Dynamic Programming Based Operation of Reservoirs
Applicability and Limits

Dynamic programming is a method of solving multi-stage problems in which decisions at one stage become the conditions governing the succeeding stages. It can be applied to the management of water reservoirs, allowing them to be operated more efficiently.

This is one of the few books dedicated solely to dynamic programming techniques used in reservoir management. It presents the applicability of these techniques and their limits in the operational analysis of reservoir systems. In addition to providing optimal reservoir operation models that take into account water quantity, the book also examines models that consider water quality. The dynamic programming models presented in this book have been applied to reservoir systems all over the world, helping the reader to appreciate the applicability and limits of these models. The book also includes a model for the operation of a reservoir during an emergency situation. This volume will be a valuable reference to researchers in hydrology, water resources and engineering, as well as to professionals in reservoir management.

K. D. W. NANDALAL is Senior Lecturer in the Department of Civil Engineering at the University of Peradeniya, Sri Lanka. His research interests include water resources systems analysis and reservoir water quality modeling.

JANOS J. BOGARDI is Director of the United Nations University Institute for Environmental and Human Security. He was co-editor of *Risk, Reliability, Uncertainty, and Robustness of Water Resource Systems* (Cambridge University Press 2002).

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Applicability and Limits

K. D. W. Nandalal
University of Peradeniya, Sri Lanka

Janos J. Bogardi
United Nations University, Bonn, Germany

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Preface

The second half of the twentieth century can clearly be identified as an epoch having a strong, lasting imprint on our paradigms and methods of resource use and management. Ideas, compassions, and concepts which dominate our thinking and debates have emerged and evolved during the last four or five decennia. Nothing manifests this better than the so-called Brundtland Report (WCED, 1987). Ever since its publication, the term and concept of sustainable development cannot be missed in any declaration or framework issued or developed in seeking better conditions for humans and the environment alike. The recent millennium was a welcome opportunity to summarize this process and endorse principles and set new objectives. As far as the ethical, political, and practical aspects of water resources management are concerned, the large intergovernmental environmental conferences like the United Nations Conference on Environment and Development (UN, 1992) and the World Summit on Sustainable Development (WSSD, 2002) can be mentioned along with the formulation of UN Millennium Development Goals (MDGs, 2000) and the Millennium Ecosystem Assessment (2005). Beyond these general conferences and assessments, where water took a substantial part of the agenda, the world water fora (Marrakech, 1997; The Hague, 2000; Kyoto, 2003; Mexico City, 2006) and the Bonn Conference on Freshwater 2001 provided the broadest platforms for stakeholder dialogue involving ministerial, NGO, scientific, professional, and other interest groups, and indigenous people participation. The impacts of these conferences were analyzed by, among others, Bogardi and Szöllösi-Nagy (2004).

Besides these events, the World Water Vision (Cosgrove and Rijsberman, 2000) and the first issue of the World Water Development Report (2003) can be mentioned as the key documents, summarizing the process of assessing the availability, use, and protection of this precious resource. Irrespective of considerable successes in putting water issues on the international agenda (such as the Group of 8 meeting in Evian in 2003), we are far from having secured the "breakthrough" towards achieving the water related MDGs and other global objectives.

A book like the present one, focusing on one methodological concept and its use in a particular form of water resources management, namely the application of dynamic programming (DP) in the operational analysis of reservoirs, would certainly be overcharged if not only the principles and the history of the idea of sustainable development, MDGs, environmental awareness and protection, and biodiversity, but also water supply, food and energy security, disaster mitigation or participatory processes, public–private partnerships, and other key issues of the present water debate were presented and discussed in the full context of their historic evolution. Yet these two lines of thought, the conceptual one describing our changing world views, and the more focused methodological development of management techniques – in this case the application of DP – are closely intertwined. Resource limitations and increasing demand pose the question of human and ecosystem survivability and reveal the urgent need for better tools and methods to match resources and demand at a certain point in space and time on the practical governance (management) scale.

Even if we concentrate only on the subject (and the inherent self-limitations) of this book, a 50-year-long saga unfolds. While storing water is certainly among the very first actions of human civilization (aptly proven by remnants of dams from antiquity) the 1950s (and the following three decades) experienced the strongest boom ever in dam building. Almost three-quarters of the dams of the worldwide total of approximately 40 000 were built between 1950 and 1980 (Takeuchi, 2002). The storage capacity thus created in many parts of the world – while not uncontroversial in its environmental impacts and other side effects – has certainly contributed to avoiding worst-case-scenario prophecies of food shortage at global scale.

However, building dams alone could not and cannot solve the problem. Half a century ago we paid more attention to sound engineering of the structures than to efficient

management of the then new facilities, or to erosion control in the upstream watersheds. Consequently, the potential of many reservoirs was not exploited to the full. Instead of refining operational rules, saving water, and saving storage space from being lost to siltation, more and more new dams were built. No wonder that, with growing environmental awareness and international eco-advocacy, the Hamletian question "to build or not to build?" was answered more and more by choosing the latter option. The creation of the World Commission on Dams (WCD), its report *Dams and Development* (2000) and the subsequent reactions of professional associations like ICOLD and ICID mark this process. In the meantime much less attention was given to the less dramatic, but nevertheless crucial question: "Do we operate our reservoirs well?" The answer to this silent question would have been and, regrettably enough, would still be no rather than yes. While the first part of this "double no," not to build new dams and not to use the existing ones to their fullest potential, could be seen as ideologically biased; the second "no" is actually unforgivable, irrespective of one's position as pro or contra dams. Improving the performance of existing reservoirs and complex reservoir systems would not only provide more water for more beneficial uses, but could also mitigate environmental impacts and significantly reduce the need for new dams. Thus a proactive approach to improve reservoir operation would ultimately ease, if not eliminate, the urgency of some "build or not to build" dilemmas.

Do we have the means to implement the necessary improvements? It is the conviction of the authors that the answer must be a resounding yes, an opinion that we believe is broadly shared by the respective scientific community.

Almost parallel to the previously described dam-building boom systems analysis, operations research (OR) techniques have emerged as new intellectual tools with which to analyze complex systems. The introduction of digital computational technology and what we today call information technology opened the door for wide-scale, practically relevant applications. As far as dynamic programming, the OR method with the biggest potential to improve reservoir operation, is concerned, the year 2007 has special significance. It marks the 50th anniversary of the pioneering paper by Bellman (1957) formulating and proving the optimality criterion of this appealing decomposition technique. This book is dedicated to observing this anniversary. Yet there is no real ground for celebration beyond commemorating a significant scientific achievement. This milestone could and should be taken as an opportunity to review why 50 years in the emerging information society, with its fast knowledge transfer mechanisms, thousands of papers, articles, lectures and conference presentations, and dozens of successful case studies, did not suffice to ensure a wide-scale breakthrough of DP based methods into real-world reservoir system operation.

The advent of desktop computational development in the 1980s and 1990s brought the opportunity for research groups to prove that DP and its derivative methods are not only exciting scientific tools, but potent techniques to be applied in improved reservoir operational management worldwide. This book confirms this peak, as most of the references originate from the last two decades.

There is an inherent and acceptable time lag between scientific discovery and development and "real-world" application. However, the students of the 1980s and 1990s are already in management positions, thus the question needs urgent attention: why have we only a handful of real practical applications like the DP based operational analysis of the reservoir system in the strategic plans of "Eau 2000" and "GEORE" of Tunisia (Bogardi *et al.*, 1994).

This book emerges from the concern of those actively involved in the development of DP based operational methods for reservoir systems. Many of the practically relevant case studies, tests of DP and stochastic dynamic programming (SDP), were carried out between 1985 and 1998 at the Asian Institute of Technology, Bangkok, Thailand, and later at the then Wageningen Agricultural University, the Netherlands, under the supervision and guidance of the second author. It is however due to the enthusiasm and dedication of the first author that this present book came into being. He not only initiated but also carried out the most overwhelming part of the work, which provides a comprehensive account of the applicability of DP based methods to derive sophisticated and yet practically relevant rules for real-world reservoir systems, operating under real-world conditions and constraints.

This work, while reflecting the entire related literature, is reliant on results published in several reports, papers, dissertations, and master theses prepared in the late 1980s and 1990s by several members of the above-mentioned research groups. The authors wish to acknowledge the implicit intellectual input and active assistance of Dr. Saisunee Budhakooncharoen, Professor Huang Wen Cheng, Dr. M. D. U. P. Kularathna, and Dr. Darko Milutin. The works of He Qing, Anne Verhoef, Dr. Bijaya Prakash Shrestha, and Dr. Dinesh Lal Shrestha are also reflected in this book. Furthermore, collaboration with Professor Ricardo Harboe, Dr. Guna Nidi Paudyal, and Professor Ashim Das Gupta as co-authors of papers and co-supervisors of some of these theses is greatly appreciated.

The aim of this book goes beyond providing the reference for our claim that DP based techniques can and should be applied for the improved operation of reservoir systems, even under conditions of changing objectives, constraints and hydro-climatic regimes as has been demonstrated recently by

Brass (Brass, 2006). We feel that, next to its contribution to bridging the gap between development and method applications, the book could be used as special reading for graduate students specializing in water resources management. In this context, this book can be seen as an extension of DP related methods and reservoir system operation supplementing the excellent textbook of Daniel P. Loucks and Eelco van Beek, *Water Resources Systems Planning and Management* (Loucks and Beek, 2005).

It is our paramount objective to contribute to the education of competent water resources managers. This book is intended to be an eye-opener for those bearing managerial responsibilities at present, and a source of inspiration and knowledge for the coming generation of water resources managers.