Floods in a Changing Climate

Risk Management

Climate change and global warming of the atmosphere are very likely to lead to an increase in flooding, and there is now an urgent need for appropriate tools to tackle the complexity of flood risk management problems and environmental impacts. This book presents the flood risk management process as a framework for identifying, assessing, and prioritizing climate-related risks, and developing appropriate adaptation responses. It integrates economic, social, and environmental flood concerns, providing support for interdisciplinary activities involved in the management of flood disasters. Rigorous assessment is employed to determine the most suitable plans and designs for complex, often large-scale, systems, and a full explanation is given of the available probabilistic and fuzzy set-based analytic tools, when each is appropriate, and how to apply them to practical problems. Additional software and data, enabling readers to practice using the fuzzy and probabilistic tools, are accessible online at www.cambridge.org/simonovic.

This is an important resource for academic researchers in the fields of hydrology, climate change, environmental science and policy, and risk assessment, and will also be invaluable to professionals and policy-makers working in hazard mitigation, water resources engineering, and environmental economics.

This volume is the fourth 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*
3 – Floods in a Changing Climate: Inundation Modelling *by Giuliano Di Baldassarre*

SLOBODAN SIMONOVIĆ has over thirty years of research, teaching and consulting experience in water resources engineering, and has received a number of awards for excellence in teaching, research and outreach. Most of his research is being conducted through the Facility for Intelligent Decision Support (FIDS) at the University of Western Ontario, where he is a Professor of Civil and Environmental Engineering and the Director of Engineering Studies with the Institute for Catastrophic Loss Reduction. His primary research focus is on the application of systems approach to, and development of the decision support tools for, management of complex water and environmental systems and the integration of risk, reliability, uncertainty, simulation and optimization in hydrology and water resources management. Dr Simonovic teaches courses in civil engineering and water resources systems, plays an active role in national and international professional organizations, and has been invited to present special courses for practicing water resources engineers in many countries. He is Associate Editor of the *Journal of Flood Risk Management*, and *Water Resources Management*, and has published over 350 articles and two major textbooks.

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Floods in a Changing Climate

Risk Management

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

4843/24, 2nd Floor, Ansari Road, Daryaganj, Delhi - 110002, India

79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108447058

First published 2012
First paperback edition 2017

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging in Publication data
Simonovic, Slobodan P.
Floods in a changing climate : risk management / Slobodan P. Simonovic.
pages cm. – (International hydrology series)
Includes bibliographical references and index.
ISBN 978-1-107-01874-7
1. Flood control. I. Title.
TC530.S565 2012
363.34´932 – dc23 2012010631

ISBN 978-1-107-01874-7 Hardback
ISBN 978-1-108-44705-8 Paperback

Cambridge University Press
978-1-108-44705-8 — Floods in a Changing Climate
Slobodan P. Simonović
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To Tanja, Dijana, and Damjan

Cambridge University Press
978-1-108-44705-8 — Floods in a Changing Climate
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What is the appropriate behavior for a man or a woman in the midst of this world, where each person is clinging to his piece of debris? What's the proper salutation between people as they pass each other in this flood?

Buddha (c. 563–483 BC)

There is a tide in the affairs of men, which, taken at the flood, leads on to fortune. . . . we must take the current when it serves, or lose our ventures.

William Shakespeare (1564–1616)

There can be no vulnerability without risk; there can be no community without vulnerability; there can be no peace, and ultimately no life, without community.

M. Scott Peck (1936–2005)

Decision is a risk rooted in the courage of being free.

Paul Tillich (1886–1965)

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Forewords

Almost every day, many people are affected by flooding. In 2011, cyclones and heavy monsoon rains triggered unusually severe seasonal flooding across Southeast Asia, affecting many nations including Thailand. The major floods in Bangkok had, by mid-December, killed at least 675 people and caused major economic impacts. In the fall 2011, there were also floods in Colombia, Australia, Kenya, and other places. Hydrologic disasters, dominantly floods but also including wet mass movements (mud slides), are responsible for just more than half of all the disasters in the period 2000–2010. During this period, these events killed, on average, more than 5,000 people per year with the total affected being about 100 million people. The total affected is the sum of injured, homeless, and people requiring immediate assistance during a period of emergency. Annual damage costs are about US$20 billion.

M. Wahlström, the United Nations Assistant Secretary-General for Disaster Risk Reduction, stated, "Over the last two decades (1988–2007), 76% of all disaster events were hydrological, meteorological or climatological in nature; these accounted for 45% of the deaths and 79% of the economic losses caused by natural hazards." She concluded her statement with: "The real tragedy is that many of these deaths can be avoided." This book on flood risk management, by Professor Slobodan Simonović, is about actions that can be taken to anticipate and prevent or mitigate harms that may be avoidable and reduce the number of deaths and lower the socio-economic impacts.

Although the impacts of a flood are usually less than an earthquake, floods occur more often. Meteorological events, such as storms, the next most common, occur less than half as often. Both are part of what we can call the climate system, and this book is addressing flood risk management in the context of climate change. In 2009, world leaders at the United Nations Climate Change Conference agreed to the Copenhagen Accord, which states in the opening paragraph: "We underline that climate change is one of the greatest challenges of our time. . . . We recognize the critical impacts of climate change and the potential impacts of response measures on countries particularly vulnerable to its adverse effects and stress the need to establish a comprehensive adaptation programme including international support." Since climate change adaptation is "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities," this book deals with how to moderate harm or specifically reduce flooding risk. Chapter 6 specifically addresses future perspectives in a changing climate.

In November 2011, governments approved the Summary for Policy Makers of the Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. The Summary for Policy Makers includes the statement: "A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events." The Special Report specifically concluded: "It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe." The Special Report states that the changes in projected precipitation and temperature changes imply possible changes in floods, but notes that there is *low confidence* in projections of changes in fluvial floods due to the *limited evidence* and because the causes of regional changes are complex. This book is addressing those relationships so with further studies based on these principles the evidence should become clearer in the future.

This book provides methods and approaches to reduce the impacts of floods that have for millennia been affecting people around the world and usually most on those most vulnerable. Now through the actions of people collectively, and specifically mostly those in developing countries, the atmospheric greenhouse gas concentrations have increased and are changing the climate. With that climate change there will be more intense precipitation events and warmer temperatures which based on physical logic implies more flooding events. Hence, the impacts on the vulnerable will increase more and raise the need for actions. Among those actions needed is the reduction of risk of flooding and that is the topic addressed in this important and timely book.

Dr. Gordon McBean, C.M., O. Ont., FRSC
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December 2011

Climate change is undoubtedly one of the most pressing issues facing society today and the potential impacts of climate change are currently a prime concern for water resource professionals. The possible impacts of climate change have the potential to dramatically alter the temporal and spatial distribution and availability of water on the Earth's surface with consequences that could be disastrous. Furthermore, climate change could, paradoxically, lead to both more frequent and severe drought conditions and flooding events that are of greater frequency and magnitude. In this book, Professor Slobodan Simonović addresses the potential impacts of increases in flood event magnitude and frequency through a comprehensive analysis of the interplay between climate change and flooding conditions with a particular focus on the role of the management of flood risk.

Professor Simonović has had a distinguished career as a water professional, consultant, educator, and researcher. I first met Slobodan more than 25 years ago when we were both faculty members at the University of Manitoba in Winnipeg, Manitoba, Canada. Through collaboration on research and consulting projects I came to appreciate the wealth of knowledge that he brings to his professional activities. Towards the end of our time in Winnipeg, we were both involved in different aspects of the Red River Flood of 1997, the so-called "Flood of the Century", in the Red River valley, a flood-prone area of Canada and the United States. Slobodan's involvement with this major flood event, and its aftermath, is but one of many examples of the practical expertise that he brings to the writing of this important and timely book. We frequently hear reports in the media of devastating flooding events, in various parts of the world, of seemingly unprecedented scope, geographic extent, and magnitude. There often follows natural speculation that the occurrence of such a flooding event, or events, must be further evidence of the impacts of climate change. This book helps to make sense of these events and provides the water professional with important tools to cope with the impacts of increases in the frequency and magnitude of flooding events and the associated societal consequences.

In this book, Professor Simonović considers not just what the impacts of climate change may be on water, and flooding in particular, but also looks at flood risk management, which can be usefully applied, as he suggests, as an effective form of climate change adaptation. Climate change adaptation through flood risk management is one of several themes that tie the parts of this book together. The book consists of four parts. The first part, entitled "Setting the Stage", deals with the central topic of flood risk management and introduces climate change and the interplay between climate change and flood risk management. An important and interesting section in this part is the very detailed case study of climate change impacts on municipal infrastructure within the City of London, Ontario, Canada. This extensive example application very nicely draws together the common intertwining threads of floods, risk, and climate change within a real-world application. The research described in this section of the book is one of the strengths of this publication. The second and third parts of the book deal with flood risk management from the perspective of a probabilistic and a fuzzy set approach, respectively. In both of these parts, flood risk management is introduced from a systems analysis context; systems analysis is another common and unifying theme for much of the material in this book. The final part of the book looks at "Future Perspectives" and again provides an essential link between the potential impacts of climate change and flood risk management with a particular focus on the importance of both of these issues to the public and also the overarching need to effectively communicate climate change impacts and flood risk management issues to the general public. These are again topics with which Professor Simonović has considerable experience.

This is an important book that will be of interest to water professionals, policy makers, researchers, and others concerned with the potential impacts of climate change on flooding events and on flood risk management.

Dr. Donald H. Burn
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January 2012

Preface

I have stated many times that I am one of the lucky few who have the opportunity to work all their professional lives in an area that they enjoy. The most enjoyable activity for me is to integrate knowledge from different fields into an approach for solving complex problems that include uncertainty. My work has brought me into contact with many people, responsible professionals, talented engineers, capable managers, and dedicated politicians. In my capacity as an academic I have also had an opportunity to work with young talented people – the future of our workforce. I learned a lot from all of them. I learned many things about the profession, I learned a lot about different cultures, and most importantly I learned about life. Thank you.

My interest in risk and flooding as a natural disaster grew from my main area of expertise – water resources systems management. From the early days of my professional career I was involved with floods and flood management, first from an engineering point of view and then later from a management point of view. Flood problems along the Morava, Sava, and Danube rivers in my country of origin – Serbia – were among the first professional challenges I had to deal with after graduation. In 1997, I was teaching at the University of Manitoba and living in Winnipeg. That was the year of the "Flood of the Century." The governments of Canada and the USA have agreed that steps must be taken to reduce the impact of future flooding on the Red River. In June 1997, they asked the International Joint Commission (IJC) to analyze the causes and effects of the Red River flood of that year. The IJC appointed the International Red River Basin Task Force to examine a range of alternatives to prevent or reduce future flood damage. I was appointed to the task force and the subsequent experience changed my life.

My work has taken me all over the world. I have had an opportunity to see flood problems in the developed and developing world, in small villages and large urban centers. Projects I have been involved with range in scale from the local to the international. I have discussed flooding issues with farmers of the Sihu area in China as well as the Minister for Irrigation and Water Resources of Egypt. I hope that my professional expertise continues to contribute to the solution of some of these problems. It definitely inspires me to continue to work with greater effort and more dedication.

For more than 35 years of personal research, consulting, teaching, involvement in policy, implementation of projects, and presentation of experiences through the pages of many professional journals, I have worked hard to raise awareness of the importance of uncertainty – objective and subjective – in the solution of complex problems. The main thrust of my work is the use of a systems approach in dealing with complexity. I have accumulated tremendous experience over the years. In that time I realized that there is an opportunity to contribute to the area of flood risk management by transferring some of the knowledge and experience from the implementation of systems thinking and systems tools to various steps of the flood risk management cycle. Writing this book offered me a moment of reflection, and it elaborates on lessons learned from the past to develop ideas for the future.

Acknowledgments

Publishing this book was made possible through the contributions of many people. I would like to start by acknowledging the publication support provided by the International Hydrologic Programme of UNESCO, and the Water Science Division team including Siegfried Demuth and Biljana Radojevic. Most of the knowledge contained in this book came from my numerous interactions with teachers, students, and colleagues throughout the world. They taught me all I know. I would like particularly to thank the students whose work is used in this text. In order of appearance in the text, they are Hyung-Ill Eum (Chapter 3), Dragan Sredojevic (Chapter 3), Lisa Bowering-Taylor (Chapter 3), Angela Peck (Chapter 3), Dejan Vucetic (Chapters 4 and 5), Ozren Despic (Chapter 5), Ibrahim El-Baroudi (Chapter 5), Taslima Akter (Chapter 5), and Mike Bender (Chapter 5). A special thank you goes to Veerakcudy Rajasekaram, who is the developer of the computer programs.

The support of my family, Dijana, Damjan, and Tanja, was of the utmost importance in the development of this book. They provide a very large part of my motivation, my goals, my energy, and my spirit. Without the endless encouragement, criticism, advice, and support of my wife Tanja this book would never have been completed.

Definitions

Uncertainty**:** lack of certainty; a state of having limited knowledge where it is impossible to exactly describe the existing state or future outcome; more than one possible outcome. Sometimes the implications of uncertainty involve risk – a significant potential unwelcome effect of system performance. For example, if you do not know whether it will rain tomorrow, then you have a state of uncertainty. If you apply probabilities to the possible outcomes using weather forecasts, you have quantified the uncertainty. Suppose you quantify your uncertainty as a 90% chance of sunshine. If you are planning a major, costly, outdoor event for tomorrow then you have risk, since there is a 10% chance of rain and rain would be undesirable. Furthermore, if this is a business event and you would lose $100,000 if it rains, then you have quantified the risk (a 10% chance of losing $100,000).

Vagueness or ambiguity is sometimes described as "second-order uncertainty," where there is uncertainty even about the definitions of uncertain states or outcomes. The difference here is that this uncertainty is about human definitions and concepts, not an objective fact of nature. It has been argued that ambiguity, however, is always avoidable while uncertainty (of the "first order") is not necessarily avoidable.

Uncertainty may be purely a consequence of a lack of knowledge of obtainable facts. That is, you may be uncertain about whether a new dyke design will work, but this uncertainty can be removed with further analysis and experimentation.

There are other taxonomies of uncertainties and decisions that include a broader sense of uncertainty and how it should be approached from an ethics perspective (Tannert *et al*., 2007). Figure 1 shows the taxonomy of uncertainties and decisions according to Tannert *et al*.

The first form of uncertainty in this scheme is objective uncertainty, which can be further divided into epistemological uncertainty and ontological uncertainty. The former is caused by gaps in knowledge that can be closed by research. In this case, research becomes a moral duty that is required to avoid dangers or risks, to realize possible benefits, or to balance risks and benefits in a rational and responsible way. On the other hand, ontological uncertainty is caused by the stochastic features of a situation, which will usually involve complex technical, natural, and/or social systems. Such complex systems are often characterized by non-linear behavior, which makes it impossible to resolve uncertainties by deterministic reasoning and/or research.

The second main form of uncertainty in Tannert's taxonomy is subjective uncertainty, which is characterized by an inability to apply appropriate moral rules. These types of uncertainty can lead to societal anxiety or conflict. Again, we can distinguish between two sub-forms of subjective uncertainty. The first is uncertainty with respect to rule-guided decisions. This is caused by a lack of applicable moral rules and we call these situations "moral uncertainties." In this case, decision-makers have to fall back on more general moral rules and use them to deduce guidance for the special situation in question. The second sub-form is uncertainty with respect to intuition-guided decisions – that is, uncertainty in moral rules. In specific situations, we can make decisions only by relying on our intuition rather than knowledge, or explicit or implicit moral rules. This means that we act on the basis of fundamental pre-formed moral convictions in addition to experiential and internalized moral models. As with rule-guided decisions, a level of deduction is used here, but in a subconscious and intuitive way. We call the decisions that stem from internalized experiences and moral values "intuitional."

Risk and reliability**:** An attempt by risk analysis experts in the late 1970s to come up with a standardized definition of risk concluded that a common definition is perhaps unachievable, and that authors should continue to define risk in their own way. As a result, numerous definitions can be found in recent literature, ranging from the vague and conceptual to the rigid and quantitative. At a conceptual level, we define risk (i) as a significant potential unwelcome effect of system performance, or (ii) as the predicted or expected likelihood that a set of circumstances over some time frame will produce some harm that matters, or (iii) as future issues that can be avoided or mitigated, rather than present problems that must be immediately addressed. More pragmatic treatments view risk as one side of an equation, where risk is equated with the probability of failure or the probability of load exceeding resistance. Other symbolic expressions equate risk with the sum

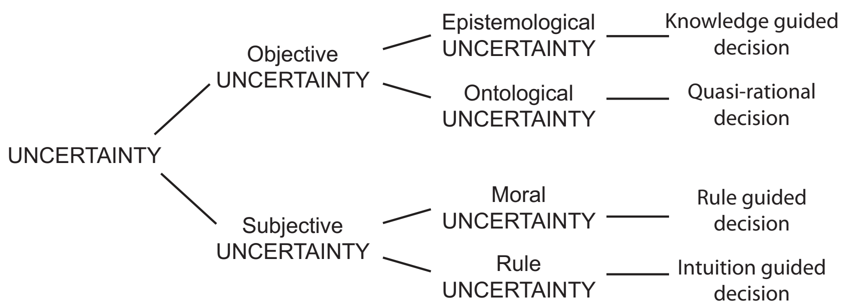

Figure 1 Taxonomy of uncertainties and decisions (after Tannert *et al*., 2007).

of uncertainty and damage, or the quotient of hazards divided by safeguards (Simonovic, 2009).

Because there is a need to understand how a potential loss might affect and be perceived by the various stakeholders, it is insufficient, and indeed can be quite misleading, for the decision-maker to consider risk solely in terms of probability and consequence. Risk involves three key issues: (i) the frequency of the loss, that is, how often the loss may occur; (ii) the consequences of the loss, that is, how large might the loss be; and (iii) the perception of the loss, that is, how a potential risk is viewed by affected stakeholders in terms of its effect on their needs, issues, and concerns.

Perhaps the most expressive definition of risk is the one that conveys its multi-dimensional character by framing risk as the set of answers to three questions: What can happen? How likely is it to happen? If it does happen, what are the consequences? (Simonovic, 2009 after Kaplan and Garrick, 1981). The answers to these questions emphasize the notion that risk is a prediction or expectation that involves a hazard (the source of danger), uncertainty of occurrence and outcomes (the chance of occurrence), adverse consequences (the possible outcomes), a time frame for evaluation, and the perspectives of those affected about what is important to them. The answers to these questions also form the basis of conventional quantitative risk analysis methodologies.

Three cautions surrounding risk must be taken into consideration: risk cannot be represented objectively by a single number alone, risks cannot be ranked on strictly objective grounds, and risk should not be labeled as real. Regarding the caution of viewing risk as a single number, the multi-dimensional character of risk can only be aggregated into a single number by assigning implicit or explicit weighting factors to various numerical measures of risk. Since these weighting factors must rely on value judgments, the resulting single metric for risk cannot be objective. Since risk cannot objectively be expressed by a single number, it is not possible to rank risks on strictly objective grounds. Finally, since risk estimates are evidence-based, risks cannot be strictly labeled as real. Rather, they should be labeled inferred at best.

Reliability is directly related to risk. In general, reliability is the ability of a system to perform and maintain its functions in routine circumstances, as well as hostile or unexpected circumstances. In engineering, for example, reliability refers to the ability of a system or component to perform its required functions under stated conditions for a specified period of time.

Vulnerability**:** Generally vulnerability is the susceptibility to physical or emotional injury or attack. In relation to hazards and disasters, vulnerability is a concept that links the relationship that people have with their environment to social forces and institutions and the cultural values that sustain and contest them. The concept of vulnerability expresses the multi-dimensionality of disasters by focusing attention on the totality of relationships in a given social situation which constitute a condition that, in combination with environmental forces, produces a disaster.

Vulnerability is also the extent to which changes could harm a system. In other words, it is the extent to which a community can be affected by the impact of a hazard. In global warming, vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

Risk management**:** Activities undertaken by an individual, organization, or government all involve some degree of risk. All activities expose people or groups to a potential loss of something they value: their health, money, property, the environment, etc. Individuals, groups, or organizations who are able to affect, who are affected by, or believe they may be affected by, a decision or activity are called stakeholders. Because different stakeholders may place different values on things, they may also view the acceptability of risk differently. As such, attempts to manage risk may be unsuccessful if one fails to recognize its complex nature.

The objective of risk management is to ensure that significant risks are identified and that appropriate action is taken to minimize these risks as much as is reasonably achievable. Such actions are determined based on a balance of risk control strategies, their effectiveness and cost, and the needs, issues, and concerns of stakeholders. Communication among stakeholders throughout the process is a critical element of this risk management process. Decisions made with respect to risk issues must balance the technical aspects of risk with the social and moral considerations that often accompany such issues.

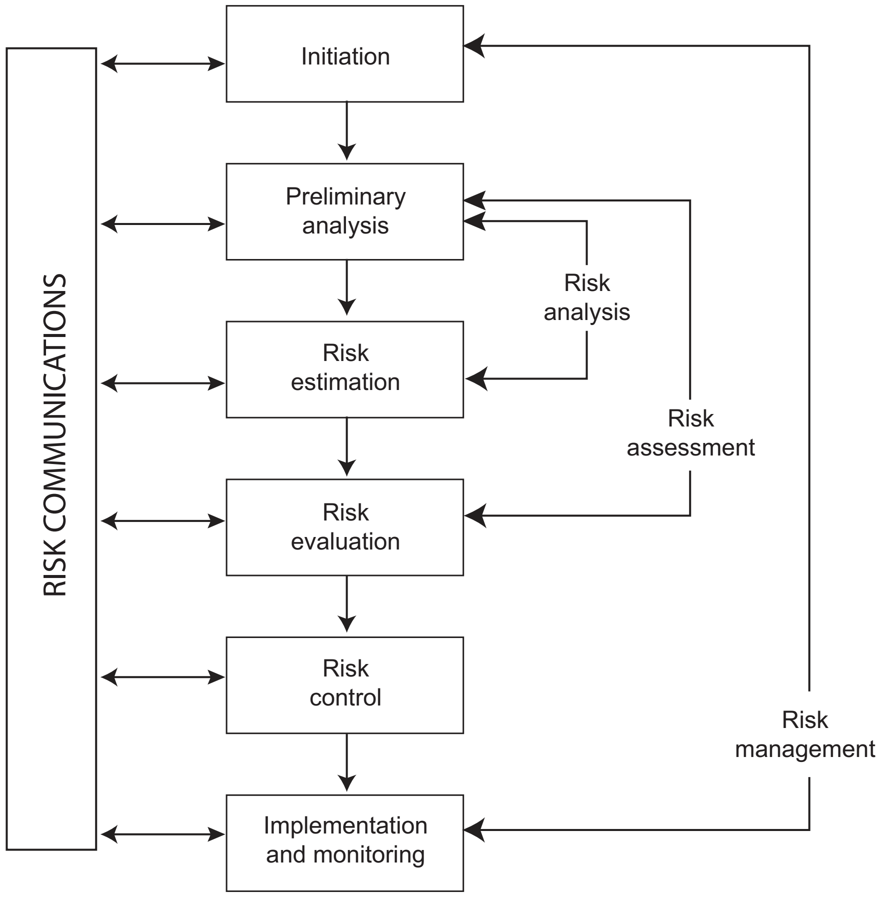

Figure 2 Steps in the process of decision-making under uncertainty.

Risk management can be defined as the systematic application of management policies, procedures, and practices to the tasks of analyzing, evaluating, controlling, and communicating about risk issues (Canadian Standards Association, 1997). Risk management for health and environmental risks uses scientific risk assessments to estimate the probable harm to persons and environments resulting from specific types of substances or activities. As such, even when decision-makers seek honestly to take into account varying perceptions of the risk in question, they are necessarily and properly constrained by the scope and limitations of their scientific assessment in recommending specific courses of action. This is an inescapable part of their duty to protect public interests and well-being to the best of their ability, taking into account the uncertainties that are always a factor in risk estimates. Leiss (2001) distinguishes between risk and risk issue management as two fundamentally different processes. The most important difference is that risk issues, as they play out in society at large, are not primarily driven by the state of scientific risk assessments. Rather, such assessments are just one of a series of contested domains within the issue. The phrase *risk issue* refers to: (i) stakeholder confrontation, or the existence of some dispute about the scope or existence of a risk and how it should be managed; (ii) intractable behavior, or the inability of professionals to change the public's risk-taking behavior; and (iii) high uncertainty, or the public expressions of concern over risk factors that are poorly characterized from a scientific standpoint, or where uncertainties in risk assessments are quite large.

***Decision-making under uncertainty*:** Statistician George Chacko (1991) defines decision-making as "the commitment of resources today for results tomorrow." Because decisions involve expectations about the future, they always involve uncertainty. Decision-making in general is concerned with identifying the values, uncertainties, and other issues relevant in a given decision, its rationality, and the resulting optimal decision. The practical application of decision theory (how people actually make decisions) is called decision analysis, and is aimed at finding tools, methodologies, and software to help people make better decisions. The most systematic and comprehensive software tools developed in this way are called decision support systems.

Decision-making under uncertainty will be described in this book as a systematic process that consists of six steps that follow a standardized management or systems analysis approach as summarized in Figure 2. Each step in the process is followed by a decision. It should be noted that the process is iterative.

Acronyms and abbreviations

ACO	Ant Colony Optimization
AMO	Atlantic Multi-decadal Oscillation
CCGP	Chance Constrained Goal Programming
CC_LB	Climate Change Lower Bound
CC_UB	Climate Change Upper Bound
CP	Circulation Pattern
CSA	Canadian Standards Association
CRED	Centre for Research on the Epidemiology of Disasters
CUP	Composition Under Pseudomeasures
DA	Dissemination Area
DICE	Dynamic Integrated Climate Change
DTM	Digital Terrain Model
EAD	Expected Annual Damage
EMS	Emergency Management Services
ENSO	El Niño–Southern Oscillation
EP	Evolutionary Programming
FCP	Fuzzy Compromise Programming
FLP	Fuzzy Linear Programming
GA	Genetic Algorithm
GCM	Global Climate Model
GDP	Gross Domestic Product
GEV	Generalized Extreme Value Distribution
GIS	Geographic Information System
GP	Genetic Programming
HEC-HMS	Hydrologic Engineering Center's (US Army Corps of Engineers) Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center's (US Army Corps of Engineers) River Analysis System
IDF	Intensity–Duration–Frequency
IFM	Integrated Flood Management
IJC	International Joint Commission
IPCC	Intergovernmental Panel on Climate Change
K-NN	K-Nearest Neighbor algorithm
LP	Linear Programming
MCS	Monte Carlo Simulation
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
NatCatSERVICE	Natural Catastrophe Service
NDBC	National Data Buoy Center
NEXRAD	Next Generation Radar
NN	Neural Network
NWS	National Weather Service
NWIS	National Water Information System
OF	Objective Function
OWA	Ordered Weighted Averaging
PCA	Principal Component Analysis
PCP	Pollution Control Plant
PDO	Pacific Decadal Oscillation
PDF	Probability Density Function
POT	Peak Over Threshold
P-CUP	Polynomial Composition Under Pseudomeasure
RCM	Regional Climate Model
SAM	Southern Annular Mode
SFCP	Spatial Fuzzy Compromise Programming
SPRC	Source–Pathway–Receptor–Consequence
SST	Sea Surface Temperature
SSTA	Sea Surface Temperature Anomaly
TIN	Triangulated Irregular Network
UNESCO	United Nations Educational, Scientific and Cultural Organization
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTRCA	Upper Thames River Conservation Authority
WCoG	Weighted Center of Gravity
WG	Weather Generator
WLD	West London Dyke
WMO	World Meteorological Organization