment vulnerability to debris flow. They focused on the Wudongde Dam, one of the tallest hydroelectric dams in the world, and identified high, medium, and low vulnerability of debris flow susceptibility at 22 nearby watersheds. The approach will be applied to the whole Wudongde Dam area to assess debris flow hazard and secure dam stability.

Zhu and Chen [21] applied the storm water management model (SWMM) to assess the urban flooding reduction impacts of different engineering designs. In the late 20th century, low impact development (LID) and best management practices (BMPs) were proposed to control urban stormwater in United States. Gradually, these concepts and measures were introduced to China. The study modeled urban flooding in a typical residential area in Guangzhou, China to evaluate the effects of LID. The results showed that existing LID practices are able to control the flooding under the rainfall scenario of 2-year return period, 2-h rainfall duration, when the rainfall peak coefficient is 0.375. The control effects of LID practices are most affected by rainfall intensity compared to rainfall duration and rainfall peak.

3. Outlook

In this special issue, it is shown that advanced watershed model development and applications are a global enterprise, motivating many new technological innovations and interdisciplinary collaborations. As a result, we can expect in the future more reliable models, improved interpretations, and broader implementation where water is driving human and ecosystem services. Yet, there are still limitations in making significant advances, which we suggest follows four basic themes:

Design of a new generation of spatially resolved computational watershed models (e.g., [22]) driven by a new generation of field measurements including real time sensor networks and remote sensing ([23,24]);

Development of co-varying physical relationships for watershed processes that represent interactions between water, soil, vegetation, atmosphere, and geologic processes (e.g., [25,26]);

Enhance transparency, provisioning, and reproducibility of watershed models and analysis (e.g., [27,28]) to enable open communication between scientists; and

Improve the transfer and clarity of watershed knowledge among water resources scientists, engineers, policymakers, and the public to improve process understanding of a coupled, human–water system (e.g. [29,30]).

Acknowledgments: This work was supported by the U.S. National Science Foundation (EAR-0725019, EAR-1239285, EAR-1331726, and IIS-1344272) and U.S. Defense Advanced Projects Agency (World Modelers Program). The author of this paper and editor of this special issue would like to thank all authors for their notable contributions to this special issue, the reviewers for devoting their time and efforts to reviewing the manuscripts, and the Water Editorial team for their great support during the review of the submitted manuscripts.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Edwards, P.J.; Williard, K.W.; Schoonover, J.E. Fundamentals of watershed hydrology. *J. Contemp. Water Res. Educ.* **2015**, *154*, 3–20. [CrossRef]
2. Clark, M.P.; Bierkens, M.F.; Samaniego, L.; Woods, R.A.; Uijlenhoet, R.; Bennett, K.E.; Pauwels, V.R.; Cai, X.; Wood, A.W.; Peters-Lidard, C.D. The evolution of process-based hydrologic models: Historical challenges and the collective quest for physical realism. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 3427–3440. [CrossRef]
3. Ehret, U.; Gupta, H.V.; Sivapalan, M.; Weijs, S.V.; Schymanski, S.J.; Blöschl, G.; Gelfan, A.N.; Harman, C.; Kleidon, A.; Bogaard, T.A. Advancing catchment hydrology to deal with predictions under change. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 649–671. [CrossRef]

4. Clark, M.P.; Fan, Y.; Lawrence, D.M.; Adam, J.C.; Bolster, D.; Gochis, D.J.; Hooper, R.P.; Kumar, M.; Leung, L.R.; Mackay, D.S. Improving the representation of hydrologic processes in Earth System Models. *Water Resour. Res.* **2015**, *51*, 5929–5956. [CrossRef]
5. Herrmann, M.; Najjar, R.G.; Kemp, W.M.; Alexander, R.B.; Boyer, E.W.; Cai, W.-J.; Griffith, P.C.; Kroeger, K.D.; McCallister, S.L.; Smith, R.A. Net ecosystem production and organic carbon balance of US East Coast estuaries: A synthesis approach. *Glob. Biogeochem. Cycles* **2015**, *29*, 96–111. [CrossRef]
6. Anning, D.W.; Flynn, M.E. *Dissolved-Solids Sources, Loads, Yields, and Concentrations in Streams of the Conterminous United States*; US Geological Survey: Reston, VA, USA, 2014.
7. Schueler, T.R.; Metropolitan Washington Water Resources Planning Board. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs*; Metropolitan Information Center: Washington, DC, USA, 1987.
8. Prince George's County. *Low-Impact Development Design Strategies: An Integrated Design Approach*; Department of Environmental Resources: Largo, MD, USA, 1999.
9. Chaibou Begou, J.; Jomaa, S.; Benabdallah, S.; Bazie, P.; Afouda, A.; Rode, M. Multi-site validation of the SWAT model on the Bani catchment: Model performance and predictive uncertainty. *Water* **2016**, *8*, 178. [CrossRef]
10. Cornelissen, T.; Diekkrüger, B.; Bogena, H.R. Using high-resolution data to test parameter sensitivity of the distributed hydrological model HydroGeoSphere. *Water* **2016**, *8*, 202. [CrossRef]
11. Son, K.; Tague, C.; Hunsaker, C. Effects of model spatial resolution on ecohydrologic predictions and their sensitivity to inter-annual climate variability. *Water* **2016**, *8*, 321. [CrossRef]
12. Muma, M.; Rousseau, A.N.; Gumiere, S.J. Assessment of the impact of subsurface agricultural drainage on soil water storage and flows of a small watershed. *Water* **2016**, *8*, 326. [CrossRef]
13. Stern, M.; Flint, L.; Minear, J.; Flint, A.; Wright, S. Characterizing changes in streamflow and sediment supply in the Sacramento River Basin, California, using Hydrological Simulation Program—FORTRAN (HSPF). *Water* **2016**, *8*, 432. [CrossRef]
14. Garee, K.; Chen, X.; Bao, A.; Wang, Y.; Meng, F. Hydrological Modeling of the Upper Indus Basin: A Case Study from a High-Altitude Glacierized Catchment Hunza. *Water* **2017**, *9*, 17. [CrossRef]
15. Li, W.; Zhang, K.; Long, Y.; Feng, L. Estimation of Active Stream Network Length in a Hilly Headwater Catchment Using Recession Flow Analysis. *Water* **2017**, *9*, 348. [CrossRef]
16. Peng, H.; Jia, Y.; Tague, C.; Slaughter, P. An eco-hydrological model-based assessment of the impacts of soil and water conservation management in the Jinghe river basin, China. *Water* **2015**, *7*, 6301–6320. [CrossRef]
17. Zhang, Z.; Huang, Y.; Huang, J. Hydrologic alteration associated with dam construction in a medium-sized coastal watershed of southeast China. *Water* **2016**, *8*, 317. [CrossRef]
18. Tang, Y.; Guo, Q.; Su, C.; Chen, X. Flooding in Delta Areas under Changing Climate: Response of Design Flood Level to Non-Stationarity in Both Inflow Floods and High Tides in South China. *Water* **2017**, *9*, 471. [CrossRef]
19. Yu, Z.-L.; Yan, D.-H.; Ni, G.-H.; Do, P.; Yan, D.-M.; Cai, S.-Y.; Qin, T.-L.; Weng, B.-S.; Yang, M.-J. Variability of Spatially Grid-Distributed Precipitation over the Huaihe River Basin in China. *Water* **2017**, *9*, 489. [CrossRef]
20. Li, Y.; Wang, H.; Chen, J.; Shang, Y. Debris Flow Susceptibility Assessment in the Wudongde Dam Area, China Based on Rock Engineering System and Fuzzy C-Means Algorithm. *Water* **2017**, *9*, 669. [CrossRef]
21. Zhu, Z.; Chen, X. Evaluating the Effects of Low Impact Development Practices on Urban Flooding under Different Rainfall Intensities. *Water* **2017**, *9*, 548. [CrossRef]
22. Duffy, C.; Shi, Y.; Davis, K.; Slingerland, R.; Li, L.; Sullivan, P.L.; Goddéris, Y.; Brantley, S.L. Designing a Suite of Models to Explore Critical Zone Function. *Procedia Earth Planet. Sci.* **2014**, *10*, 7–15. [CrossRef]
23. Brantley, S.L.; DiBiase, R.A.; Russo, T.A.; Davis, K.J.; Eissenstat, D.M.; Dere, A.L.; Neal, A.L.; Brubaker, K.M.; Arthur, D.K. Designing a suite of measurements to understand the critical zone. *Earth Surf. Dyn.* **2016**, *4*, 211–235. [CrossRef]
24. Tauro, F.; Selker, J.; van de Giesen, N.; Abrate, T.; Uijlenhoet, R.; Porfiri, M.; Manfreda, S.; Caylor, K.; Moramarco, T.; Benveniste, J. Measurements and Observations in the XXI century (MOXXI): Innovation and multi-disciplinarity to sense the hydrological cycle. *Hydrol. Sci. J.* **2017**, *63*, 169–196. [CrossRef]
25. Paniconi, C.; Putti, M. Physically based modeling in catchment hydrology at 50: Survey and outlook. *Water Resour. Res.* **2015**, *51*, 7090–7129. [CrossRef]

26. Li, L.; Maher, K.; Navarre-Sitchler, A.; Druhan, J.; Meile, C.; Lawrence, C.; Moore, J.; Perdrial, J.; Sullivan, P.; Thompson, A. Expanding the role of reactive transport models in critical zone processes. *Earth-Sci. Rev.* **2017**, *165*, 280–301. [CrossRef]
27. Yu, X.; Duffy, C.J.; Rousseau, A.N.; Bhatt, G.; Pardo Álvarez, Á.; Charron, D. Open science in practice: Learning integrated modeling of coupled surface-subsurface flow processes from scratch. *Earth Space Sci.* **2016**, *3*, 190–206. [CrossRef]
28. Hutton, C.; Wagener, T.; Freer, J.; Han, D.; Duffy, C.; Arheimer, B. Most computational hydrology is not reproducible, so is it really science? *Water Resour. Res.* **2016**, *52*, 7548–7555. [CrossRef]
29. Sanderson, M.R.; Bergtold, J.S.; Heier Stamm, J.L.; Caldas, M.M.; Ramsey, S.M. Bringing the "social" into socio-hydrology: Conservation policy support in the Central Great Plains of Kansas, USA. *Water Resour. Res.* **2017**, *53*, 6725–6743. [CrossRef]
30. Chen, X.; Wang, D.; Tian, F.; Sivapalan, M. From channelization to restoration: Sociohydrologic modeling with changing community preferences in the Kissimmee River Basin, Florida. *Water Resour. Res.* **2016**, *52*, 1227–1244. [CrossRef]