Floods in a Changing Climate

Hydrologic Modeling

Hydrologic modeling of floods enables more accurate assessment of climate change impacts on flood magnitudes and frequencies. This book synthesizes various modeling methodologies available to aid planning and operational decision-making, with emphasis on methodologies applicable in data-scarce regions, such as developing countries. Topics covered include: physical processes that transform precipitation into flood runoff, flood routing, assessment of likely changes in flood frequencies and magnitudes under climate change scenarios, and use of remote sensing, GIS, and DEM technologies in modeling of floods to aid decision-making. Problems included in each chapter, and supported by links to available online data sets and modeling tools accessible at www.cambridge.org/mujumdar, engage the reader with practical applications of the models.

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

This volume is the second 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: Inundation Modelling *by Giuliano Di Baldassarre*
3 – Floods in a Changing Climate: Risk Management *by Slodoban Simonović*

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Foreword

How much *higher* does the flood wall need to be built? How much *larger* does the reservoir spillway need to be? How much *more* capacity is needed in the urban drainage system? These are the type of questions that floods are confronting, given expected changes in rainfall intensity, timing and volume of peak flows, and sea levels under climate change.

There are no simple answers. In fact, climate change is just one driver of flood risk amongst many others. Rapid urbanization, development in floodplains, removal of natural vegetation, artificial drainage, and so forth, can all compound flooding. Therefore, it is helpful to regard the climatic hazard as a multiplier of flood risk that may already be increasing because of other socio-economic trends and/or human changes to the landscape. It then follows that the adaptation responses will involve cooperation amongst many disciplines: the hydrologist to quantify the impact of environmental changes on river flows; the economist to weigh up the costs and benefits of different options; the geographer to see the broader socio-physical context of the scheme and non-structural choices; the engineer to implement the design and devise operational rules; and the politician to persuade taxpayers to pay for the project!

The unavoidable truth is that structural measures for reducing flood risk need hard numbers to dimension the flood wall, spillway, and drainage system. This is challenging enough under present climate conditions because we seldom have long enough hydrometeorological records (if any); the records we have may be corrupted by other long-term changes in the river basin; and there is plenty of subjectivity in our methods for estimating extreme flow statistics. To add climate change to this situation is to present a technical challenge steeped in uncertainty. Meanwhile, the engineer still needs numbers to get the project underway.

The scientific community offers the practitioner a bewildering set of methodologies. For example, there are many different ways of conjuring future rainfall intensity: regional climate downscaling (using physical or statistical models); Monte Carlo and re-sampling techniques for constructing large synthetic rainfall series based on available data; or just specifying a plausible range of values for sensitivity testing. Indeed, given the large and irreducible uncertainties in climate model predictions, a strong case can often be made for simpler methods. Depending on the risk–reward, a climate change safety margin may be set without even referring to climate models. In situations where the structure has a short (less than 20 years) life-span, the concern will be climate variability not climate change. In other heavily discounted cases, future climate changes may be irrelevant to the viability of a scheme and shorter-term goals may be paramount.

Despite the large uncertainty in future flood risk, hydrologists still have plenty to offer adaptation planners. More accurate, timely, and clearly articulated flood warnings will continue to improve the safety of vulnerable populations living with unavoidable flooding. Simulations of flood depths and areas will help planners to zone floodplains and regulate development in hazardous places. Field monitoring and modeling will contribute to improved understanding of the physical processes that generate extreme floods in different environments. Remotely sensed data and seasonal forecasts can inform the operation of infrastructure to optimize benefits across multiple objectives (such as flood control, hydropower production, and water supply). Such activities are not always perceived as adaptation, but they do contribute to flood risk management just as much as the wall, spillway, and drainage system.

The authors of this book are to be commended for guiding practitioners, step-by-step, through some of the analytical tools and techniques for evaluating flood risk under non-stationary climate conditions. The true benefit will come from recognizing the part played by these approaches within a larger armoury of strategies for managing flood hazards over coming decades and beyond.

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Preface

This book has been developed under the coordination of Professor Siegfried Demuth, International Hydrology Programme, Chief of the Hydrological Systems and Global Change Section and Scientist in Charge of the International Flood Initiative, and Dr. Biljana Radojevic of the Division of Water Sciences, UNESCO.

The book presents methodologies for hydrologic modeling of floods and for assessing climate change impacts on hydrology, with specific focus on impacts on flood magnitudes and frequencies. The following topics are covered with a view to training the reader in the use of hydrologic models for assessing climate change impacts: (i) review of basic hydrology that includes physical processes transforming precipitation into flood runoff, intensity–duration–frequency relationships, and flood routing; (ii) recent modeling tools of artificial neural networks and fuzzy inference systems for river discharge forecasting and flood routing; (iii) use of climate projections provided by the general circulation models (GCMs) for assessing likely changes in flood frequencies; and (iv) use of remote sensing, global information system (GIS) and digital elevation model (DEM) technologies in modeling of floods to aid decision-making.

The novelty of the book lies in synthesizing various methodologies available to help in planning and operational decision-making, in the face of climate change. Exercise problems discussed in the text and those presented at the end of the chapters are intended to train a reader on applications in practical settings. Two case studies are discussed in detail in Chapter 6 to help the reader understand the use of the methodologies for long-term planning, in real situations. The book is intended to serve as a reference document to practicing hydrologists, especially those with responsibilities of assisting in decision-making with respect to floods, graduate students, professionals, researchers, and members of governmental and non-governmental agencies interested in impacts of changing climate on floods.

Bringing together the basic material available in classical textbooks on hydrology and the advanced material available only in the recently published research papers in a coherent form in a book is a challenge. The authors were confronted with the difficulty of presenting fundamental topics, such as estimation of flood runoff, hydrologic flood routing, and frequency analysis, that are available in standard text books along with advanced topics of statistical downscaling of GCM simulations, fuzzy inference systems, and use of satellite remote sensing in hydrologic modeling. The authors believe that such a mix of topics will be of immense use to a new entrant to the field of hydrologic modeling for climate change impact assessment.

The book comprises six chapters. Chapter 1 provides an introduction to climate change impacts on hydrology, and sets the tone for the remainder of the book. Chapter 2 provides the necessary background on basic hydrology and use of hydrologic models for planning and management of floods. Chapter 3 presents methodologies commonly employed to obtain projections of flood magnitudes and frequencies under future climate change, with GCMs and hydrologic models. A review of techniques for downscaling large-scale atmospheric variables to station-scale hydrologic variables is also provided in this chapter. Chapter 4 introduces remote sensing (RS), covering the topics of spectral reflectance curves, RS platforms, digital images, image processing including rectification, enhancement, and information extraction. The role of RS in hydrologic modeling is discussed through examples. Use of GIS and DEMs in hydrologic modeling is discussed in Chapter 5. Synthesis of climate change impacts, uncertainties, RS, GIS, DEM, and hydrologic models is demonstrated through two case studies in Chapter 6. Future perspectives on hydrologic modeling under climate change are presented in Chapter 6.

The topic of climate change impact assessment is of recent origin, and the authors had to rely on contemporary research, especially in the chapters dealing with climate change impact assessment and use of remote sensing and GIS for hydrologic modeling. The authors have used material from their own recently published research papers extensively in the book.

The contribution to Chapter 3 by Dr. Deepashree Raje, a post-doctoral research associate at IISc Bangalore when the first draft of the book was prepared, was significant and valuable. Considerable help was provided by Ms. J. Indu, research student, in the preparation of Chapter 5. The authors are grateful to their students, Ms. Arpita Mondal, Mr. Ujjwal Saha, Ms. Divya Bhatt, Mr. Laxmi Raju, Dr. Reshmidevi, Dr. Dhanya, and Ms. Sonali Pattanayak for their help in providing solutions to the numerical examples and in preparation of figures. Ms. Chandra Rupa, a Project Associate at IISc, helped the authors in the preparation of numerical examples and in formatting the figures, tables, and text. Her assistance is gratefully acknowledged.

Glossary

Climate change Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2007).

Climate model A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties (IPCC, 2007).

Climate projection A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/ radiative forcing scenarios used, which are based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty (IPCC, 2007).

Climate scenario A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models (IPCC, 2007).

Climate variability Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability) (IPCC, 2007).

Digital elevation models (DEMs) DEMs are data files that contain the elevation of the terrain over a specified area, usually at a fixed grid interval over the surface of the Earth. The intervals between each of the grid points are always referenced to some geographical coordinate system such as latitude/longitude or Universal Transverse Mercator (UTM) coordinates. When the grid points are located closer together, more detailed information is available in the DEM. The details of the peaks and valleys in the terrain are better modeled with a closer grid spacing than when the grid intervals are very large.

Downscaling Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model (IPCC, 2007).

Emissions scenario A scenario is a plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships. Concentration scenarios, derived from emissions scenarios, are used as input to a climate model to compute climate projections (IPCC, 2007).

Geographic information systems (GIS) GIS is a system of hardware and software used for storage, retrieval, mapping, and analysis of geographic data. Spatial features are stored in a latitude/longitude or UTM coordinate system, which references a particular place on the Earth. Descriptive attributes in tabular form are associated with spatial features. Spatial data and associated attributes in the same coordinate system can then be layered together for mapping and analysis. GIS can be used for scientific investigations, resource management, and development planning.

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Remote sensing Remote sensing (RS) is the art and science of obtaining information about an object or feature without physically coming in contact with that object or feature. It is the process of inferring surface parameters from measurements of the electromagnetic radiation (EMR) from the Earth's surface. This EMR can be either reflected or emitted radiation from the Earth's surface. In other words, RS is detecting and measuring electromagnetic energy emanating or reflected from distant objects made of various materials, to identify and categorize these objects by class or type, substance, and spatial distribution (American Society of Photogrammetry, 1975).

Troposphere The lower part of the terrestrial atmosphere, extending from the Earth's surface up to a height varying from about 9 km at the poles to about 17 km at the equator, in which the temperature decreases fairly uniformly with height.

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Abbreviations

AMC	Antecedent Moisture Content
ANN	Artificial Neural Network
AOGCM	Atmospheric Oceanic General Circulation Model
ARI	Average Recurrence Interval
AVSWAT	ArcView Soil and Water Assessment Tool
BP	Back Propagation
CCA	Canonical Correlation Analysis
CGCM	Coupled General Circulation Model
CN	Curve Number
CP	Circulation Pattern
CRF	Conditional Random Field
CWG	Conditional Weather Generator
DEM	Digital Elevation Model
DHM	Distributed Hydrologic Model
DN	Digital Number
EMR	ElectroMagnetic Radiation
ENSO	El Niño–Southern Oscillation
FCC	False Color Composite
FDFRM	Fuzzy Dynamic Flood Routing Model
GCM	General Circulation Model (Global Climate Model)
GEV	Generalized Extreme Value
GHG	GreenHouse Gas
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center – River Analysis System
HRU	Hydrologic Response Unit
IDF	Intensity–Duration–Frequency
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISRO	Indian Space Research Organisation
KNN	K-Nearest Neighbor
LSAV	Large-Scale Atmospheric Variable
LSM	Land Surface Model
MATLAB	MATrix LABoratory
MF	Membership Function
MHM	Macroscale Hydrologic Model
MSLP	Mean Sea Level Pressure
NARR	North American Regional Reanalysis
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NHMM	Non-homogeneous Hidden Markov Model
NIR	Near Infrared
NRCS	Natural Resources Conservation Service (formerly known as Soil Conservation Service)
NRMSE	Normalized Root Mean Square Error
PCA	Principal Component Analysis
PDO	Pacific Decadal Oscillation
RBF	Radial Basis Function
RCM	Regional Climate Model
RMSE	Root Mean Square Error
RS	Remote Sensing
SCS	Soil Conservation Service (now known as Natural Resources Conservation Service)
SDSM	Statistical DownScaling Model
SMOS	Soil Moisture and Ocean Salinity
SPI	Standardized Precipitation Index
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topography Mission
SSFI	Standardized Stream Flow Index
SVL	Soil–Vegetation–Land
SVM	Support Vector Machine
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TCC	True Color Composite
TRMM	Tropical Rainfall Measuring Mission
UNESCO	United Nations Education, Social and Cultural Organisation
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VCS	Variable Convergence Score
VIC	Variable Infiltration Capacity
VPMS	Variable Parameter Muskingum Stage hydrograph
WG	Weather Generator