Runoff Prediction in Ungauged Basins

Synthesis across Processes, Places and Scales

Predicting water runoff in the mostly ungauged water catchment areas of the world is vital to practical applications such as the design of drainage infrastructure and flooding defences, for runoff forecasting and for catchment management tasks such as water allocation and climate impact analysis.

This important new book synthesises decades of rigorous analytical research from around the world, forming a holistic approach to catchment hydrology, and providing a one-stop resource for hydrologists in both developed and developing countries. It brings together results from individual location-based studies with comparative analysis along gradients of climate and landscape features. Topics include data for runoff regionalisation and the prediction of runoff hydrographs, flow duration curves, flow paths and residence times, annual and seasonal runoff, and floods.

Illustrated with many case studies, and including a final chapter on recommendations for researchers and practitioners, this book is written by expert international authors involved in the prestigious International Association of Hydrological Sciences (IAHS) Predictions in Ungauged Basins (PUB) initiative. It is a key resource for academic researchers in the fields of hydrology, hydrogeology, ecology, geography, soil science, and environmental and civil engineering, and professionals working with water runoff in ungauged water basins.

Günter Blöschl is Professor of Hydrology, Director of the Centre for Water Resource Systems, and Head of the Institute of Hydraulic Engineering and Water Resources Management at the Vienna University of Technology. He has published extensively on subjects related to hydrology and water resources and served as an editor and associate editor for ten of the best scientific journals in the field. Professor Blöschl has been elected Fellow of the American Geophysical Union and the German Academy of Science and Engineering, has chaired the International Association of Hydrological Sciences (IAHS) Predictions in Ungauged Basins (PUB) initiative, and has been elected President of the European Geosciences Union. Recently he has been awarded the prestigious Advanced Grant of the European Research Council (ERC).

Murugesu Sivapalan is Professor of Civil and Environmental Engineering, and of Geography and Geographic Information Science at the University of Illinois. He was founding chair of the International Association of Hydrological Sciences (IAHS) Predictions in Ungauged Basins (PUB) initiative. He has published extensively on catchment hydrology in several international journals and is Executive Editor of the European Geosciences Union's *Hydrology and Earth System Sciences* journal. Professor Sivapalan has also received the European Geophysical Society's John Dalton Medal, the International Hydrology Prize of the IAHS, and the Hydrological Sciences Award and the Robert E. Horton Medal of the American Geophysical Union. He was also the recipient of the Centenary Medal of the Australian Government and an Honorary Doctorate of the Delft University of Technology.

Thorsten Wagener is Professor of Water and Environmental Security in the Department of Civil Engineering at the University of Bristol. He is a Vice President of the International Association of Hydrological Sciences, editor of the journal *Hydrology and Earth System Sciences*, and associate editor of several other journals. Dr Wagener has been awarded DAAD (Deutscher Akademischer Austauschdienst) fellowships, an IEMSS Early Career Excellence Prize, Best Paper Awards of the *Journal of Environmental Modeling and Software*, a US EPA Early Career Award, the Walter Huber Civil Engineering Research Prize of the American Society of Civil Engineers, an Alexander von Humboldt Foundation Fellowship, and an Education and Public Service Award of the Universities Council for Water Resources.

Alberto Viglione is a Research Hydrologist at the Vienna University of Technology. During 2004–7 he conducted doctoral research on 'Non-supervised statistical methods for the prediction

of hydrological variables in ungauged sites' at the Hydraulic Department of the Politecnico of Turin. He has authored or co-authored numerous papers in hydrology, particularly on floods, from both statistical and process-based perspectives, and on hydrological characterisation of river basins. Dr Viglione has developed software for regional frequency analysis and rainfall–runoff modelling under the R environment, which is available online. He also acts as a reviewer for several prestigious journals, and has been involved in a number of research projects related to hydrology and flood frequency analysis in Italy, Austria and several other European countries.

HUBERT SAVENIJE is Professor of Hydrology and Head of the Water Resources Section at the Delft University of Technology and also serves as Editor-in-Chief of *Hydrology and Earth System Sciences* and *Physics and Chemistry of the Earth*. He is President-Elect of the International Association of Hydrological Sciences (IAHS) as well as Chair of the IAHS Predictions in Ungauged Basins (PUB) initiative. Professor Savenije has published widely in several leading international journals and was Vice Rector at UNESCO-IHE, Institute for Water Education. He is Past-President of Hydrological Sciences of the European Geosciences Union (EGU), and Past-President of the International Commission on Water Resources Systems of the IAHS. He has been awarded, among other things, the Henry Darcy Medal of the EGU and the EGU Batch Award.

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EDITED BY

GÜNTER BLÖSCHL
Technische Universität Wien, Austria

MURUGESU SIVAPALAN
University of Illinois, Urbana-Champaign, USA

THORSTEN WAGENER
University of Bristol, UK

ALBERTO VIGLIONE
Technische Universität Wien, Austria

HUBERT SAVENIJE
Technische Universiteit Delft, the Netherlands

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Contributors

Ghazi Al-Rawas
Sultan Qaboos University, Department of Civil & Architectural Engineering, College of Engineering, PO Box 33, Al-Khodh, P.C. 123, Muscat, Sultanate of Oman

Vazken Andréassian
Irstea, UR Hydrosystèmes et Bioprocédés, 1 rue Pierre-Gilles de Gennes CS 100 30, 92761 Antony Cedex, France

Tianqi Ao
Sichuan University, Department of Hydrology and Water Resources, College of Water Resources and Hydropower, No. 24, Yihuanlu Nanyiduan, Chengdu, Sichuan 610065, China

Stacey A. Archfield
US Geological Survey, 10 Bearfoot Road, Northborough, MA 01532, USA

Berit Arheimer
Swedish Meteorological and Hydrological Institute, Folkborgsvägen 1, 601 76 Norrköping, Sweden

András Bárdossy
University of Stuttgart, Institute of Hydraulic Engineering, Pfaffenwaldring 61, 70569 Stuttgart, Germany

Trent Biggs
San Diego State University, Department of Geography, 5500 Campanile Drive, San Diego, CA 92182–4493, USA

Günter Blöschl
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222–2, 1040 Vienna, Austria

Theresa Blume
Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 5.4 Hydrology, Telegrafenberg 14473 Potsdam, Germany

Marco Borga
University of Padova, Department of Land and Agroforest Environments, via dell'Università 16, 35020, Legnaro (PD), Italy

Helge Bormann
University of Siegen, Department of Civil Engineering, Paul-Bonatz-Str. 9–11, 57068 Siegen, Germany

Gianluca Botter
Università di Padova, Dipartimento IMAGE, Via Loredan 20, 35131 Padova, Italy

Tom Brown
University of Saskatchewan, Centre for Hydrology, Kirk Hall, 117 Science Place, Saskatoon, SK, S7N 5C8, Canada

Donald H. Burn
University of Waterloo, Department of Civil and Environmental Engineering, 200 University Avenue West, Waterloo, Ontario, N2L 3G1, Canada

Sean K. Carey
McMaster University, School of Geography & Earth Sciences, General Science Building, Rm 238, 1280 Main Street West, Hamilton, Ontario, L8S 4L8, Canada

Attilio Castellarin
University of Bologna, Department DICAM,Viale Risorgimento 2, 40136 Bologna, Italy

Francis Chiew
CSIRO Land and Water – Black Mountain, Christian Laboratory, Clunies Ross Street, GPO Box 1666, ACT 2601, Australia

François Colin
Montpellier SupAgro, UMR LISAH, 2 Place Pierre Viala, 34060 Montpellier Cedex 2, France

Paulin Coulibaly
McMaster University, School of Geography and Earth Sciences, Office GSB 235, 1280 Main Street West, Hamilton, Ontario, L8S 4L7, Canada

Armand Crabit
INRA, UMR LISAH, 2 Place Pierre Viala, 34060 Montpellier Cedex 2, France

Barry Croke
The Australian National University, Integrated Catchment Assessment and Management Centre (iCAM) and National Center for Groundwater Research and Training, The Fenner School of Environment and Society, iCAM, Bldg 48a, Linnaeus Way, Canberra ACT 0200, Australia

Siegfried Demuth
UNESCO, Section on Hydrological Systems and Global Change, Division of Water Sciences, Natural Sciences Sector, 1 rue Miollis, 75 732 Paris Cedex 15, France

Qingyun Duan
Beijing Normal University, GCESS, 19 Xinjiekouwai, Beijing 100875, China

Giuliano Di Baldassarre
UNESCO-IHE, Institute for Water Education, Westvest 7, 2601 DA Delft, the Netherlands

Thomas Dunne
University of California-Santa Barbara, Bren School of Environmental Science & Management, Bren Hall 3510, Santa Barbara, CA 93106–5131, USA

Ying Fan
Rutgers University, Department of Earth and Planetary Sciences, Wright Laboratories, 610 Taylor Road, Piscataway, NJ 08854–8066, USA

Xing Fang
University of Saskatchewan, Centre for Hydrology, Kirk Hall, 117 Science Place, Saskatoon, SK, S7N 5C8, Canada

Boris Gartsman
Laboratory for Land Hydrology and Climatology, Pacific Geographical Institute FEB RAS, Radio Street 7, Vladivostok 690041, Russia

Alexander Gelfan
Russian Academy of Sciences, Watershed Hydrology Laboratory, Water Problems Institute, 3 Gubkina Str., 119333 Moscow, Russia

Mikhail Georgievski
State Hydrological Institute, Remote Sensing Methods and GIS Lab, 23 second line, St Petersburg, 199053, Russia

Nick van de Giesen
Delft University of Technology, Water Resources Section, Stevinweg 1, 2628 CN Delft, the Netherlands

David C. Goodrich
USDA-ARS, Southwest Watershed Research Center, 2000 E Allen Rd, Tucson, AZ 85719–1596, USA

Hoshin V. Gupta
The University of Arizona Tucson, Department of Hydrology & Water Resources, Harshbarger Building Room 314, 1133 East North Campus Drive, AZ 85721–0011, USA

Khaled Haddad
University of Western Sydney, Building XB, Kingswood School of Engineering, UWS Locked Bag 1797, Penrith, NSW 2751, Australia

David M. Hannah
University of Birmingham, School of Geography, Earth and Environmental Sciences, Edgbaston, Birmingham, B15 2TT, UK

H. A. P. Hapuarachchi
Bureau of Meteorology, GPO Box 1289, Melbourne, VIC 3001, Australia

Hege Hisdal
Norwegian Water Resources and Energy Directorate (NVE), Hydrology Department, PO Box 5091, Maj., N-0301 Oslo, Norway

Kamila Hlavčová
Slovak University of Technology, Department of Land and Water Resources Management, Radlinského 11, 813 68 Bratislava, Slovak Republic

Markus Hrachowitz
Delft University of Technology, Water Resources Section, Stevinweg 1, 2600 GA Delft, the Netherlands

Denis A. Hughes
Rhodes University, Institute for Water Research, PO Box 94, Grahamstown, 6140, South Africa

Günter Humer
Dipl.-Ing. Günter Humer GmbH, Feld 16, 4682 Geboltskirchen, Austria

Ruud Hurkmans
University of Bristol, University Road, Bristol, BS8 1SS, UK (Previously at Wageningen University, Hydrology and Quantitative Water Management Group, Droevendaalsesteeg 3a, 6708 PB Wageningen, the Netherlands)

Vito Iacobellis
Politecnico di Bari, Dipartimento di Ingegneria delle Acque e di Chimica, Campus Universitario, Via E. Orabona 4, 70125 Bari, Italy

Elena Ilyichyova
Russian Academy of Sciences, Siberian Branch, V. B. Sochava Institute of Geography, Ulan-Batorskaya St. 1, Irkutsk, 664033, Russia

Hiroshi Ishidaira
University of Yamanashi, Interdisciplinary Graduate School of Medicine and Engineering, 4–3–11 Takeda, Kofu, Yamanashi 400–8511, Japan

Graham Jewitt
University of KwaZulu-Natal, School of Agricultural, Earth and Environmental Sciences, PBag X01, Scotsville, 3209, South Africa

Shaofeng Jia
Chinese Academy of Sciences, Institute of Geographical Sciences and Natural Resource Research, No. 11A Datun Road, Beijing 100101, China

Jeffrey R. Kennedy
US Geological Survey, 520 N. Park Ave, Suite 221, Tucson, AZ 85719, USA

Anthony S. Kiem
The University of Newcastle, Environmental and Climate Change Research Group, School of Environmental and Life Sciences, Faculty of Science and Information Technology, Callaghan, NSW 2308, Australia

Robert Kirnbauer
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222–2, 1040 Vienna, Austria

Thomas R. Kjeldsen
Centre for Ecology & Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK

Jürgen Komma
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222, 1040 Vienna, Austria

Leonid M. Korytny
Russian Academy of Sciences, Siberian Branch, V. B. Sochava Institute of Geography, Ulan-Batorskaya St. 1, Irkutsk, 664033, Russia

Charles N. Kroll
SUNY College of Environmental Science and Forestry, Environmental Resources Engineering, Syracuse, NY 13210, USA

George Kuczera
The University of Newcastle, Faculty of Engineering and Built Environment, Engineering A130, University Drive, Callaghan, NSW 2308, Australia

Gregor Laaha
University of Natural Resources and Life Sciences, Institute of Applied Statistics and Computing, Gregor Mendel-Str. 33, 1180 Vienna, Austria

Henny A. J. van Lanen
Wageningen University, Hydrology and Quantitative Water Management Group, Droevendaalsesteeg 3a, 6708 PB Wageningen, the Netherlands

Hjalmar Laudon
Swedish University of Agricultural Sciences (SLU), Department of Forest Ecology and Management, 901 83 Umeå, Sweden

Jens Liebe
United Nations University, UN-Water Decade Programme on Capacity Development (UNW-PC), UN Campus, Hermann-Ehlers-Str. 10, 53113 Bonn, Germany

Shijun Lin
Guangdong Research Institute of Water Resources and Hydropower, No.116 Tianshou Road, Tianhe district, Guangzhou city, 510635, China

Göran Lindström
Swedish Meteorological and Hydrological Institute, Folkborgsvägen 1, 601 76 Norrköping, Sweden

Suxia Liu
Chinese Academy of Sciences, Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research, No. A11 Datun Road, Beijing 100101, China

Jun Magome
University of Yamanashi, Interdisciplinary Graduate School of Medicine and Engineering, 4–3–11 Takeda, Kofu 400–8511, Japan

Danny G. Marks
USDA Northwest Watershed Research Center, 800 Park Blvd., Ste 105, Boise, ID 83712–7716, USA

Dominic Mazvimavi
University of the Western Cape, Department of Earth Sciences, Private Bag X17, Bellville 7535, Cape Town, South Africa

Jeffrey J. McDonnell
Global Institute for Water Security, National Hydrology Research Centre, University of Saskatchewan, 11 Innovation Boulevard, Saskatoon SK S7N 3H5, Canada

Brian L. McGlynn
Duke University, Nicholas School of the Environment, Division of Earth and Ocean Sciences, Box 90328, Durham, NC 27708, USA

Kevin J. McGuire
Virginia Polytechnic and State University, VA Water Resources Research Center and Department of Forest Resources and Environmental Conservation, 210-B Cheatham Hall (0444), Blacksburg, VA 24061, USA

Neil McIntyre
Imperial College London, Department of Civil and Environmental Engineering, Imperial College Road, London, SW7 2AZ, UK

Thomas A. McMahon
The University of Melbourne, Department of Infrastructure Engineering, Victoria 3010, Australia

Ralf Merz
The Helmholtz Centre for Environmental Research (UFZ), Department Catchment Hydrology, Theodor-Lieser-Straße 4, 06120 Halle/Saale, Germany

Robert A. Metcalfe
Ontario Ministry of Natural Resources, c/o Trent University, DNA Building, 2140 East Bank Drive, Peterborough, Ontario, K9J 7B8, Canada

Alberto Montanari
University of Bologna, Department DICAM, Viale Risorgimento 2, 40136 Bologna, Italy

David Morris
Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, OX10 8BB, UK

Roger Moussa
INRA, UMR LISAH, 2 Place Pierre Viala, 34060 Montpellier Cedex 2, France

Lakshman Nandagiri
National Institute of Technology Karnataka Surathkal, Department of Applied Mechanics and Hydraulics, Srinivasnagar, Mangalore, Karnataka, 575025, India

Thomas Nester
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222–2, 1040 Vienna, Austria

Taha B. M. J. Ouarda
Masdar Institute of Science and Technology, Masdar City, Abu Dhabi, PO Box 54224, United Arab Emirates

Ludovic Oudin
Université Pierre et Marie Curie Paris 6, Boite 123, 4 Place Jussieu, 75252, Paris Cedex 05, France

Juraj Parajka
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222–2, 1040 Vienna, Austria

Charles S. Pearson
National Institute of Water and Atmospheric Research, PO Box 8602, Riccarton, Christchurch 8440, New Zealand

Murray C. Peel
The University of Melbourne, Department of Infrastructure Engineering, Victoria, 3010, Australia

Charles Perrin
Irstea, UR Hydrosystèmes et Bioprocédés, 1 rue Pierre-Gilles de Gennes, CS 10030, 92761 Antony Cedex, France

John W. Pomeroy
University of Saskatchewan, Centre for Hydrology, Kirk Hall, 117 Science Place Saskatoon, SK, S7N 5C8, Canada

David A. Post
CSIRO Land and Water – Black Mountain, Christian Laboratory, Clunies Ross Street, GPO Box 1666, ACT 2601, Australia

Ataur Rahman
University of Western Sydney, School of Computing, Engineering and Mathematics, Locked Bag 1797, Penrith NSW 2751, Australia

Liliang Ren
Hohai University, State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, No. 1 Xikang Road, Nanjing 210098, China

Magdalena Rogger
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222–2, 1040 Vienna, Austria

Dan Rosbjerg
Technical University of Denmark, Department of Environmental Engineering, Miljoevej, Building 113, DK-2800 Kongens Lyngby, Denmark

José Luis Salinas
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222–2, 1040 Vienna, Austria

Jos Samuel
McMaster University, Department of Civil Engineering, 1280 Main St. West, Hamilton, Ontario, L8S 4L7, Canada

Eric Sauquet
Irstea, UR HHLY Hydrology-Hydraulics, 3 bis quai Chauveau – CP 220, 69336 Lyon, France

Hubert H. G. Savenije
Delft University of Technology, Water Resources Section, Stevinweg 1, 2628 CN Delft, the Netherlands

Takahiro Sayama
Public Works Research Institute, International Centre for Water Hazard and Risk Management, 1–6 Minamihara, Tsukuba, Ibaraki 305–8516, Japan

John C. Schaake
1A3 Spa Creek Landing, Annapolis, MD 21403, USA

Kevin Shook
University of Saskatchewan, Centre for Hydrology, Kirk Hall, 117 Science Place, Saskatoon, SK, S7N 5C8, Canada

Murugesu Sivapalan
University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, 2524 Hydrosystems Laboratory, 301 N. Mathews Ave., Urbana, IL 6180, USA

Jon Olav Skøien
Joint Research Centre – European Commission, Institute for Environment and Sustainability, Land Resource Management Unit, Via Fermi 2749, TP 440, I-21027 Ispra (VA), Italy

Chris Soulsby
University of Aberdeen, Northern Rivers Institute, St. Mary's Kings College, Old Aberdeen, AB24 3UE, UK

Christopher Spence
Environment Canada, National Hydrology Research Centre, 11 Innovation Boulevard, Saskatoon, Saskatchewan, S7N 3H5, Canada

R. 'Sri' Srikanthan
Bureau of Meteorology, Water Division, GPO Box 1289, Melbourne 3001, Australia

Tammo S. Steenhuis
Cornell University, Biological and Environmental Engineering, 206 Riley Robb, Ithaca, NY 14853–5701, USA

Jan Szolgay
Slovak University of Technology, Department of Land and Water Resources Management, Radlinského 11, 813 68 Bratislava, Slovakia

Yasuto Tachikawa
Kyoto University, Department of Civil and Earth Resources Engineering, Graduate School of Engineering, C1 Nishikyo-ku, Kyoto 615–8540, Japan

Kuniyoshi Takeuchi
Public Works Research Institute, International Centre for Water Hazard and Risk Management, 1–6 Minamihara, Tsukuba-shi, Ibaraki-ken 305–8516, Japan

Lena M. Tallaksen
University of Oslo, Department of Geosciences, Postboks 1047, Blindern, N-0316 Oslo, Norway

Dörthe Tetzlaff
University of Aberdeen, Northern Rivers Institute, St. Mary's Kings College, Old Aberdeen, AB24 3UE, UK

Sally E. Thompson
University of California, Department of Civil and Environmental Engineering, 760 Davis Hall, Berkeley 94720–1710, USA

Elena Toth
University of Bologna, Department DICAM, Viale Risorgimento 2, 40136 Bologna, Italy

Peter A. Troch
The University of Arizona, Department of Hydrology and Water Resources, John W. Harshbarger Building, 1133 E James E. Rogers Way, Tucson, AZ 85721, USA

Remko Uijlenhoet
Wageningen University, Hydrology and Quantitative Water Management Group, Droevendaalsesteeg 3a, 6700 AA Wageningen, the Netherlands

Carl L. Unkrich
USDA-ARS, Southwest Watershed Research Center, 2000 E Allen Rd, Tucson, AZ 85719–1596, USA

Alberto Viglione
Vienna University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Karlsplatz 13/222, 1040 Vienna, Austria

Neil R.Viney
CSIRO Land and Water – Black Mountain, Christian Laboratory, Clunies Ross Street, GPO Box 1666, ACT 2601, Australia

Richard M. Vogel
Tufts University, Department of Civil and Environmental Engineering, Anderson Hall, 200 College Avenue, Medford, MA 02155, USA

Thorsten Wagener
University of Bristol, Department of Civil Engineering, Queen's Building, University Walk, Bristol, BS8 1TR, UK

M. Todd Walter
Cornell University, Biological and Environmental Engineering, 222 Riley Robb, Ithaca, NY 14853–5701, USA

Guoqiang Wang
Beijing Normal University, College of Water Sciences, Xinjiekouwai Street 19, Haidian, Beijing, China

Markus Weiler
Albert-Ludwigs-University of Freiburg, Institute of Hydrology, Fahnenbergplatz, 79098 Freiburg, Germany

Rolf Weingartner
University of Bern, Institute of Geography and Oeschger Centre for Climate Change Research, Hallerstrasse 12, 3012 Bern, Switzerland

Erwin Weinmann
Monash University, Department of Civil Engineering, Building 60, Victoria 3800, Australia

Hessel Winsemius
Deltares, Inland Water Systems, Rotterdamseweg 185, 2600 MH Delft, the Netherlands

Ross A. Woods
National Institute of Water and Atmospheric Research (NIWA), PO Box 8602, Riccarton, Christchurch 8440, New Zealand

Dawen Yang
Tsinghua University, Department of Hydraulic Engineering, 100084 Beijing 100084, China

Chihiro Yoshimura
Tokyo Institute of Technology, Department of Civil Engineering, 2–12–1-M1–4, Ookayama, Tokyo 152–8552, Japan

Andy Young
Wallingford HydroSolutions Ltd, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, OX10 8BB, UK

Gordon Young (IAHS President)
34 Vincent Avenue, PO Box 878, Niagara on the Lake, Ontario, L0S 1J0, Canada

Erwin Zehe
Karlsruhe Institute of Technology, Institute of Water Resources and River Basin Management, Kaiserstraße 12, 76129 Karlsruhe, Germany

Yongqiang Zhang
CSIRO Land and Water – Black Mountain, Christian Laboratory, Clunies Ross Street, GPO Box 1666, ACT 2601, Australia

Maichun C. Zhou
South China Agricultural University, College of Water Conservancy and Civil Engineering, Wushan Road, Tianhe District, Guangzhou 510642, China

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Foreword

Prediction in ungauged basins: context, challenges, opportunities

Society increasingly looks to science for predictions, or at least explanations, of events, resources and hazards. Examples appear continually in government committee hearings, serious newspapers and television channels, and international re-insurance industries, to choose one commercial example. This expectation is particularly obvious in the case of water. People are nervous about (for example) water shortages, crop-threatening droughts, floods, water chemistry and pricing. Hydrologists would be wise to improve the capacity and reliability of their predictions to respond to this societal need.

Prediction is commonly thought of as a fundamental capability of science. Observations and understanding, conceptualised as explanatory theories, allow predictions, which then can be tested to refute or increase confidence in the original theory. In hydrology, the quality of these tests does not typically match up with tests in some other sciences that apply laboratory-tested principles and models to the environment. We have much to learn from disciplines, such as atmospheric science, physical oceanography and astrophysics, that have been successful at applying laboratory-tested principles at large scales in complex environments. Although it is true that hydrology has to contend with the interactions of more media (rock, soil, vegetation, engineered structures) than do the disciplines mentioned, there are still intellectual traditions, organisational approaches, analytical methods, and technologies to be learned from them in order to test the generality of landscape-scale hydrological theories.

Empirical investigation, including experimentation, is another fundamental tool of science. Hydrological investigations are conducted in a wide variety of environments – with diverse climates, topography, soils, land cover and manipulation by humans. They also occur at a wide range of temporal and spatial scales, and involve single or multiple processes. It is difficult to organise the vast amount of information from these studies into coherent theories. Diverse results are then seen as contradictory or at least leading to so much confusion that prediction is impossible. Yet, it should not be surprising that results from different locations differ in magnitude, even in the absence or presence of certain processes. Theories predict such a result, and allow organised interpretation and resolution of differences in measured magnitudes. Yet the bulk of the hydrological literature comprises a conceptually disordered resource of 'unique' descriptions, single-process studies and methods, but few attempts at organisation through the medium of broadly applicable, quantitative theory, or even conceptually organised descriptive summaries, that would facilitate both understanding and prediction. This is the 'fragmentation' problem, which the Predictions in Ungauged Basins (PUB) initiative has reduced to an encouraging degree, as this book illustrates.

There is a resilient meta-hypothesis in hydrological science that quantitative theories of linked hydrological processes at landscape scale, implemented and tested in a transparent and rigorous manner, could leverage the extensive body of environmental measurements into more reliable predictions. This is an interesting and challenging, if still unproven, idea. Such a development would require improvements in the conduct of both modelling and empirical investigations – a trajectory assessed in this book for the specific case of runoff predictions in ungauged basins (and by extension, unrecorded conditions in monitored locations).

The first attempt at promulgating general hydrological theory, based on fluid mechanics and thermodynamics, was Eagleson's 1970 book *Dynamic Hydrology*, followed by his suite of papers in *Water Resources Research* (1978) laying out a statistical dynamic formulation of various linked components of a land-surface water budget. Earlier attempts to develop theories of single processes, such as the work of Darcy, Richards, Horton, Theis, Toth, Penman and Monteith, had pointed the way, but Eagleson provided a guide for integration. More recent contributions by many people have illuminated ways of dealing with the representation of processes at a wide range of scales, and with the unwelcome fact that many material properties important in hydrology exhibit large, but crudely measured and poorly understood spatial variations.

The current book is an assessment of progress in combining models with new data-collection and processing tools to make predictions of streamflow, and therefore of associated hydrological fluxes such as evaporation and groundwater storage changes. It embraces the scientific approach of making a model-based prediction and then testing it, and recording the errors in an objective manner. Such a strategy measures progress in skill development and facilitates judicious assessment of the reliability of predictions. This is not common in hydrology, where calibration routinely hides uncertainties in process representation, landscape and material properties, and spatial variability of atmospheric events. However, the global survey of prediction methods indicates that tested, integrative modelling of biophysically controlled hydrological mechanisms is still a minority activity in catchment-scale streamflow predictions. Most predictions still consist of summaries, calibrations and extrapolations of strictly empirical information.

The local, empirically focused approach has obvious utility for making certain kinds of predictions within the interpolated range of measurements, although many hydrologists have emphasised the degree to which uncertainties debilitate the use of such predictions, even in that range. The approach is even more unreliable when it is applied to the important domains that society cares about, which lie outside of monitored localities (the ungauged basin), outside of the recorded range of 'possible' events, and in conditions of climate and land cover that may not yet exist but are anticipated. For these (true) prediction challenges, according to the meta-hypothesis, there would be value if we had methods based on a sound scientific platform of mechanistic understanding and rigorous testing. We would then know *how well* we could predict, and we would be able to agree on critical uncertainties, and to focus scientific research and technological innovation on them. But we are unlikely to select either of these foci if most hydrological predictions continue to be pragmatically ad hoc, not rigorously tested and compared, and aimed at generating locally acceptable solutions, rather than transferable hydrological understanding. The PUB initiative has made progress in overcoming these parochial vices.

It is often said that the urgent applicability of hydrological knowledge to human affairs encourages short cuts and discourages exploitation of the best practices of science. Although this may be understandable in specific applications under limitations of time and resources, there is no fundamental reason why the subsidised research community needs to limit its investigations in the same way. The research community is free to address the meta-hypothesis that rigorously formulated biophysical process models could assimilate new and better landscape measurements to yield predictions tested in the same way that some other environmental sciences achieve. This would not require that a prediction be correct at the first attempt, and it would allow an incorrect prediction to be explained by investigating whether the form of a mechanistic representation or the value of a critical parameter were accurate, rather than calibrating the prediction against measured output and announcing success. The book assesses progress in this direction.

Making this suggestion is not to argue against current hydrological practice. Much of it is required for urgent policy and management (remember that José Ortega y Gasset said, 'Life cannot wait until the sciences have explained the universe scientifically.'). Nevertheless, given the widespread dissatisfaction with hydrologists' ability to predict flood discharges or water yields in ungauged basins or those expected to result from climate change and other anthropogenic disturbances, surely there is an argument to be made for some investment in a different, more distinctively scientific strategy on the part of some hydrologists. The results could generate a higher-yielding strategy for the discipline.

The global organisation of the PUB initiative has also fostered an intermediate approach to organising the diversity of knowledge and approaches to runoff prediction, even for conditions and scales for which rigorous mechanistic models are not yet formulated, or at least parameterised, adequately for reliable predictions. This approach involves comparative hydrology – comparing results and the success of prediction methods at representing hydrological outcomes for different regions and scales. The strategy, referred to in the book as hydrological synthesis, is a formal way of comparing hydrological experience in diverse circumstances (I would say through the interpretation of available theory wherever possible), and is a welcome approach to ordering hydrological knowledge. Hydrological synthesis converts the disordered body of case study results into a gradually expanding sample of geographical range (or 'parameter space') that can be compared and interpolated. It raises questions about how regional differences and the general behaviour of hydrological response result from the nature of landscape–atmosphere interactions over time scales ranging from seconds to landform evolution time. The compilation of responses and predictions produces insights about which factors are critical controls on hydrological response at various scales. It also indicates the progress made in prediction at each scale, and the hydrological uncertainties requiring resolution. Synthesis through comparison of results and localities also encourages the use of information on patterns of hydrological landscape features, such as topography, soil and plant communities, to choose prediction methods, to group useful information and to apply results. These patterns are strongly correlated because they have evolved interactively, and the associations between them tend to limit the variability of hydrological response into clusters and trends, albeit with a still-unwelcome (for prediction) degree of variability. However, the PUB strategy has successfully organised knowledge, yielded transferable generalisations, and highlighted hypotheses for further investigation, as the book documents.

The fluid mechanical and thermodynamic theories of biophysical mechanisms at various scales needed for improving predictions are more securely developed and tested, at least at laboratory scale, than is the other part of the hydrological prediction problem – which is to attach

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these theories to the very complex boundaries and material properties of landscape features. The need to choose temporal and spatial resolutions for making these connections leads to challenging uncertainties about the operations of the mechanistic theories themselves. Although the problem is often characterised as a need for better *parameterisation* (which in hydrological modelling usually means some form of averaging of response to a stimulus), or for higher-*resolution* modelling with the same equations, there is often a need for better *formulation* in the sense of representing better *how* a process works, or even *which* process is working. For example, the volume and timing of runoff into a channel could be calculated as (a) the result of overland flow from a long contributing area with variable abstraction of water from the flow and a high surface resistance or (b) of unsaturated and then saturated subsurface flow from a shorter contributing area with different forms of flow resistance and water storage along the flow path. One could calibrate either representation against measurements of rainfall and runoff from a catchment. However, extrapolations of resulting predictions based on the inaccurate formulation to much larger rainstorms, snowmelt, drier initial conditions, timber harvest or other reasonably likely conditions would not be reliable. The unreliability could lead directly to misinformation if the prediction were required to predict not simply runoff but also soil-moisture patterns and evaporation, erosion, water quality, land management or effective pollution regulation (for example). This problem of improving process formulation, as it relates to hydrological prediction at landscape scale, needs to be tackled systematically through field measurement campaigns, modelling 'experiments' and syntheses of the kind documented here that search for environmental patterns and extend knowledge beyond individual case studies. The attractiveness of the challenge is that it invites new discoveries, based on new forms of measurement at a still-unsampled range of scales, as well as improvements in technology and physical and mathematical technique.

The landscape-features side of the problem is also an essential and attractive research target, but it also is challenging. Critical quantities vary in complicated, irregular and wide-ranging ways, and for some of them there is no agreed-upon measurement method. An extra impediment arises because the disciplines that have studied these features have attracted fewer scientists with an appetite for quantitative, theory-based generalisation. Thus, we have relatively few high-quality measurements of hydrological landscape properties and few quantitative theories of how coherent patterns and random variations develop in the first place, or how they differ from place to place. Technological developments have occurred in the measurement of surface hydrological properties, such as topography and albedo, and new data-processing methods for analysing and representing patterns are being employed. But the measurement and useful representation of subsurface material properties and geometry remains a serious impediment to prediction. Modelling the co-evolution of landscape patterns is beginning to develop, which should constrain the number and types of patterns that need to be considered for hydrological prediction.

In addition, field scientists need to engage with the task of theory-building in order to make useful measurements of critical properties that would encourage coherent progress in hydrological prediction. Field studies need to be designed and reported in a manner consistent with theoretical generalisation and hypothesis testing. The task of field studies is not only to report on exceptional circumstances (although these extend the sampling of geographical conditions), but to gradually extend understanding in a coherent and replicable manner. Often, reports that are portrayed as defying conventional wisdom turn out, at least qualitatively, to be physically reasonable and even predictable when extant theory is applied to the local circumstance. The strategy of hydrological synthesis – a formal way of comparing hydrological experience in diverse circumstances (I would say through the interpretation of available theory, wherever possible) – emphasised in this book is a welcome approach to ordering hydrological knowledge and setting an agenda for new discoveries and generalisations.

The book expresses an enduring aspiration of the community that established the International Association of Scientific Hydrology (since renamed as International Association of Hydrological Sciences). It re-focuses the goal of one branch of that community on a distinctively scientific approach to understanding and utilising hydrology at a time when technological advances in measurement and computation are becoming available for creative exploitation in the service of humankind. This is an exciting prospect.

Thomas Dunne

Preface

Sustainable management of river basins requires a variety of tools that can generate runoff predictions over a range of time and space scales. The most widely used predictive tools for runoff are essentially data-driven, i.e., they are estimated from gauged data. Unfortunately, in most catchments around the world runoff is not gauged. In any given region, in any part of the world, only a small fraction of the catchments possess a stream gauge where runoff is gauged. All other catchments have no stream gauge, and are therefore ungauged, and yet runoff information is needed almost everywhere people live for a multitude of management purposes.

Lack of universal theories or equations applicable directly at the catchment scale has led to a plethora of models being developed and used for predicting runoff. These models differ markedly in their model concepts and structure, their parameters, and the inputs they use. They also differ in terms of what dominant processes they represent, and the scales at which they make predictions. Most models are developed by people with different disciplinary backgrounds, while benefiting from local observations, experiences and practices, which are influenced by local climate conditions and catchment characteristics. Consequently, they tend to have unique features not applicable in other places: every hydrological research group around the world seemingly studies a different object: their local catchment. The net result has been considerable fragmentation, a 'cacophony', and a dissipation of effort that is not conducive to further advances.

The Decade on Predictions in Ungauged Basins (PUB) launched by the International Association of Hydrological Sciences (IAHS) in 2003 was aimed at achieving major advances in the capacity to make predictions in ungauged basins, through harnessing improved understanding of climatic and landscape controls on hydrological processes. The future vision of PUB was indeed to help make a transformation 'from cacophony to a harmonious melody'. One of the clear tasks that the PUB initiative set out to achieve was to address the fragmentation of modelling approaches through *comparative evaluation*: 'Classify model performances in terms of time and space scales, climate, data requirements and type of application, and explore reasons for the model performances in terms of hydrological insights and climate–soil–vegetation–topography controls.' This book has completed such a comparative evaluation, which is one of its major highlights.

However, PUB also had a higher ambition. It was felt that focusing on a grand problem such as PUB, which needed to draw heavily on new fundamental and theoretical advances in hydrology and associated earth system sciences to address the immediate problem-solving needs of society, had the potential benefit of enabling hydrology to meet both its scientific and its societal obligations. In other words, PUB was also seen as the vehicle to advance and revitalise the science of hydrology. Indeed, over the past decade, the PUB community has made huge strides in advancing both predictive capability and fundamental understanding of hydrological processes, working together in a concerted and coordinated manner. The PUB effort has helped to challenge long-held assumptions and question common paradigms, and has increased the constructive dialogue between different sub-disciplines and schools of thought.

So, as PUB comes to an official close, this book represents one contribution to PUB, which can be seen as another important step both in the development of PUB and in the growth of hydrology as a holistic earth science. This book does not even pretend to document all of the advances and contributions that the PUB community has achieved. These are substantial and should not go unnoticed, and will be documented in some other form. This book is mainly and explicitly focused on a synthesis of runoff predictions in ungauged basins, organised across processes, places and scales. This synthesis attempts to place current practice, experience and prediction uncertainty of a range of prediction methods in an ordered way, so that new insights can be gained not only about the methods themselves but also about how runoff variability changes across processes, places and scales. We believe we have succeeded in bringing some order to the disorder, to the extent of at least partially helping to transition 'from cacophony to a harmonious melody', even if it meant asking new questions that only future research can answer. We believe that this is a positive development both for predictions and for the science. This is also reflected in the organisation of the book, as one whole, internally self-consistent tome, with one coherent theme, rather than a collection of chapters that focus on several different PUB themes that one could equally well produce under the circumstances. We had to make a choice about the organisation of the book in our quest for the 'harmony'; we hope that it made a difference, since there was a clear price we had to pay for achieving this harmony.

The book started as a PUB benchmark report, but over time metamorphosed into a synthesis, mainly building on a comparative assessment of thousands of studies from all around the world, with predictive uncertainty assessed along the axes of processes, places and scales, and interpreted hydrologically. The literature on the current state of the art of runoff predictions, in terms of the various signatures, was reviewed by over 130 contributing authors, and organised into several chapters. The painstaking effort of comparative assessment was carried out by several able assistants in Vienna, who toiled hard to do the analyses and generate new insights from them, with the support of several of the book contributors as well as the cooperation of scores of the original study authors, who provided the data sources needed for the assessment. All of the chapters went through numerous (countless) revisions by the contributors themselves, and then by the editors, as part of the overall synthesis effort.

The evolution of both the outlines and the contents of the book over the past three years or more was a process unto itself, confusing and confounding editors and contributors alike as it moved along, crystallising into its present shape only in the final few months. In other words, the editorial process was a co-evolutionary process, no less a complex system than the catchment that is the subject of our study. In that sense, the 'blind men and the elephant' metaphor applies to the book just as it does to the PUB initiative. Some messages that appear in the synthesis chapter were not there at the beginning, or were only vaguely there, and emerged through the process of writing the book. In that sense, the synthesis did serve its purpose. However, we are humble enough to admit that the book is not the end, but only the end of a beginning, and we remain blind men, still blind to the true reality that is catchment hydrology. Hopefully, there is a broader vision that challenges the narrow vision that has helped us to shape this book.

Readers will not fail to notice scores of photographs of real catchments in colour throughout the book. Our decision to include them is a tribute to the late Vit Klemeš, former President of the IAHS, and comes from our determination that catchments henceforth be seen as inimitable objects that are alive, and not just defined by the techniques and abstractions we may use, from time to time, to analyse them. In a series of papers, Klemeš emphasised the primacy of process understanding over techniques in hydrological research. Techniques are certainly needed for predictions in ungauged basins, but the focus in this book – as in much of the PUB initiative – has been on the hydrology, with the techniques playing an essential but supporting role. It is the hydrological interpretation of the patterns that various analysis techniques and models produced that takes centre stage in this book.

The contents of the book, in a sense, reflect the lessons learned from the diversity offered by nature's own experiments, as expressed through the thousands of studies surveyed in this book. Through its comparative performance assessment of methods across processes, places and scales, the book takes an approach to generalisation through learning from the differences and similarities between catchments around the world. It throws light on the status of PUB at the present moment and can serve as a benchmark against which future progress can be judged. Along the way, the book has also come out with a new scientific framework that can potentially guide future efforts aimed at improving runoff predictions in ungauged basins and at advancing the science of hydrology. This proposed new framework has centred on a higher-level synthesis of what we can learn from individual places with generalised understanding gained from comparing the differences between places, thus benefiting from legacies of co-evolution. Maybe this is too esoteric to include in a book on predictions, or maybe it will trigger new ways of doing things; only time will tell.

This book is aimed at hydrologists, earth and environmental scientists with an interest in water, especially early career scientists, aspiring graduate students and practitioners, as well as hydrology teachers. Yet it is not a textbook, manual, handbook nor even a monograph. It puts predictions in a new light, it makes catchment hydrology more coherent and exciting, and runoff variability and water balance more holistic. Perhaps the book can serve as a ready reference for students and new entrants to hydrology wanting to get a sense of the holistic nature of catchment water balance, and to imagine new and innovative ways to make runoff predictions. We hope that, in the long run, it will change the way hydrology is taught, researched and practised.

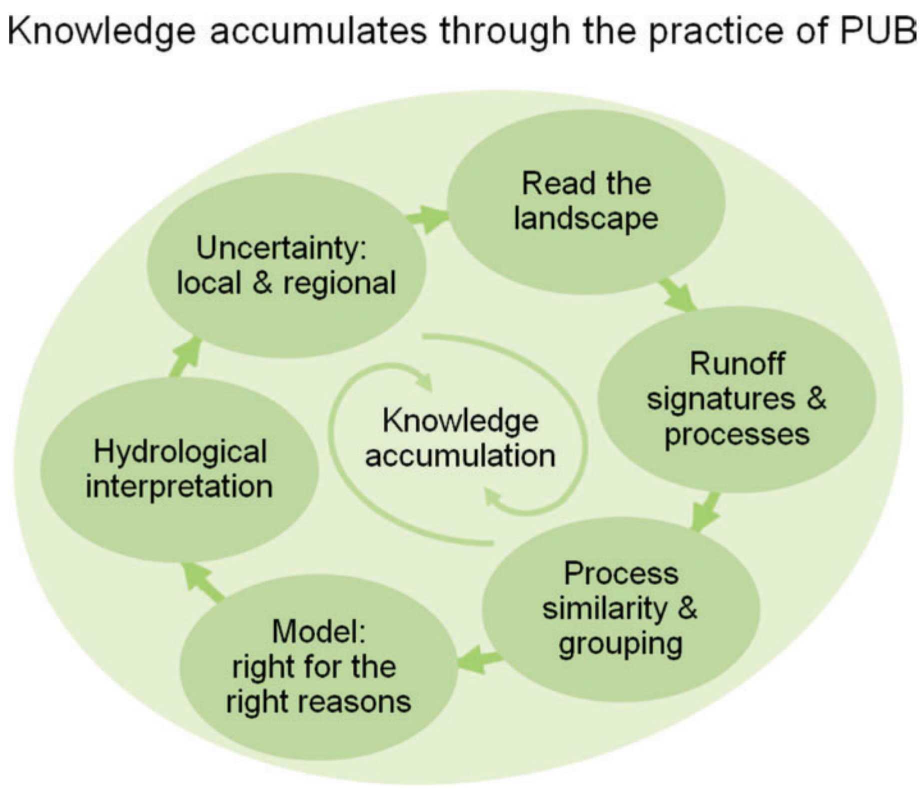
The book owes its genesis to the IAHS Predictions in Ungauged Basin initiative. We are truly grateful to the IAHS for having the wisdom and courage to start such a 10-year global effort, and for bringing the hydrological community together globally on such a daunting task. We could not have completed this book without the underlying community support that IAHS managed to pull together. Indeed, the synthesis presented in the book is built on the collective experience, inputs and insights of a large number of researchers around the world, and is therefore truly a grassroots effort, even if the grass roots are no longer visible. We as editors hope that, in spite of the challenges and frustrations faced along the way, it has been a worthwhile effort and that the final product reflects well on the best intentions and profound wisdom of the hydrology community, and the high ambitions of the PUB initiative. We are grateful to Kuniyoshi Takeuchi for having the foresight to launch the initiative and to him and subsequent Presidents (Arthur Askew and Gordon Young), and Secretary-General Pierre Hubert, for providing unconditional support to the PUB initiative generally, and to this book project in particular. We are also grateful to Jeff McDonnell and John Pomeroy, the other two PUB Chairs, for leading PUB during their terms in a way that the PUB spirit never wavered, and PUB continued to make progress towards its goals.

We would like to profusely thank the 130 contributors, including coordinating contributors, for their efforts at pulling together material for the various chapters, and for putting up with us as we continually edited the material to the point that, very truly, not one sentence that any author contributed remains intact in the book. We thank them all for having faith in the editors to the end, in spite of the obvious frustrations. Special thanks to Magdalena Rogger, Thomas Nester, Jürgen Komma, Juraj Parajka, Jose Luis Salinas, Emanuele Baratti, Rasmiaditya Silasari, Patrick Hogan and Gemma Carr for the invaluable assistance they rendered towards the comparative assessment exercise, redrawing of the figures, editing, proofreading and overall project management. Without their efforts, this book would never have seen the light of day. We would also like to acknowledge the financial support of the Austrian Academy of Sciences through the Predictions in Ungauged Basins project, and the US National Science Foundation through the Hydrologic Synthesis project, and the institutional support of our respective employers, especially Vienna University of Technology and the University of Illinois, for making available considerable resources to enable us to work together over extended periods. We are grateful to Thomas Dunne for being willing to write a foreword to the book; the PUB initiative benefited from Tom's wisdom during its formative stages, and it is gratifying that he followed the initiative to its end and was able to read the book and offer wise thoughts once again to potential readers. Finally, we would like to extend our thanks to our respective families for putting up with our long absences, in both body and spirit, over the three years that it took to complete this book.

G. Blöschl
M. Sivapalan
T. Wagener
A. Viglione
H. H. G. Savenije
(Editors)

Abstract

This book is devoted to predicting runoff in ungauged basins (PUB), i.e., predicting runoff at those locations where no runoff data are available. It aims at a synthesis of research on predictions of runoff in ungauged basins across processes, places and scales as a response to the dilemma of fragmentation in hydrology. It takes a comparative approach to learning from the differences and similarities between catchments around the world. The book also provides a comparative performance assessment (in the form of blind testing) of methods that are being used for predictions in ungauged basins, interpreted in a hydrologically meaningful way. It therefore throws light on the status of PUB at the present moment and can serve as a benchmark against which future progress on PUB can be judged. In so doing, the book has also come out with a new scientific framework that can guide the advances that are needed to underpin PUB and to advance the science of hydrology as a whole. The synthesis presented in the book is built on the collective experience of a large number of researchers around the world inspired by the PUB initiative of the International Association of Hydrological Sciences, which makes it truly a community effort. It has provided insights into the scientific, technical and societal factors that contribute to PUB. On the basis of the synthesis presented in this book, recommendations are made on the predictive, scientific and community aspects of PUB and of hydrology as a whole.


Knowledge accumulates through the practice of PUB
Read the landscape
Runoff signatures & processes
Process similarity & grouping
Model: right for the right reasons
Hydrological interpretation
Uncertainty: local & regional
Knowledge accumulation