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Floods in a Changing Climate

Inundation Modelling

Floodplains are among the most valuable ecosystems for supporting biodiversity and providing environmental services, and are also home to approximately one-sixth of the world population. As a result, flood disasters currently affect more than 100 million people a year. Flood inundation models are a valuable tool in mitigating increasing flood fatalities and losses. This book demonstrates how these models enable us to make hazard predictions for floodplains, support appropriate land use and urban planning, and help discourage new human settlements in flood-prone areas. It provides an understanding of hydraulic modelling and floodplain dynamics, with a key focus on state-of-the-art remote sensing data, and methods to estimate and communicate uncertainty. Additional software and data tools to support the book are accessible online at www.cambridge.org/dibaldassarre.

This is an important resource for academic researchers in the fields of hydrology, climate change, environmental science and natural hazards, and will also be invaluable to professionals and policy-makers working in flood risk mitigation, hydraulic engineering and remote sensing.

This volume is the third in a collection of four books within the International Hydrology Series on flood disaster management theory and practice within the context of anthropogenic climate change. The other books are:

1 – Floods in a Changing Climate: Extreme Precipitation *by Ramesh Teegavarapu*
2 – Floods in a Changing Climate: Hydrologic Modeling *by P. P. Mujumdar and D. Nagesh Kumar*
4 – Floods in a Changing Climate: Risk Management *by Slodoban Simonović*

Giuliano Di Baldassarre is a Senior Lecturer at the UNESCO-IHE Institute for Water Education in Delft, the Netherlands, and also works as the Coordinator of the EC FP7 KULTURisk project, which aims at prevention of water-related disasters through evaluation of different risk prevention measures. His teaching and research interests include: floodplain processes and inundation modelling, hydroinformatics and remote sensing data, statistical hydrology, and flood management under uncertainty. Dr Di Baldassarre serves as an editor of *Hydrology and Earth System Sciences*, and guest editor of *Physics and Chemistry of the Earth and Hydrological Processes*, and is also the author of more than 30 peer-reviewed journal articles and more than 60 other publications including invited book chapters and conference proceedings. His scientific papers have received more than 200 citations, and his achievements have been recognized by a number of prizes, including the Outstanding Young Scientist Award from the European Geosciences Union.

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To my Family

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Water is the cause at times of life or death, or increase of privation, nourishes at times and at others does the contrary; at times has a tang, at times is without savour, sometimes submerging the valleys with great floods. In time and with water, everything changes.

Leonardo da Vinci, *circa* 1500

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Forewords

Everybody speaks about climate change these days, yet not everybody recognizes that most of the impacts of climate variability will be manifested through, with and by water. Whether one speaks about sea level rise or increasing flood frequencies, or the combined effect of the two in the case of coastal areas, it is water that will be the agent of change, for water connects. It connects environmental systems with the social ones; in fact it connects all the major development objectives as set by the Millennium Development Goals (MDGs) as well as matters related to food and energy security. It is, therefore, critical to understand the response of hydrologic systems to extremes.

How will flooding patterns in general change in response to the global drivers that will have regional, national and even local impacts? Is it indeed only climate variability and change that is the main driver behind changes in flood dynamics? How will flood risks change in relation to the global drivers? And what is indeed the most important driver that will influence flood risk management, say, in forty years when there will be approximately nine billion human beings on the Earth? Will it be climate variability or other global drivers linked to population change, such as land-use changes, migration from rural to urban areas, technology or the expected unprecedented growth of cities? Climate change will likely contribute to increased uncertainty, and thereby risk; however, the main driver that will cause further significant changes in flood dynamics is population increase and the resulting human interventions in the workings of the hydrologic cycle.

The water science community is grappling with a major question: Is it true that the hydrologic cycle is accelerating? Because if this is indeed the case then we have the primary proof that the climate system changes and moves outside the deviations linked to normal climate variability. If that is the case then we have the principal proof that flood frequencies do indeed increase and for that matter the probability of other hydrologic extremes, such as droughts, occurring more often will indeed increase. As a net result we will have more floods.

QED, one would be tempted to say. However, we do not have the solid evidence that the hydrologic cycle indeed accelerates at a global scale. There is no global trend observed yet that would indicate either an increased flow or a decreased flow. There are some rivers where flow patterns display a decreasing trend, while there are others which show an increasing flow tendency. Overall no clear trend can be identified. Even at continental scale the balance between increasing versus decreasing flows seems to be all right.

One reason to come to this conclusion might be that indeed the hydrologic cycle is not accelerating and the overall system is at equilibrium. The other conclusion one might have is somewhat more prosaic: we simply do not know enough about the workings of the hydrologic cycle. One reason behind that is that the statistical hypothesis and tools we use are too weak to detect the change. After all, we are still using a toolbox that contains tools designed to handle stationary processes. That assumption is surely not true any more in our exponentially changing world. The second reason is the age-old issue of data scarcity. First of all, the time series we have are relatively short to make inferences for large time scales that typically characterize climate change, even if the data sets started in the late nineteenth century. Second, the issue of spatial scarcity is even more striking. Take, for instance, the case of Africa where data availability is very scarce due to historical and other reasons. On top of these, there is a third reason why we are facing problems in properly managing flood risk as a function of various drivers, and that is the sizeable gap that exists in our understanding of the relevant processes.

Irrespective of these issues and uncertainties, one thing seems to be quite certain: flood vulnerability and risks will no doubt increase in the coming decades. Owing to the fact that more and more people are moving into flood-prone areas it is no longer sufficient to issue forecasts for the flood hydrographs alone, as the two-dimensional character of flooding will dominate the success of flood management activities.

This fact alone underlines the huge importance of Giuliano Di Baldassarre's present book. What the reader is presented with in this volume is a systematic treatment of flood inundation modelling ranging from the theoretical backgrounds of unsteady flow all the way up to the making and interpretation of floodplain mapping. Di Baldassarre has done very commendable work by putting in one comprehensive framework both the relevant theory and its applications. A great number of examples, ranging from

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urban flood modelling to the evaluation of floodplain management strategies, and exercises help the understanding of the underlying concepts.

The material presented herein could be used in various teaching courses at different levels and also as a case study book in flood management. Therefore, I would like to recommend this excellent volume wholeheartedly for both academics and practitioners involved in flood management as the knowledge contained in the volume will certainly help reduce the risks of flood inundation and thereby will help in moving towards sustainable water management.

Professor A. Szöllösi-Nagy
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There are scientific issues related to earth sciences that are extremely important for our everyday life and have benefited much from recent research results and improved environmental monitoring. Inundation modelling is an excellent example where the progress is amazing. Scientists have recently been able to deal with the increasing problems related to inundations through an efficient synthesis between technical capabilities, improved computational means and research advances. Indeed, illustrating the above progress, to further help translating research results into technical practice, is an excellent idea and this book does the job in a clear and exhaustive manner.

Water has always been a key driver of social development and therefore living with, and protecting from, water has always been one of the arts of humanity. Today the art is becoming more challenging due to the increasing needs originating from the improving social welfare. The recent flood events that have occurred all over the world have pointed out the urgent necessity to predict how water expands over floodplain and urban areas. Such events clearly show that we are not prepared enough to deal with water flowing over roads and among houses, while recent research results show that such events can be modelled and their effect predicted, by profiting from extraordinarily improved monitoring capabilities. Therefore, the above art, which was recently enriched with important contributions, needs to be supported with new educational tools.

This is the reason why I enthusiastically appreciated the idea of Giuliano Di Baldassarre writing this book. It is uncommon to see a young scientist writing a book, and therefore I am very much delighted to see his signature under this timely and precious contribution. Indeed, it shows that the motivation, preparation and clarity of ideas that support young scientists are an invaluable contribution to science and society. When I read these pages I could not avoid my thoughts pleasingly going back to 6 years ago, remembering the time when Giuliano and I were working together on his Ph.D. research and every day I was impressed by his rigorousness with details and clarity. One of the reasons why research is a very rewarding job is the opportunity to meet extraordinary persons.

What I particularly like in this book is the emphasis that is given to uncertainty estimation for decision-making, which is tackled here with an original approach that makes use of several sources of information. Chapters 5, 6 and 7 bring forward an original contribution that will open the doors to further research activity. In particular, an important issue is highlighted that is often not considered enough, namely, uncertainty in the boundary conditions for hydraulic modelling. Finally, this book emphasizes the opportunity to include social forcing in environmental modelling. Environment and society are linked and conditional on each other: understanding the underlying connections is a fundamental step forward to improving living conditions and, in particular, reducing flood risk.

I warmly address to Giuliano Di Baldassarre my personal appreciation. I also would like to thank all the readers of these few words, which I wrote with great pleasure.

Professor A. Montanari
University of Bologna

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Preface

Floodplains are among the most valuable ecosystems for providing goods and services to the environment and supporting biodiversity. At the same time, it is estimated that almost one billion people, the majority of them the world's poorest inhabitants, currently live in floodplains. As a result, flooding is nowadays the most damaging natural hazard worldwide. Damage and fatalities caused by flood disasters are expected to further increase dramatically in many parts of the world because of continuous population growth in floodplains as well as changes in land use and climate.

Over the past decades, I have been looking at different methods – developed by hydrologists, ecologists, engineers and geomorphologists – to observe and analyse floodplain systems. These floodplain models range in complexity from simply intersecting a plane representing the water surface with digital elevation models to sophisticated solutions of the Navier–Stokes equations. Some of these models have been proved to be useful tools in floodplain management, understanding sediment dynamics and flood risk mitigation. For instance, their ability to predict inundation extents can be used to reduce the potential flood damage by supporting more appropriate land use and urban planning, raising the awareness of people living in flood-prone areas, and discouraging new human settlements in floodplains.

Thus, I was really glad when I was contacted by Slobodan Simonovic and given the opportunity to write this book, dealing with floodplain dynamics and inundation modelling, as one of the collection of books within the International Hydrology Series on flood disaster management theory and practice within the context of climate change.

And here we are. This book, *Floods in a Changing Climate: Inundation Modelling* – prepared under the responsibility and coordination of Siegfried Demuth, UNESCO International Hydrological Programme (IHP), Chief of Hydrological Systems and Global Change Section and scientist responsible for the International Flood Initiative (IFI), and Biljana Radojevic, Division of Water Sciences – is intended for graduate students, researchers, members of governmental and non-governmental agencies and professionals involved in flood modelling and management. A number of revision exercises are included in the book to promote more effective learning of concepts within academic environments. Access to online electronic resources including software for one-dimensional (1D) and two-dimensional (2D) hydraulic modelling is also provided.

The book is structured as follows: Introduction, Theory (Part I), Methods (Part II), and Applications (Part III). Throughout the book, particular attention is given to, on the one hand, the challenge of dealing with the estimation of the uncertainty affecting any modelling exercise, and, on the other hand, the opportunity given by the current proliferation of remote sensing data to improve our ability to model floodplain inundation processes. The first part of the book (Chapters 2 and 3) provides a concise, but as comprehensive as possible, mathematical description of the basic hydraulic principles, steady and unsteady flow equations, numerical and analytical solutions. The second part (Chapters 4–7) is the core of the book and its structure reflects the steps necessary for the implementation of hydraulic modelling of floods: data acquisition, model building, model evaluation, and elaboration of model results in a GIS environment. Lastly, the third part (Chapters 8–11) shows four different example applications of flood inundation modelling in a rapidly changing world: analysis of urban floods, changes in flood propagation caused by human activities, changes in stage–discharge rating curves, and evaluation of different floodplain management strategies.

In conclusion, I would like to highlight that this book could not have been made without the kind and substantial contributions of Paul Bates, Luigia Brandimarte, Tim Fewtrell, Jeff Neal, Ioana Popescu, Durga Lal Shrestha, and András Szöllösi-Nagy. Also, I would like to acknowledge my father Domenico Di Baldassarre for kindly drawing some of the figures, as well as Francesco Dottori and Leonardo Alfonso Segura for providing precious support during the book writing process. Lastly, the book includes concepts and thoughts that emerged by interacting with colleagues and friends over the past few years. Here, I feel I must mention, in completely random order: Micah Mukolwe, Alberto Montanari, Philip Tetteh Padi, Doug Alsdorf, Elena Toth, Kun Yan, Stefan Uhlenbrook, Alessio Domeneghetti,

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