

What is the role of hydrological science in the age of machine learning?

Grey Nearing

*Upstream Tech, Public Benefit Corporation
University of Alabama - Department of Geological Sciences*

Scale-Relevant Theories: Holy Grail or Tilting at Windmills

1986

WATER RESOURCES RESEARCH, VOL. 22, NO. 9, PAGES 465-585, AUGUST 1986

Looking for Hydrologic Laws

JAMES C. I. DOOGUE

Department of Engineering Hydrology, University College, Galway, Dublin, Ireland

The search for regularities in hydrologic relationships is discussed against the background of the general types of predictive models used in science. The various approaches to the study of water are compared and contrasted. The ideas discussed are illustrated by examples from the development of techniques in flood hydrology and by personal conclusions on the sources for new hypotheses in flood hydrology and the possibility of their verification.

1. INTRODUCTION

1.1. Relation of Hydrology to Science

Fifty years ago, there was only a handful of books and a handful of scientists. This for the most part was a science of the past. This for the most part was a science of the past. This for the most part was a science of the past.

Randomness

Complexity

Unorganized complexity (aggregates)

Organized complexity (systems)

Organized simplicity (mechanisms)

Analytical treatment

Statistical treatment

Copyright 1986 by the American Geophysical Union.

Page number 460295

0043-1397/86/0000-0000\$05.00

465

1987

Water for the Future: Hydrology in Perspective (Proceedings of the Rome Symposium, April 1987). IAHS Publ. no. 164, 1987.

Towards a new paradigm in hydrology

KEITH BEVEN

Department of Environmental Science, University of Lancaster, Lancaster, LA1 4YQ, UK

ABSTRACT Hydrological scientists are faced with the problem (common to many of the field sciences) of complexity at small scales leading to relative simplicity (the hydrograph) at large scales. Little or no success has been gained in relating the former to the latter.

Hydrological scientists are faced with the problem of complexity at small scales leading to relative simplicity (the hydrograph) at large scales. Little or no success has been gained in relating the former to the latter.

A SHORT PATHOLOGY OF HYDROLOGICAL SCIENCE

There is an increasing body of evidence that hydrological science is in some disarray. Exhibit A: studies of the isotopic content of the waters of storm hydrographs (see for example, Sklash & Fawcett, 1979; Herrmann & Stichler, 1980; Kennedy *et al.*, 1986) have provided convincing evidence that traditional methods of "baseflow separation", still presented in recent textbooks and used in

393

2019

Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: <https://www.tandfonline.com/loi/rlthj20>

Twenty-three unsolved problems in hydrology (UPH) – a community perspective

Günter Blöschl, Marc F.P. Bierkens, Antonio Chambel, Christophe Cudennec, Georgia Destouni, Aldo Fiori, James W. Kirchner, Jeffrey J. McDonnell, Hubert H.G. Savenije, Murugesu Sivapalan, Christine Stumm, Elena Toth, Elena Volpi, Gemma Carr, Claire Lupton, José Salinas, Borbála Széles, Alberto Viglione, Hafzullah Aksoy, Scott T. Allen, Anam Amin, Vazken Andréassian, Berit Arheimer, Santosh K. Aryal, Victor Baker, Earl Bardsley, Marlies H.

Unsolved Problem #6: What are the hydrological laws at the catchment scale and how do they change with scale?

Dugo, Salvatore Grimaldi, A. B. Gupta, Björn Guse, Dawei Han, David Hannah, Adrian Harpold, Stefan Haun, Kate Heal, Kay Helfricht, Mathew Herneberger, Matthew Hipsey, Hana Hlavčiková, Clara Hohmann, Ladislav Holko, Christopher Hopkinson, Markas Hrachowitz, Tissa H. Illangasekare, Ashar Inam, Camyla Innocente, Erkan Istanbuluoğlu, Ben Jarrah, Zahra Kalantari, Andis Kalvans, Sonu Khanal, Sina Khatami, Jens Kiesel, Mike Kirkby, Wouter Knoben, Krzysztof Kochanek, Silvia Kohnová, Alla Kolehnikina, Stefan Krause, David Kremer, Heidi Kreibich, Harald Kunstmann, Holger Lange, Margarida L. R. Liberato, Eric Lindquist, Timothy Link, Junguo Liu, Daniel Peter Loucks, Charles Luce, Gil Mahé, Olga Makarieva, Julien Malard, Shamsghul Mashayeva, Shreedhar Maskey, Josep Mas-Pla, Maria Mavrou-Guerguino, Maurizio Mazzoleni, Sebastian Mernild, Bruce Dudley Mearns, Alberto Montanari, Hannes Müller-Thömy, Alireza Nabizadeh, Fernando Nardi, Christopher Neale, Natalia Nesterova, Bakhran Nurtaev, Vincent O. Odongo, Subhabrata Panda, Saket Pande, Zhonghe Pang, Georgia Papacharalampous, Charles Perrin, Laurent Pfister, Rafael Pimentel, Maria J. Polo, David Post, Cristina Prieto Sierra, Maria-Helena Ramos, Maik Renner, José Eduardo Reynolds, Elena Ridolfi, Riccardo Rigon, Monica Riva, David E. Robertson, Renzo Rosso, Tirathankar Roy, João H.M. Sá, Gianfausto Salvadori, Mel Sandells, Bettina Schaefli, Andreas Schumann, Anna Scoblog, Jan Seibert, Eric Servat, Mojtaba Shafiei, Ashish Sharma, Moussa Sidibe, Roy C. Sidle, Thomas Skaugen, Hugh Smith, Sabine M. Spiessl, Lina Stein, Ingelin

1986

Looking for Hydrologic Laws

JAMES C. I. D.

Department of Engineering Hydrology

The search for regularities in hydrologic general types of predictive models used in compared and contrasted. The ideas discussed techniques in flood hydrology and by per hydrology and the possibility of their ve

1. INTRODUCTION

1.1. Relation of Hydrology to Science

Fifty years ago, there was only a handful of bookshelves available to the hydrologist who to establish a sound scientific basis for his practice. Today, there is an embarrassing abundance of monographs, journals and symposia proceedings clamoring for his or her attention. Is hydrology now an established science? Is hydrologic practice now firmly based on scientific principles?

This paper deals with the problems raised by the for regularities and for laws in hydrology. In emphasize the challenge implicit in such a search, attention will be paid to flood hydrology in which enterprise is particularly difficult. It is proposed to the subject within the context of predictive mod-

the subject within the context of predictive and explanatory theories in science generally. Such an approach can be useful not only for the purpose of emphasizing the position of hydrology as one of the earth sciences but also because such an approach could lead to the suggestion of analogies which can be so fruitful in the construction of models.

Following an introductory section on the nature of the scientific method, an outline is given of the contrasting approaches of analytical mechanics and statistical mechanics and the problems involved in dealing with systems of intermediate size. Attention is then turned to the vari-

proaches to the study of water movement and the parametrizing at a macroscale the effect of microprocesses that are not explicitly included in the macro model. Finally, the historical development of current methods of flood hydrology is reviewed against the background of the foregoing material. The purpose of the whole exercise is to provide a critical appraisal of the current state of the art.

The term model is used to describe a system simpler than the prototype system and which can represent but not all of the characteristics thereof. Accord-

some but not all of the characteristics thereof. According to a model is related to those particular aspects of the behavior of the prototype for which understanding or prediction is required. It is important to realize that a model is a theory and to distinguish between models that are

Copyright 1986 by the American Geophysical Union.

Paper number 6W0295.
0043-1397/86/006W-0295\$05.00

469

1987

Water for the Future: Hydrology in Perspective (Proceedings of the Rome Symposium, April 1987). IAHS Publ. no. 164, 1987.

There is an increasing body of evidence that hydrological science is in some disarray. Exhibit A: studies of the isotopic content of the waters of storm hydrographs (see for example, Sklash & Farvolden, 1979; Herrmann & Stichler, 1980; Kennedy *et al.*, 1986) have provided convincing evidence that traditional methods of "baseflow separation", still presented in recent textbooks and used in

2019

Hydrological Sciences Journal

 Taylor & Francis
Taylor & Francis Group

www.tandfonline.com/loi/rhsi20

ydrology

istopace Cudennec,
 McDonnell, Hubert
 ana Toth, Elena
 zéles, Alberto
 len Andreassian,
 ley, Marlies H.
 Berghuijs, Keith
 morim, Michael E.
 Brocca, Router
 Chen, Yangbo
 rtyan P. Clark,
 vild, Felipe P.
 ica M. Driscoll,
 ris, Farmer, James
 ris, Benjamin
 Gartsman, Simon
 van Ghariar, Tom
 fia P. González-
 Han, David
 Ifrich, Andrew
 hmann, Ladislav
 H. Illangasekare,
 h Jarihani, Zahra
 s Kiesel, Mike
 vová, Alka Kolechkina,
 stmann, Holger
 lino, Junguo Liu,
 leva, Julio Maldar,
 Pla, Maria Mavrova-
 eadler, Michael
 izadeh, Fernando
 Nurtayev, Vincent
 Panz, Georgia

apresentando trabalhos científicos. Os autores são: Alexander Pfister, Rafael Pimentel, Maria J. Polo, David Post, Cristina Prieto Sierra, Maria-Helena Ramos, Maik Renner, José Eduardo Reynolds, Elena Ridolfi, Riccardo Rigon, Monica Riva, David E. Robertson, Renzo Rosso, Thirthankar Roy, João H.M. Sá, Gianfausto Salvadori, Mel Sandells, Bettina Schaeffli, Andreas Schumann, Anna Scolobig, Jan Seibert, Eric Servat, Mojtaba Shafiei, Ashish Shharma, Moussa Sidibe, Roy C. Sidle, Thomas Skauken, Hugh Smith, Sabine M. Spiessl, Lina Stein, Ingeborg

Deep Learning for PUB

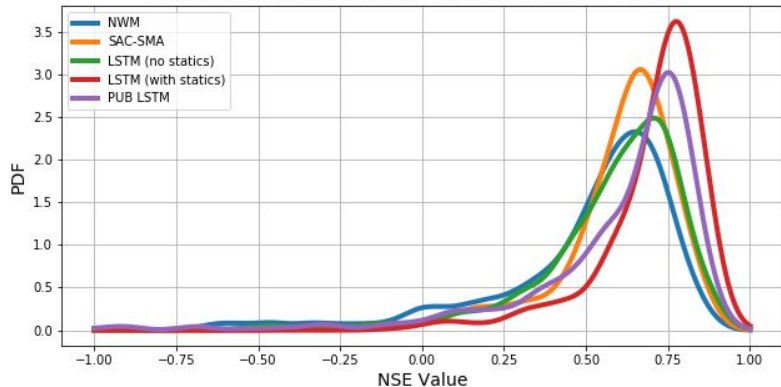
Water Resources Research

Technical Reports: Methods

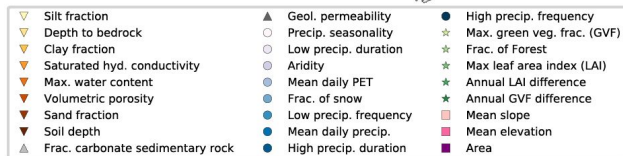
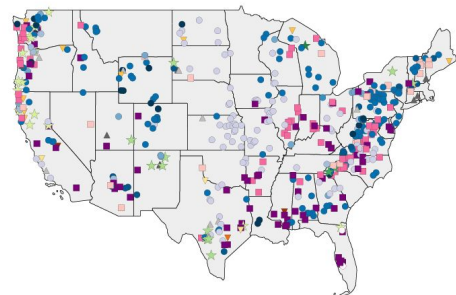
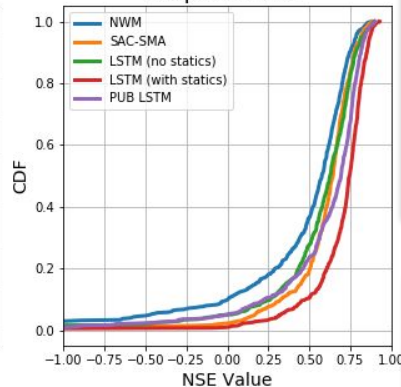
Towards Improved Predictions in Ungauged Basins: Exploiting the Power of Machine Learning

Frederik Kratzert, Daniel Klotz, Mathew Herrnegger, Alden K. Sampson, Sepp Hochreiter, Grey S. Nearing

Kernel Densities of NSE Values over 531 Basins

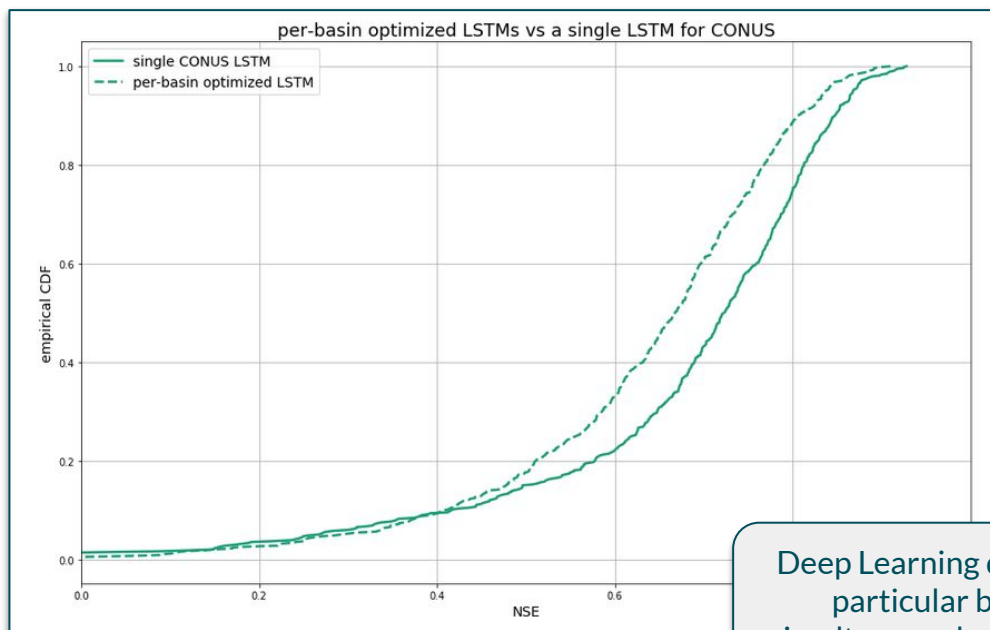


Empirical CDF

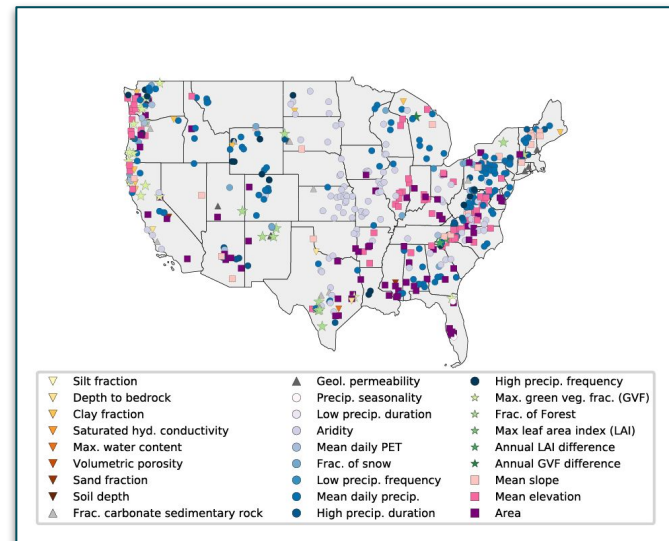


Deep learning gives better streamflow predictions, on average, in ungauged basins than the conceptual model calibrated to individual gauged basins.

Learning a General Model



Deep Learning does **better** in any particular basin if trained simultaneously on multiple basins.



Learning Hydrologic Similarity

Hydrol. Earth Syst. Sci., 23, 5089–5110, 2019
<https://doi.org/10.5194/hess-23-5089-2019>
 © Author(s) 2019. This work is distributed under
 the Creative Commons Attribution 4.0 License.



Hydrology and
 Earth System
 Sciences



**Towards learning universal, regional, and local hydrological
 behaviors via machine learning applied to
 large-sample datasets**

Frederik Kratzert¹, Daniel Klotz², Guy Shalev², Günter Klambauer¹, Sepp Hochreiter^{1,*}, and Grey Nearing^{3,*}

¹LIT AI

²Google

³Departm

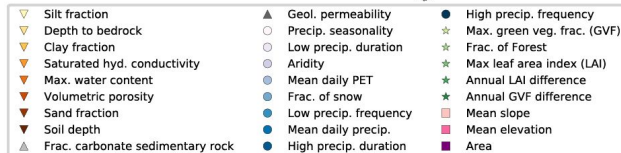
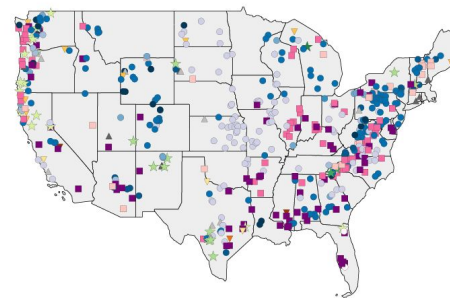
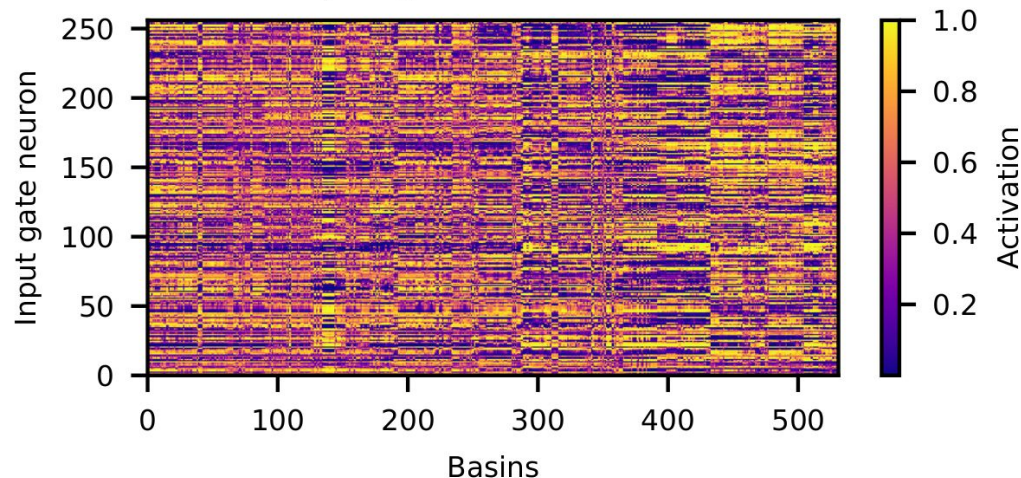
*These a

Corresp

Received

Revised:

Input gate activations



The model learns a catchment-specific 'fingerprint' based on observable catchment characteristics, and uses this to relate rainfall-runoff behaviors in different catchments.

Scale-Relevant Theories: Holy Grail or Tilting at Windmills

1986

1987

2019

WATER RESOURCES RESEARCH, VOL. 22, NO. 9, PAGES 465-585, AUGUST 1986

Looking for Hydrologic Laws

JAMES C. I. D.

Department of Engineering Hydrology

The search for regularities in hydrologic general types of predictive models used in compared and contrasted. The ideas discussed techniques in flood hydrology and by per hydrology and the possibility of their vi-

1. INTRODUCTION

1.1. Relation of Hydrology to Science

Fifty years ago, there was only a handful of books available to the hydrologist who to establish a sound scientific basis for his practice. Today, there is an embarrassing abundance of monographs, journals and symposia proceedings cluttering his or her attention. Is hydrology now an exact science? Is hydrologic practice now firmly based on scientific principles?

This paper deals with the problems raised by the for regularities and for laws in hydrology. It emphasizes the challenge implicit in such a search; attention will be paid to flood hydrology in which enterprise is particularly difficult. It is proposed to the subject within the context of predictive model explanatory theories in science generally. Such an approach can be useful not only for the purpose of emphasizing the position of hydrology as one of the earth sciences but because such an approach could lead to the suggestion of analogies which can be so fruitful in the construction and development of theories [Pohj, 1990].

Following an introductory section on the nature of scientific method, an outline is given of the contrast between approaches of analytical mechanics and statistical methods and the problems involved in dealing with systems of intermediate size. Attention is then turned to the various approaches to the study of water movement and the problem of parameterizing at a macroscale the effect of microscale processes that are not explicitly included in the model. Finally, the historical development of current methods of flood hydrology is reviewed against the background of the foregoing material. The purpose of the whole exercise is to provide the context for the formulation of a strategy for the development of a body of hydrologic knowledge that is both scientifically respectable and practically useful.

The term model is used to describe a system which is simpler than the prototype system and which can reproduce some but not all of the characteristics thereof. According to a model is related to those particular aspects of the behavior of the prototype for which understanding or prediction is required. It is important to realize that a model is not a theory and to distinguish between models that are con-

Water for the Future: Hydrology in Perspective (Proceedings of the Rome Symposium, April 1987). IAHS Publ. no. 164, 1987.

Hydrological Sciences JOURNAL

Hydrological Sciences Journal

Taylor & Francis Group

www.tandfonline.com/loi/rhsj20

Hydrology

Stéphane Cudennec, Hubert Mauch, Elena Zéles, Alberto Ken Andréassian, Jelle Marlies H. Berghuijs, Keith Ammorim, Michael E. Brocca, Wouter Chen, Yangbo ryan P. Clark, David, Felipe P. Mica M. Driscoll, J. Farmer, James iris, Benjamin Gartsman, Simon van Gharari, Tomia P. Gonzalez-Han, David Hricht, Mathew ohmann, Ladislav H. Illangasekare, J. Jirihari, Zahra s Kiesel, Mike yá, Alla Kolehckina, Hstmann, Holger link, Junguo Liu, Jeva, Julien Malard, Pla, Maria Mavrouge Dudley Misstear, Alzadeh, Fernando am Nurtaev, Vincent nghe Pang, Georgia

Stéphane Cudennec, Hubert Mauch, Elena Zéles, Alberto Ken Andréassian, Jelle Marlies H. Berghuijs, Keith Ammorim, Michael E. Brocca, Wouter Chen, Yangbo ryan P. Clark, David, Felipe P. Mica M. Driscoll, J. Farmer, James iris, Benjamin Gartsman, Simon van Gharari, Tomia P. Gonzalez-Han, David Hricht, Mathew ohmann, Ladislav H. Illangasekare, J. Jirihari, Zahra s Kiesel, Mike yá, Alla Kolehckina, Hstmann, Holger link, Junguo Liu, Jeva, Julien Malard, Pla, Maria Mavrouge Dudley Misstear, Alzadeh, Fernando am Nurtaev, Vincent nghe Pang, Georgia

Why do we lack scale-relevant theories of watersheds?

Possible Reasons:

- Heterogeneity Dominates:** There is simply little consistency across different watersheds, so no theory exists.
- Lack of Data:** We lack sufficient observations (type, scale, scope) to discover consistencies.
- Lack of Skill:** There is enough information in available observation data, we simply haven't made the discovery.

Popper distinguished between empirical science. He requires of any scientific system that "it must be possible for an empirical scientific system to be refuted by experience." Popper goes on to develop such principles and rules as will ensure the testability, i.e., the falsifiability of scientific statements.

There is an increasing body of evidence that hydrological science is in some disarray. Exhibit A: studies of the isotopic content of the waters of storm hydrographs (see for example, Sklash & Farvolden, 1979; Herrmann & Stichler, 1980; Kennedy et al., 1986) have provided convincing evidence that traditional methods of "baseflow separation", still presented in recent textbooks and used in