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Project No. E-24-646 (R6119-0A0) **GTRC/GIT** **DATE** 04 / 14 / 86

Project Director: A.O. Esogbue **School/~~xxx~~** ISyE

Sponsor: National Science Foundation

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Title: Workshop on Dynamic Programming and Water Resources

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August 1988

PROCEEDINGS OF
THE BELLMAN CONTINUUM
SPECIAL NSF WORKSHOP ON DYNAMIC PROGRAMMING
AND WATER RESOURCES

by

Augustine O. Esogbue

Completion Report

ECE-8609130

Initiated: April 1986

Completed: March 1988

School of Industrial and Systems Engineering
Atlanta, Georgia 30332

In cooperation with

NATIONAL SCIENCE FOUNDATION

AUTHOR

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THE BELLMAN CONTINUUM:
PROCEEDINGS OF SPECIAL NSF WORKSHOP ON
DYNAMIC PROGRAMMING AND WATER RESOURCES SYSTEMS

EXECUTIVE SUMMARY

The field of water resources planning, design, and management contains an assortment of important but complex problems whose efficient treatment can be approached via various tools of operations research and systems engineering. Among the most potent and popular of such methodologies is dynamic programming. The use of this problem solving philosophy and technique has grown very rapidly in recent times. This growth is due in part to the advances in computational techniques of dynamic programming and the advent of powerful computational devices such as supercomputers, parallel computing, etc.

As part of the Bellman Continuum, a gathering of professional associates of Professor Bellman dedicated to the furtherance of his works, a Special Workshop on Dynamic Programming and Water Resources sponsored by the National Science Foundation was held at the Georgia Institute of Technology, Atlanta, Georgia from June 25 - 27, 1986. This volume contains the Conference program and Summaries of papers presented at, as well as those submitted to, that Workshop. It is also a completion of a long project, under the inspiration of Professor Bellman, to write a book on the subject entitled Dynamic Programming for Optimal Water Resources Analysis under production by Prentice Hall.

Since dynamic programming has become identified as one of the most applicable techniques in water resources systems management, the Workshop sought to facilitate its appropriate and increased usage by practitioners, model builders and technique developers. Because, as in any other field, there have been some bad as well as excellent papers written on the subject, we initially sought only the inputs of experts from different parts of the world. Unfortunately, a number of the invitees were unable to participate. We however believe that the authors of the summaries presented here have made invaluable contributions which will advance the field.

The conference program was divided into nine sections. The first part motivates the subject of the Workshop and includes surveys of origins and uses of dynamic programming in water resources and how both fields have complemented each other. Nina Bellman gives an insider's view of the origin of the name dynamic programming, and I provide the interconnection of the subject with water resources. In particular, the keynote paper by Warren A. Hall, Elwood Mead Professor of Engineering at Colorado State University and formerly Director, Office of Water Research and Technology, U.S. Department of the Interior, but read by George Tauxe, discusses the employment of the philosophy of dynamic programming in conceptualizing, formulating and solving practical water resources systems engineering problems that may arise in different lands. The emphasis is in its use in developing national and regional water management policies. Just as Bellman is referred to as the father of dynamic programming so can Hall be called the father of dynamic programming and water resources.

Part Two deals with Water Supply Planning and Management. This section is appropriately introduced by David Word, Chief of the Water Resources Branch of the Georgia Department of Natural Resources. He discusses a number of key water problems of the State, the organizational setup and practical strategies for dealing with those problems. His full text is included.

To show the relevance of the papers to practical existing problems of the sort that may be faced by different states, regions or countries, we include the paper by Bernd Kahn of the Environmental Resources Center, Georgia Institute of Technology, which highlights some of the major water resources research problems of the State of Georgia.

To motivate the technical subject of the conference, my paper presents a Taxonomy of various models occrring in the literature. It is an important and monumental task in which the state of the art is reviewed and classified using a taxonomic scheme developed specifically for the subject. From this, some conclusions on the problems and research needs are drawn. Kher and Sorooshian's paper deal with models for water demand identification while Buras was to have discussed the use of dynamic programming in optimal management of stream acquifer systems. The section is concluded with Odanaka's paper for optimal pumping strategies in groundwater management.

Most water resources problems or projects are multifaceted, multidimensional and even multistaged. Part Three introduces multiobjective dynamic programming as it relates to the optimal analysis of multiobjective-multipurpose and large scale water resources systems.

In Part Four, the methods of dynamic programming and associated algorithms which are useful in the modeling of large scale water resources systems are presented. The emphasis is on the development of techniques which can aid in models of greater fidelity as well as intelligent methods for obtaining results from such otherwise complex models. This section contains papers by George Tauxe and a related one by John Labadie and Daniel Fontane.

Part Five contains papers on water quality, and industrial waste treatment systems. Included are contributions by Hiroshi Sugiyama, who discusses an intelligent readily computable dynamic program for improving the water quality via optimal aeration, and J. Hugh Ellis, who presents a model for sequencing industrial waste treatment.

In Part Six, problems of water supply and distribution particularly efficient management aspects are considered. New methodologies as well as successful real life applications, as for example in England, are reported. The authors include Bryan Coulbeck and C. H. Orr, as well as Augustine Esogbue and Chae Y. Lee.

Section Seven deals with real time operation of reservoirs with emphasis on stochastic models. In the Taxonomy paper, it was shown that considerable attention has been paid to the subject recently in the literature. Therefore, it was not surprising that it attracted special interest of both model builders and users at the Workshop particularly during the round table discussion that followed. The authors are Matthew Sobel, Ramesh Sharda and M. A. El Tayeh, Aristides Georgakakos, E. G. Read, Peter Kitanidis and Roko Andricevic.

In Section Eight, problems of flood control management are addressed. Morin et al. discuss the use of a hybrid algorithm to select and sequence some combination of structural and nonstructural flood management alternatives.

The final section deals with successful application studies with emphasis on reservoir and hydropower management. The section contains papers for on line control and successful real life applications notably in New Zealand and Egypt. The primary authors are Read and Boshier from New Zealand, and Coulbeck and Orr both from the United Kingdom.

The full papers of the contents of this Proceedings were, for the most part, reviewed by me, my graduate students, colleagues and some carefully selected experts worldwide and then merged into an edited Volume. I have also written a considerable portion of the resultant manuscript. Various problems arising in water resource systems engineering are treated. The book contains approaches and data which should prove useful to managers, practitioners and model developers as well. It summarizes and clarifies previous models as well as presents new results including some from recently completed doctoral dissertations. It brings, for the first time in one volume, information and material that hitherto had been scattered in various journals and technical libraries. Students, researchers, and all those interested in the efficient use of an important tool such as dynamic programming in the resolution of pressing and difficult problems of managing our scarce water resources, should find this volume a timely addition to the library, both reference and text of water resource systems engineering.

I acknowledge with much gratitude the support of the National Science Foundation, Nina Bellman and members of the Bellman Continuum, all the contributors of the material from which this Proceedings was prepared. I am also grateful to the conference participants, the Coca Cola Company, my mentor and friend Dick Bellman, who introduced me to the art of using dynamic programming, and Warren Hall, who excited my interest in the use of the method to address various problems occurring in water resources. The support of Dr. Thomas E. Stelson, Vice President for Research at the Georgia Institute of Technology, as well as the secretarial assistance of Ms. Joanne Lewis are also gratefully acknowledged.

Augustine O. Esogbue, Ph.D.
Professor, and Project Principal
Investigator

PROCEEDINGS OF

THE BELLMAN CONTINUUM
SPECIAL NSF WORKSHOP ON DYNAMIC PROGRAMMING AND WATER RESOURCES

HELD AT
THE GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA

Contents

PART ONE

INTRODUCTION: OVERVIEW AND ORIGINS OF DYNAMIC PROGRAMMING AND WATER RESOURCES SYSTEMS ENGINEERING

PART I: INTRODUCTION: OVERVIEW AND ORIGINS OF DYNAMIC PROGRAMMING

I.1. ON THE ORIGIN OF THE NAME DYNAMIC PROGRAMMING

NINA BELLMAN

The first thing Richard Bellman always said about dynamic programming was that it was a theory of multi-stage decision processes. He said that it was the only one he knew of, but another theory might be developed sooner or later. He didn't think so, but thought it not impossible.

When asked why he called his theory of multi-stage decision processes dynamic programming, he began with a statement to the effect that it was not programming at all, and that in some ways the choice of name was unfortunate. Then he would explain the reason for the name.

The ideas which resulted in dynamic programming began to take shape after World War II. He first began to promote the theory during the first Eisenhower Administration. Charles Wilson, of General Motors, was Secretary of Defense. Wilson saw no need for most research. He had downplayed it at General Motors, and continued the same policy in government.

Dick worked for the Rand Corporation in the '50's. At that time Rand was funded almost entirely by the Air Force, and as a think tank was particularly vulnerable to budget cuts on the ground that nothing tangible was produced there. In fact, Dick took a half-time position at UCLA in the Engineering Department in 1953, because of the shortage of money at Rand.

That is the background for the choice of name of dynamic programming. Dick wanted a name that would make it acceptable to the people who were in charge of distributing grants. Programming had a practical sound to it. Besides, the word was fast being popularized by other powerful developments such as linear programming. He liked the word dynamic programming because it is an exciting word for a powerful tool.

Years later, Dick wished he could have chosen a more descriptive name. He decided that the early '80's was too late to change a familiar name. With all the recent changes in the names of large corporations, he might have felt differently now.

I.2. DYNAMIC PROGRAMMING AND WATER RESOURCES: ORIGINS AND INTERCONNECTIONS

AUGUSTINE O. ESOGBUE

Introduction and Origin

For nearly three decades since the first reported use of dynamic programming to treat a water resources development problem appeared in the English literature [16], the method and its many variants have been employed in a variety of ways to address a gamut of problems connected with various aspects of water resources systems.

In a study for the U.S. Office of Water Resources and Technology, U.S. Department of the Interior dealing with a systems approach to integrative urban water-land management, the use of systems techniques was surveyed and documented [7]. It was found that dynamic programming was one of the most highly favored techniques in water resources systems analysis. In fact, it then ranked second to simulation but ahead of linear and nonlinear programming combined. Most important, the appeal of the method has grown rather rapidly in recent years. It is expected that the growth pattern will continue in the future. This growth is not only in number but in types and size of problems addressed.

As shown in Table 1, the problem areas ranged from reservoir operation and design to water distribution, sequencing and expansion of facilities, water resources planning, conjuctive use, water quality and irrigation management. To fully understand the variety of the techniques, models and problems addressed, we developed the matrix which is reproduced in Table 1.

In a follow up study [10] in which we critically evaluated a number of the reported studies using various systems techniques in urban water management, we were again impressed by the prominent place of dynamic programming. We were primarily interested in the transferability of those techniques and models to urban water management in a manner which will facilitate their use by the practitioners. Consequently, we focused on approaches to make published work usable by the practitioners. Figure 1 shows the suggested mechanism considered instructive for enhancing the transferability of these techniques. We note that short courses, seminars and symposia were considered important avenues for furthering the goal of developing and transferring appropriate water resources systems technology. Thus, the workshop sponsored by the National Science Foundation, is an attempt to implement one of the foregoing suggested technology transfer approaches.

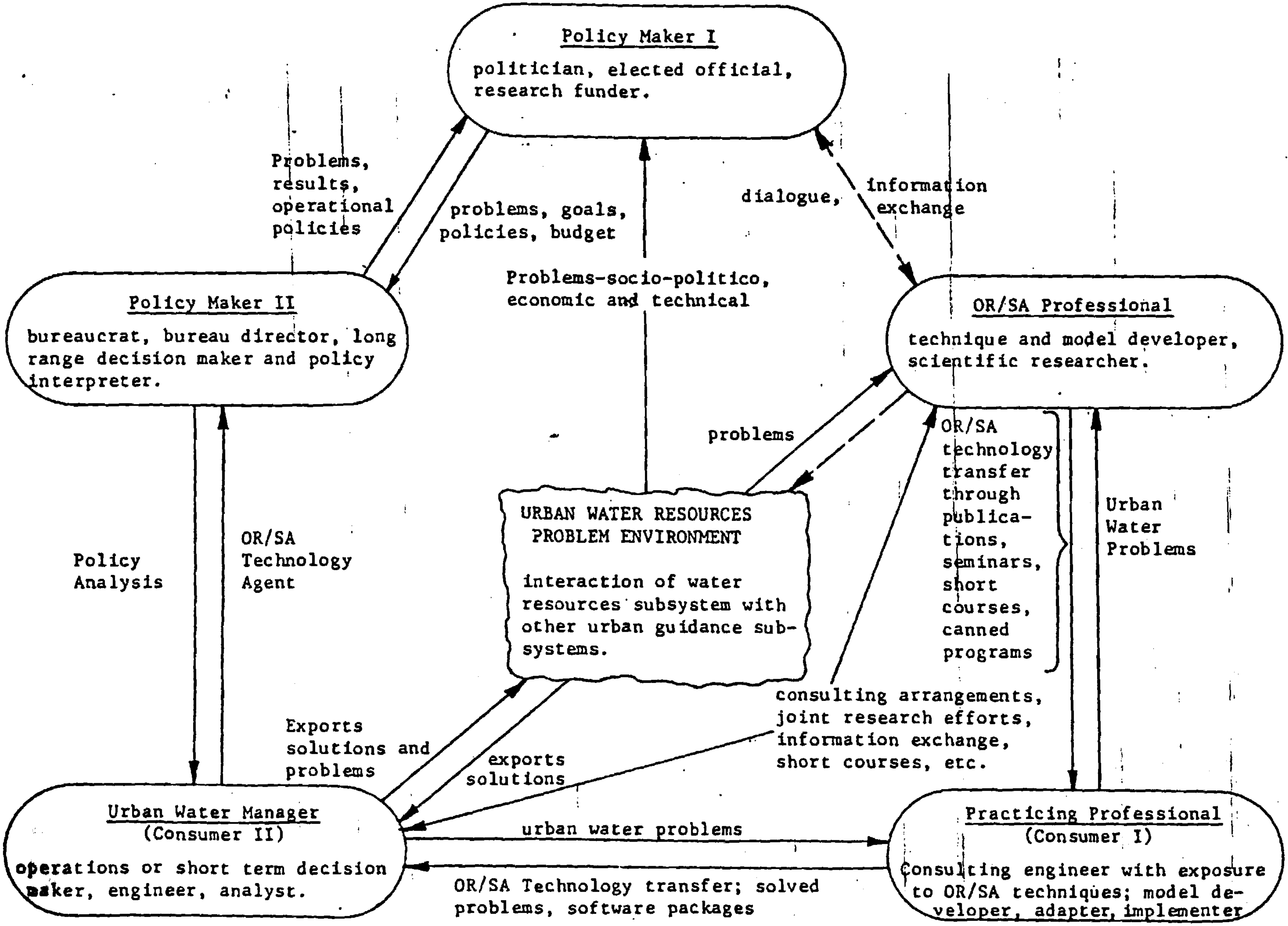
Many of the foregoing sentiments were collaborated recently by Yakowitz in his review of the applications of dynamic programming in water resources [35]. In his extensive survey of the subject, both the problem areas, techniques and needs were discussed.

Ever since the development of dynamic programming and water resources systems analysis and optimization, there has been a curious

TABLE 1 TWO-WAY CLASSIFICATION OF SYSTEMS ANALYSIS TECHNIQUES APPLIED TO WATER RESOURCES MANAGEMENT
(Entries represent # of papers selected from the Literature of the period 1965 to April 1976.)

SOLUTION TECHNIQUE / PROBLEM AREA		PRIMARY TECHNIQUES				OTHER TECHNIQUES										UNCLASSIFIED			TOTALS
		Linear Programming 1	Dynamic Programming 2	Simulation 3	Statistical Method 4	Nonlinear Programming 5	Integer Programming 6	Quadratic Programming 7	Geometric Programming 8	Network Analysis 9	Queueing Theory 10	Project Scheduling 11	Forecasting 12	Economic Analysis 13	Input-Output Analysis 14	Mathematical Models 15	Systems Analysis 16	Other 17	
Water Supply 1	I	7	6	5	1	1	2	1	1		1			1	3	5	3	10	47
Conjunctive Use 2		2	5	1						1				1			2	3	15
Water Quality 3		6	6	9	5	2	1						1	4		10	5	19	68
Water Treatment 4		4	2	5	1							1		2		1	4	6	26
Waste Treatment 1	II		3	2					1				1			5	5	10	27
Water Distribution 2		2	6	6	1	1				1						2	3	2	24
Water Storage 3																1		1	2
WR Planning 4			4	4		2	2						1	3			7	9	32
WR Evaluation 1	III	5		1	1									4			1		12
WR Development 2			2												1		1	1	5
WR Sequencing/Expansion 3		1	6									6		1		1	1		16
WR Management 4		3	2	5	1		1	1	1					3		6	4	40	67
WR Data Collection 1	IV	2																	2
WR Data Systems 2					1														1
WR & Land Use Planning 3				1															1
WR Interrelationships 4				4											1				5
Water Pricing 1	V		2	2	1											2		2	9
Water Demand 2		1			4								7			2			14
Flood Control 3		4	1	1	1									2		3	2	8	22
Urban Runoff/Watersheds 4			2	14	6				1							4		2	29
Streamflow 1	VI			4												1		1	6
Sewer Design 2		1	3	1	1													1	7
Reservoir Design 3		3	2	3	2	1					1		1					7	20
Reservoir Operation 4		7	11	3	8	2					1			1		1	1	12	47
Recreational Facilities 1	VII			1	1								1			1			4
Plant Location 2										1									1
Rainfall 3				1	2														3
River Yield 4					1														1
Totals		48	63	73	38	9	6	2	4	3	3	7	12	22	5	46	39	134	153

Fig 1. A Model for the Transfer of Systems Technology to Urban Water Resources (Source [10])



symbiotic relationship between the two. For example, it was correctly pointed out by Yakowitz that water resources problems were among the first real world laboratory for testing the applicability of dynamic programming to non defense issues. Attempts to solve certain large scale systems problems arising in water resources systems have led to the development of certain computational techniques in dynamic programming. An example is the method we called "imbedded state space dynamic programming" developed in connection to deal with the computational difficulties of solving certain sequencing and scheduling problems in capacity expansion of water supply projects [30]. Several doctoral theses, both in civil and environmental engineering with emphasis on water resources, have been written using dynamic programming as the principal analytic tool. See, for example, Sule [33] who considers the operations of a multiple purpose reservoir. Similarly, several doctoral dissertations within mathematics, engineering and operations research have been written on theoretical and computational aspects of dynamic programming using water resources problems as their leitmotif. One example is Morin [29]. On the practical side, the now well known Central Valley project in California uses policies generated from research work at the UCLA Water Resources Center. The models stem from the work of Warren A. Hall and Ronald Shepard and their associates both at UCLA and Berkeley. The origins of these efforts are the dynamic programming models reported by Hall et al. [20].

Yakowitz [35] aptly summarizes this relationship in the following:

> "Water resource problems have served as a stimulus to the development of dynamic programming itself, and many of the studies to be surveyed have attracted the attention of workers outside hydrology. Water allocation problems suggested by Warren Hall are to be found in Bellman's [1957, p. 144] foundational book. A reservoir operations problem figures prominently in Larson's [1968] exposition of the state increment dynamic programming technique. Moreover, a reservoir control problem is among the few selected applications studied in the recent treatise on stochastic dynamic programming by Dynkin and Yushkevich [1979]. An unmistakable conclusion is that water resource problems serve as an excellent impetus and laboratory for dynamic programming developments; conversely, progress in making dynamic programming applications in water resources economically viable depends on further advances in theoretical and numerical aspects of dynamic programming."

A major impediment to a more widespread and universal application of dynamic programming to water resources problems is the vastly publicised but exaggerated problem known as the curse of dimensionality [1]. The curse of dimensionality is due primarily to the exponential growth in rapid access storage necessary to perform the computational solution of the functional equation of dynamic programming, as the number of state variables increases. Another but less inhibiting problem is the computational time requirements of certain dynamic programming models. Although real, there have been substantial advances in the theory, computation and algorithms of dynamic programming all geared to reducing dimensionability. Among these techniques are state increment dynamic programming [Larson (27)], method of the tube [Durling (8)], method of the tree [Wong (8)], differential dynamic programming [26], discrete differential dynamic programming [23], dynamic programming and partial differential equations [Bellman & Angel (8)], terminal state dynamic programming [Collins (8)], imbedded state space dynamic programming [Morin & Esogbue (31)], nonserial dynamic programming [Esogbue (11)] and an array of methodologies for stochastic systems (24, 25). Most of all, the advances in computer technology (both hardware and software) but notably micro and super computers, have revolutionized the field of dynamic programming.

In spite of the foregoing, practitioners in the theory and applications of dynamic programming and water resources systems field have not capitalized optimally on this relationship through appropriate interaction and technology transfer. A major cause of this dilemma is that those involved in the theoretical developments are not reasonably familiar with important water resources problems and environment. Conversely, those in water resource systems are not familiar with the breakthroughs in dynamic programming. Additionally, there have been unfortunate but inevitable abuses such as erroneous applications of the methodology. We hasten to point out that other fields and methodologies have also suffered from similar excesses.

Objectives of the Workshop

In view of the above brief analysis, a workshop bringing together practitioners, water resources model builders and developers of dynamic programming methodology, both the theory and algorithms, was considered not only timely but necessary. The objective was to bring about the much needed interaction among the key participants and to review the history, assess the state of the art, and prognosticate about future appropriate developments as well as linkages so that more breakthroughs in the application of dynamic programming to solve larger and more water resources problems can take place. An additional important objective was the identification, isolation and grouping of the major research issue needs, and problems which when successfully resolved would enhance the utility of dynamic programming in various application areas but particularly water resources systems. To aid this exploitation of the methodology by practitioners, the presentations and discussions from the workshop were compiled, reviewed and edited into this volume which will constitute a major reference work for students, researchers, practitioners, as well as funding agencies. This will be a step in the right direction for dynamic programming as suggested by Bellman and for water resources as initiated by Warren Hall.

The topics include various aspects of dynamic programming both theoretical and computational and their use to model, analyze and design a gamut of water resources systems problems from supply to irrigation as detailed in the Taxonomy presented by Esogbue [13] in this volume.

Previous Meetings or Documents on the Subject

As far as we could determine there had never been any workshop or meeting of this kind. There had, of course, been some meetings on dynamic programming as for example the International Conference in 1977 at Vancouver, British Columbia. That led to the book, Dynamic Programming and Its Applications edited by M. L. Puterman and published by Academic Press in 1978 [32]. There, however, does not appear to have been any other conferences devoted totally to dynamic programming.

There have been numerous meetings on the use of systems techniques in water resources including a 1969 workshop which I directed entitled "Operations Research and Systems Engineering in Complex Water Resources Systems." This was held at Case Western Reserve University in Cleveland, Ohio and attended by professionals and educators from across the U.S. and abroad.

Similar but different short courses, both in orientation, structure and audience, include the ones on Large Scale Systems organized at UCLA and the annual short courses given by Dr. Yacov Haimes when he was at Case Western Reserve University on Multilevel Hierarchical Techniques and Water Resource Systems.

Clearly, papers dealing with the use of dynamic programming to model water resource systems abound in various journals and have been presented at various meetings of numerous professional societies. These are reviewed in the chapter on Taxonomy. Of special note is the review paper by Yakowitz [35].

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I.3 DYNAMIC PROGRAMMING AND PRACTICAL WATER RESOURCES SYSTEMS ENGINEERING

WARREN A. HALL

Introduction

Some thirty years have passed since I was first introduced to Dr. Richard Bellman, and to his then new dynamic programming concepts. I had just returned to UCLA from U.C. Davis (1956) where I had initiated a program of laboratory and field research directed toward irrigation engineering and management. My new assignment, as Assistant Dean for Undergraduate Studies, required that my research program be reoriented from field work to something I could work on at my desk. Several years earlier, I had worked a bit with optimization in connection with some maritime cargo loading research, and it seemed to me that there was a wide open opportunity to apply some of these ideas to water resources planning and management. Dean Boelter suggested that I contact a "Dick Bellman" at RAND. With what in retrospect would appear to be a lot of brass, I called Dr. Bellman and asked him to come see me, and at my convenience (I explained how busy I was!).

Had I realized that his daily consulting fee at that time was greater than my monthly salary--before deductions--I doubt that I would have had the courage to call at all. Fortunately for me, ignorance was bliss, for Dick responded to my invitation immediately and showed up at my office precisely on time. We had several hours of discussion which proved to be extremely valuable to me. I can't say the value was reciprocal, but I do remember that he was highly enthusiastic the entire time and that I had to terminate the session around 7 p.m.

This was just the first of many such meetings over the following years, during which he patiently worked to remove my ignorance and misconceptions, and to help develop my understanding of optimization analysis as being something rather special and distinct from the mathematical modeling of physical behavior which dominated my own thinking.

This patience was typical of Dick's attitude toward anyone who wanted to learn and was willing to put in the effort. On the other hand, he could be very short with anyone who wanted a cookbook for optimization and even completely non-responsive to persons who wanted to argue that his theory was incorrect. I recall one paper which purported to show that dynamic programming could not possibly be valid. I could not understand the reasons, so I asked Dick about it. After he explained, I asked him why he didn't respond. His answer was so classical Bellman. "Why should I? He is the one who is wrong!" Here was a man who not only knew the mathematics of optimization but also understood the optimal use of his own time.

It is always pleasant to reminisce about one's personal associations with a great man, but I have been asked to present a paper on the use of dynamic programming for water resources planning and management. I have two options. One is to present the results of some specific systems engineering studies for the optimization (broadly defined) of the Mahanadi River Basin in east Central India. The other is to elaborate on the use of the concepts and principles of dynamic programming (as I understood them from my contacts with Dick Bellman) which have proved to be very useful for me and my colleagues in India's Central Water Commission for the process of developing appropriate formulations of the planning problems of that river basin system.

I will choose the latter, because I believe that it may be most useful to the participants at this conference. During the past thirty years, in my work in India, the Middle East, Latin America and the U.S. I have been increasingly impressed with something Dick tried to tell me in the beginning. Optimization is the process of selecting a specific set of actions (decisions) implicitly or explicitly embedded in a particular problem formulation, in such a manner that no feasible change in that set will produce a resultant situation considered by the decision maker to be "better" (my paraphrase). However, as he informed me, the formulation of the problem must be a correct representation of the actual planning and/or management situation and the full responsibility for that formulation and its validity rests with the user of the models, including those classified as "optimization models." He considered that I was the user (and so I visualized my role), hence it was my responsibility to provide a proper formulation in the first place. His words, almost exactly, were "If you can express your problem in mathematical form, and if that form has these essential characteristics, then dynamic programming can efficiently and effectively find the optimal decision set you seek." He also pointed out some advantages of DP over some of the possible alternative procedures, particularly the "invarient embedding" aspect which gave not only the specific optimal decision set for the specific magnitudes of the conditions, but also gave all other optimal decision sets for all other magnitudes of these conditions (state variables). This is clearly an important advantage for planning large scale systems where one cannot be certain in advance what those conditions might be. It is even more advantageous when complex systems must be broken down into manageable components, as will be discussed later.

To pursue Bellman's admonition in a way which I hope will be taken as constructive criticism to improve analysis, the major reason for the seeming reluctance of practicing professional engineers to utilize our optimization models "off the shelf" is to be found in the in adequacies of our problem formulations. A review of the water resources systems engineering literature (including my own contributions) will show that virtually all begin with a postulated problem formulation. That formulation is only infrequently justified. Even then, it is clear that the author had his own mind's eye model of a particular planning situation. Usually that model is only implicitly presented and the reader is left to deduce the problem visualized from the mathematical treatment. Before anyone reacts negatively to this paragraph, please read the next.

The problem described above is inherent in the research process by which mathematical optimization models must be created. Real planning problems are much too variable, in both generality and specifics, to allow formulation of a Master Optimization Model (MOM) for any and all water resources problems. Most of us who have been contributing to the literature have done so in the role of scientists developing scientifically sound models for the optimization of our specific versions of the water resources problems. Regardless of how "generalized" we try to make those models, the very process of generalization rules out certain specific conditions (special cases). Thus what we have produced and presented is a smorgasbord of useful ideas and approaches which should be interpreted with Bellman's admonition: "if your problem, when you formulate it, looks like this, then this procedure should prove useful for your planning and management purposes." Again I must repeat that the general problem formulation deficiency is both inherent in the research process and necessary if any progress is to be made. If I have a criticism at all, it is that we haven't been careful to label our results with Bellman's equivalent of the Surgeon General's warning.

To back up my contention regarding the variability of both problems and problem situations I would like to cite a few examples from my own experience. In 1965 the UCLA group (Hall, Butcher, Roefs, Esogbue, Haimes, Tauxe, Shephard, Parikh, and, earlier, Buras, Burton and Howell) completed a study of the northern California river-reservoir systems and their unitized operation, in cooperation with the State of California. The State officials were very pleased with our results. We sent a copy of the report to the Bureau of Reclamation. Subsequently a group of USBR engineers came to visit me, explaining that it was an interesting study but not much use to them. With less than half an hour of discussion, I had to agree that they were absolutely right! This admission, however, did not diminish the value of the study to the California Department of Water Resources one bit. Note that exactly the same physical systems and purposes were involved. Our formulation was a reasonably valid formulation of that system from the point of view of the problems faced by the State of California. It was a totally invalid formulation from the point of view of the problems faced by the Bureau of Reclamation. I personally doubt that any feasible formulation could be created which would be valid for both sets of problems. Although a lot of excellent progress has been made by the continuation UCLA group (under the direction of Dr. William Yeh), the Bureau's original problems, as they presented them to me, have not yet been adequately formulated.

Subsequently, I was asked by Harza Engineering to see what I could come up with respect to a similar multiple reservoir, multiple purpose system in Honduras. I accepted, fully confident that our California studies provided just what was needed. They did not. They did provide building blocks, but substantial modifications were necessary before the results were even close to being satisfactory.

Next I was asked to outline a systems engineering approach to a hydroelectric and irrigation project in Peru. I was sure that now I had the models in hand, but once again major revisions were required. I was also asked by the Government of Iraq to prepare a systems engineering analysis of a major multiple purpose reservoir system. Again I had to make significant revisions in what (again) I was previously willing to bet was a fully adequate problem formulation. What I did not know until later was that the Russians and a European firm had each conducted such an analysis, but both analyses had been rejected by the Government Engineers as not being responsive to their problems. I suspect they may have used their unmodified models off the shelf. After the major revisions which I made to my earlier models, the results were accepted by the Government.

They then asked me to conduct another analysis on the same river but for the downstream reservoir sites and water use areas. This was done cooperatively with Motor Columbus of Baden, Switzerland. By this time I was prepared. Although the basic concepts were the same and some of the elements could be used as building blocks, once again several major revisions were necessary before either we or they were satisfied that we were resolving their planning problem.

A similar result occurred in the study by the Systems Engineering Unit, Central Water Commission, Government of India for which I served as Senior Project Advisor, under the auspices of the United Nations. Major revisions were required to suit even the general India conditions. During these studies we tried to use, directly, most of the principle models available in the literature (including reports) but without success. This was seldom because of errors in the models. Usually, it was due to an inadequate representation of Indian conditions, problems and objectives in the original formulation of the models.

That statement includes my own models, each of which was based on formulations that were useful in California, Honduras, Peru and/or Iraq. Working as a team we were able to make modifications which permitted use of some of those models for certain problem situations encountered in the Mahanadi. Yet when we were asked to look at similar problems a bit further south in India we had still more changes to make.

These examples are presented to emphasize two points. One is that the task of problem formulation is by far the most important for practical application of systems engineering techniques and models to water resources planning and management. This phase cannot be done using mathematical models only. It can only be done satisfactorily if the formulator also understands the implications of what has not been included and adjusts his formulation so that these can be taken into account. The second is that, in my experience there is no "MOM" available now or in the foreseeable future which can serve for the optimization of any specific case in water resources planning or operation as a Master Optimization Model requiring no more than programming and data input.

Even though there is no MOM for water resources, it does not follow that classical research is useless for professional practice. Recall Bellman's argument that the formulation of the optimization problem is the sole responsibility of the engineer who intends to use it to arrive at his recommendations. If he does not adequately understand his own problem (and many do not appear to have such an understanding), he probably won't come up with satisfactory recommendations with or without mathematical optimization models. If he does, then he can develop his own skills in problem formulation. He can use the scientific literature as building blocks for assuring maximum solvability of his formulation. As is the case in using physical building blocks, considerable cutting and fitting may still be necessary.

However, it is my contention, again based on my own experience nationally and internationally, that if any engineer tries to use anyone's optimization (including my own) off the shelf as if it were a MOM, he is very likely to come up with something potentially disastrous for his own professional reputation. Under such circumstances it is hardly amazing that there has been little use of optimization models off the shelf from the literature. Most practicing professionals have had little opportunity to develop the skills necessary for problem formulation using mathematical optimization models. They have developed, almost by instinct, the skills for problem formulation using judgmental optimization, but these skills are constrained by the limitations on human capacity for keeping large numbers of factors and magnitudes in proper focus.

These comments, if accepted as valid, would appear to suggest more university attention on the educational aspects of water resources systems engineering, at least in the immediate future. Research is important and must be done if adequate progress is to be made. However, insofar as practical applications in professional practice are concerned, it seems to me that something is lacking in the "technology transfer" aspects. This is a university function as much as research. Although it doesn't seem to get much attention at promotion and tenure time, the long term ability of the university to attract water research funds (directly or indirectly) most assuredly will depend on how well this job is done. We don't do much bragging today.

To get a better idea of what needs to be done, I should review the basic elements of the planning process as this relates to systems engineering. There are three indispensable elements. The first is the function of problem formulation, discussed at some length above. The second is the mathematical analyses of the formulation, well exemplified for water resources by two or three decades of scholarly publications plus specialized engineering reports. This is the mathematical model realm of dynamic programming (including all extensions), linear programming, quadratic programming, integer programming, various search techniques, etc. Finally, there is the function of evaluation of both the results of the analysis and, implicitly, the original formulation.

For effective professional planning, the three steps are highly interactive, with multiple feedback loops required so that the final evaluation in phase 3 has adequate practical utility for the de facto decision makers (plural) who have the final word.

At present I would argue that (1) the practicing professionals have far too little understanding or appreciation of optimization models, particularly their structure and functions--the same deficiencies Dr. Bellman and his colleague, Dr. Kalaba, tried to correct in my own capabilities back in 1956. Courses in optimization theory have recently become relatively common in undergraduate and graduate curricula. However, by and large, these are courses which present the theory of the classical optimization techniques. Most get bogged down in the arithmetic processes of linear programming. They touch inadequately or not at all on the two most important phases, problem formulation and evaluation of the analyses when made.

I must confess to a good measure of these inadequacies in my own undergraduate and graduate courses. In a large part it is because it is so much easier and rewarding to the instructor to teach the theory of analysis than the practice of problem formulation and analysis evaluation. The latter two phases can be very frustrating to a student accustomed to precision physical models. Also in large part, it is due to our role as educators and research scientists. Our days are quite well filled with these two tasks, leaving little or no time for getting practical experience with the other two phases of planning, particularly in the role of responsible professional planners. Even in our consulting work we are essentially advisors. The client has to be responsible for the ultimate evaluation of our advice and our formulation, so once again it is far easier for us to advise on the analytical phase than on either the formulation or evaluation phases.

With nothing more than my own isolated experience to offer as proof, I have come to the conclusion that the first and last phases are similar to engineering design. That is, they can be learned (mainly by experience) but they cannot be taught. As with design in our engineering curricula, we could offer a "problem formulation" course or an "analysis evaluation" course. These courses could include some pedagogical guidelines "do's and dont's), but, it would have to be up to the student to teach himself how to formulate problems and how to evaluate the analyses. The course could only provide the opportunity for such learning in an environment where mistakes and errors are teachers, not inadvertent destroyers of professional reputations.

As an alternative, such a course could be conducted (not taught) as a part of the professional in-house training programs of water resources agencies. This would have major advantages if the course conductors always included both academic types and successful practicing water resources professionals. The latter presently do not use much in the way of modern systems engineering models, but they have in fact been formulating, analyzing (with judgment, supplemented by simulation models) and evaluating the analyses. The fact that they are successful, suggests that they have mastered the three phases for themselves. The academicians can guide the formulations of the participants in the direction of incorporating the power of mathematical logic. In the way the two types of course conductors would be highly complementary in approach, outlook and ideas for getting on with the task.

Several pages back, I promised I would try to show how the underlying principles and logical thought process of dynamic programming have been useful to me in the professional practice of systems engineering. The proceeding digression into the phases of professional practice was made in order to set the stage, for without those ideas, my discussion might seem somewhat void of purpose. Let me return to my basic objective.

To begin with, I am going to describe dynamic programming logic from a non-mathematical point of view, and relate it to the problems of technology transfer of any and all optimization models into practical, useful, cost effective applications. What I hope to show is that almost the same logic--in verbal descriptive form--provides most of the "do" and "don't" guiding principles for problem formulation and analysis evaluation.

Dynamic programming has been described as a "sequential decision process." I won't deny this attribute, but of far greater importance to water resources system problem formulation would be its description as a "decomposition--recomposition" or "disaggregation-reaggregation" decision process.

To help illustrate the problems faced by the engineer in the task of problem formulation, let me cite an exaggerated example. In most water development engineering reports I have read, the purpose stated is to provide so many acre feet or millions of cubic meters of water per year at minimum cost. Taking such a statement at face value as the properly formulated objective of water resources planning, and using it in any optimization model, the optimal decision would clearly be, don't provide any reservoir storage. If any water is stored, evaporation losses will increase, otherwise the mathematical expectation of the maximum water available is the mean annual flow. That, or any lesser amount, can be obtained at zero (minimum) cost without a reservoir. Since water is water (in the above statement) it makes no difference to the mathematical model whether the amount available at any time is above or below average by any amount.

Clearly this is an improperly formulated problem in almost any non-trivial case. What is wrong? The basic function or purpose of the water system is to take a natural occurrence of water with a highly stochastic, unreliable distribution over time and space, and convert it to a more desirable time-place distribution, with the required attributes of reliability in time and place, quality characteristics, etc., as needed for the technology of its use for other systems. These other systems in turn are intended to accomplish more basic goals and objectives.

I may have left something out, but everything in the above statement of purpose is an integral part of the performance of every water resources system. My improper, exaggerated example took certain engineering reports at face value, ignoring both time and space distributional requirements as well as the all important reliability characteristics, all of which were only implied. No resource, water or otherwise, has value unless it has the time and place reliability required by the technology of its own. For most uses, the long term investment in that technology far exceeds the corresponding share of water resources investment cost. This means that, despite a few good examples and a lot of wishful thinking, these water use technologies are not going to change at the whim of the water planner. The few examples of successful change that might be cited, all involved little or no modification of current investments. If changes are to be made, they must also be met with high, stable reliability.

To accomplish the time-place-reliability-quantity-quality transformation, certain facilities have been utilized for thousands of years. Each of these facilities has its own unique function. Reservoirs (surface or groundwater) provide storage capacity to allow the reregulation of flow with respect to time and temporal reliability. Pipes and open channels, natural or man-made, perform the function of spacial distribution and spacial reliability.

Now let us initially associate Bellman's activities or stages with these functions to be accomplished rather than to the individual elements and various impacts on social, economic, political and other objectives. First look at them from an overall point of view. Storage capacity is the only available, technically feasible means of modifying the temporal availability of water. Using Bellman's principle of optimality, the water resources systems cannot be optimal unless this function is performed at minimum cost in terms of other resources used, including the direct environmental, social and other important impacts of providing and operating that storage capacity.

Similarly, channels, natural or man-made, are the only technology we have for modifying the spacial distribution of water to one considered to be more desirable.

Stopping here for the moment, we have identified two separate and distinct generalized subsystems which have separate and distinct functions. From a pure mathematics point of view we could optimize each without regard to the other. However, there exists an interdependence between the two subsystems. Whatever indices are used to describe the actual quantities of resource ultimately made available over time, those particular quantities must also be reliably distributed over space. Therefore if we should optimize each system separately, as a function of this final output level, it will be a simple matter to find the optimal combinations of those two systems.

Note this statement is valid regardless of how those costs and other impacts are evaluated, and regardless of what uses might ultimately be made of the water resource provided. It is also valid for virtually every water resources development system.

I could similarly describe other water resources subsystems, each of which has its function to perform. For each, however, the central interconnecting variable is usually that same quantity of water.

Of course the phrase "quantity of water" really refers to a vector-like quantity which involves the optimal hourly, daily, monthly distribution functions of the "quantity" over the year. It also includes a specific set of requirements concerning the reliability characteristics (a required probability function). However, because of the "technology" constraint, these are either not decision variables or become at most potential secondary decision levels, involving decision makers normally outside the authority of water resource agencies. Thus these parameters should be included as an appropriate set of potentially alterable constraints, associated with the variable "quantity of water." Similar statements can be for other aspects of the resource such as energy (in or out), flood peak mitigation, etc.

The above arguments were used by our (India) Systems Engineering Unit project to make a fairly general first cut formulation of the very complex multi-objective water resource development potential (including existing works) for the Mahanadi River. This first cut was a decomposition model in the spirit of Bellman's principle of optimality. The total system could not be optimal unless these functions were accomplished optimally. Because of the small number of interacting properties, the time and reliability modified output of the river regulation subsystem is the input to the spacial distribution system. The dynamic programming concept of making an optimal combination of these two subsystems provides the model for an optimal recomposition. The many physical, environmental and social constraints are easily imposed on this analysis.

The arguments are not quite complete. If all regulation occurred upstream of all water distribution, the decomposition-recomposition given would be complete. As for the Mahanadi in India, this is frequently not the case, It was necessary (but not difficult) to prescribe a simple iterative process, with one or two iterations, whereby individual elements of one or the other of these subsystems would be constrained by the feasibility of sending or receiving water between such elements. This is by way of explanation only. These refinements are not essential to the "guiding principles" of problem formulation being presented here, i.e., the principle of using the functions (purposes) of various parts of the complex system to disaggregate it logically into conveniently formulated sub-problems and subsystems.

If the development were limited to one reservoir site and one water use sub area we could stop here. In most cases there are a number of alternate reservoir sites and alternate areas of use. To illustrate the next steps consider that there are a number of reservoir sites, at each of which, all or part of the time and reliability regulation could be accomplished. Invoking Bellman's principles, the overall time-reliability regulation should be accomplished with maximum cost-effectiveness (however defined). Furthermore each reservoir in the system makes its own contribution to the reregulation. The nature of this contribution in fact is different for reservoirs in series or in parallel. This can be properly reflected in the decomposition-recomposition models. Suffice it to say for purposes of this presentation, each reservoir should be best capable of making whatever contribution might be expected of it in the final optimal plan and to do so at minimum cost. That is, we need the function representing the optimal contribution as a function of cost, or vice versa. The recombination of the individual reservoirs can then be accomplished using the principles, and usually the algorithms of dynamic programming. It is at each of these stages that the appropriate feasibility constraints created by the other major subsystems are to be included as suggested above. A similar statement can be made for the distribution system, the water use subsystem and all other functional subsystems.

I could describe this process in more detail, and with a broader representation of functions of subsystems, but that is not my purpose today. I only want to show how the concepts of Bellman's dynamic programming were used to guide us in the proper formulation of our systems engineering problem. Obviously there were still a lot of specific characteristics that caused difficulties, not the least of which were the hydrological characteristics of the monsoon rains and consequent runoff, and the somewhat nebulous definition of "reliability" imposed on us as a judgmental optimization of that issue by higher authorities. I will only comment on the latter by admitting I felt, on the bases of my experience elsewhere, including my own irrigated form, that the prescribed definition of reliability was far from optimal. After a lot of discussion and computational experience with the results (evaluation phase), I now consider that this judgmental optimization is going to prove to be very close to the proper conclusion for many if not most conditions in India.

Bellman's concepts, which he expressed in dynamic programming, have had another very significant impact on our work in India. Although the stated "objectives" of water development in India are heavily flavored with references to economic development, famine prevention, and employment, there are in fact hundreds of objectives, in the sense of consequences to be enhanced or avoided. Thus any significant planning effort would or should involve multiple-objective optimization considerations.

The problem was that few if any of the expressed or implied objectives could be measured with any degree of quantitative confidence, let alone be related by mathematical functions to the specific decisions involved in water resources development. That comment includes the commonly advocated economic impact objective. One could come up with crude estimates of people affected, based on not too reliable demographic data, but for all practical purposes these basic or primary objectives were so speculative that no useful purpose could possibly be served by their inclusion in any mathematical optimization model whether a MOM or a site specific formulation.

Again Bellman to the rescue! By utilizing the above guiding principles for the formulation of our problem in terms of mathematical models, we were able to perform a satisfactory "pareto optimum" analysis to obtain the non-inferior set using only four "objective indices" none of which is primary. These were (1) quantity of water (properly regulated in time and space), (2) capacity of the reservoir system, (3) reserve capacity for flood peak mitigation and (4) hydroelectric energy, also properly regulated in time and place.

This particular set has some very important properties. First given the technologically required time-place distributions of water and energy and their corresponding (but different) reliability requirements, the impact of any particular non-inferior set on virtually all other "objectives" can be estimated directly from the magnitudes of the elements of that set, with the assurance that it is the "best" that can be done without degrading one or more other objectives. Second, the results demonstrate the marginal effects of those technological time, space, reliability constraints, thus allowing an evaluation of the desirability of making reasonable modifications thereof. Note that for reasons described earlier these adjustments must be long term modifications. While they can (and should) be considered as potential decision variables, they must be fact be parametrically adjusted and only in terms of long term beneficial effects. When this is done, the reoptimization of the system is a matter of a few minutes of computer analysis, plus the usual post analysis evaluation.

Finally, from the above it would seem clear that these four decision parameters constitute a relatively simple framework for multiple objective analysis, each element of which has physical significance and is readily modeled using the mathematics of cardinal numbers. All other objectives can be evaluated, either quantitatively or qualitatively, as necessary, in terms of these four objective indices.

One last remark should be made about the use of dynamic programming concepts. In addition to the assertions above, there are significant equity considerations involved in the siting and sizing of individual reservoirs, aqueducts and other facilities constituting the water resources system. In our studies we used a very efficient "hand calculation" dynamic programming procedure (SYMPDYNPRO) which I developed for the Honduras study. The simple tables created in the process clearly revealed what Bellman referred to as "second best, third best," etc., options, thus allowing on the spot trade-off concessions between purely qualitative objectives and the quantitative objectives being used in the analysis. Normally these kinds of objectives are related to specific units of the facilities provided, hence this "multiple objective" trade-off analysis can be readily and accurately made at that point (stage) of the analysis.

Most computer programs written for D.P. do not automatically print out these intermediate computational results. However, these details have proved to be invaluable to us and, in practice, the additional computer printout cost is negligible--essentially one table for each "stage" of the combinatorial process. Our intention (not yet implemented) is to provide this capability in our D.P. subroutines.

Summary

I realize this paper is over-long and I have not yet begun to touch all the things that could and perhaps should be said. Let me terminate it with a brief summary of the points I have tried to make, not necessarily in order. First, I tried to call attention to a serious gap existing between research and practical application of systems engineering, and argued that the heart of this gap lies in the problem formulation and analysis evaluation phases of the planning process. Second, I argued that capability (skill) in these two deficient areas can be learned but probably cannot be taught. Third, I tried to show how the ideas and concepts of dynamic programming have proved to be more useful to me in the practice of systems engineering than have the formalisms of D.P. or any other optimization technique. Fourth, I argued that those same concepts can be utilized as guidelines for effective and accurate problem formulation, in that they constitute a practical basis for simplification of the problem to be formulated, using the well defined functional (purpose) requirements for each component subsystem or facility. Finally I argued that the primary computational result need only be the non-inferior set of four basic objective indices from which all other objective impacts may be evaluated for any non-inferior set.

My overall summary is a simple statement that Bellman, through his concepts and principles of dynamic programming, has had and will continue to have far greater impacts on water resources planning and management than might be anticipated from the purely mathematical processes involved.

PART TWO

WATER SUPPLY PLANNING AND MANAGEMENT

PART II: THE STATE OF GEORGIA'S RESOURCES MANAGEMENT STRATEGY

II.1 STATE WATER RESEARCH MANAGEMENT PLAN

DAVID M. WORD

The framework of Georgia's water resources management strategy consists of the following four key elements which are supported by Georgia's Water Quality Control Act, Grounwater Use Act and Safe Drinking Water Act:

- Water Withdrawal Permitting Program
- Public Water System Supervision Program
- Emergency Water Shortage Plan
- Georgia's Water Budget (Water Availability and Use Reports)

Each of these elements is briefly summarized below.

Withdrawal Permit Program

Georgia's water resources management strategy is implemented in large part by a system of water withdrawal (use) permits which allocate the water resources and protect the water rights of the user. Enacted by the Ground Water Use Act of 1972 and the 1977 Amendments to the Georgia Water Quality Control Act, these statutes require non-agricultural water users withdrawing more than 100,000 gallons per day from the State's ground or surface waters to first obtain a permit from EPD. Uses ongoing when the respective laws were enacted were permitted for the quantities in use at the time. However, expansion of existing permits and new permits, particularly for surface water sources, impose requirements on the permittee to protect the water resource while making beneficial use of the State's waters.

For surface water sources, new or expanded withdrawals may not reduce the flow in a stream below the 7Q10 flow at the withdrawal point. The "7Q10" is the average lowest flow over a seven-day period that will occur on the average of once every ten years. The 7Q10 is accepted by the State as the minimum flow necessary for maintaining fisheries and for water quality protection. State regulations require Georgia's water pollution control facilities to be designed and operated so that the State's water quality standards are met at all stream flows equal to or greater than the 7Q10. Hundreds of industrial and municipal water pollution control plants worth well over a billion dollars have been constructed in Georgia on the basis of meeting water quality standards when stream flows equal or exceed the 7Q10.

The practical effect of requiring passage of the 7Q10 flow is that some sort of water storage must be provided to maintain a water user's source reliability during drought periods (such as 1986). Since most communities expect 100% source reliability, resource development is the principal means of providing storage to assure that reliability while also allowing the 7Q10 flow to pass. Communities and industries with substantial raw water storage were able to meet their water demands with minimal problems during the drought of 1986. The passage of a minimum flow (such as 7Q10) helps to assure that a given water withdrawal does not have unreasonable adverse effects on downstream water users, as well as protecting the fishery and water quality of the source stream.

To ensure that water is used efficiently and that emergency situations can be handled in an orderly fashion, permitted waterdrawers are now being required to develop water conservation plans as a condition of their withdrawal permits. Water conservation plans generally have two main objectives: reduction of routine water demand and managing water supply emergencies. Reduction of routine water demand involves day-to-day efforts to conserve water, such as recycling backwash water at treatment plants, leak detection programs and metering all connections. Drought contingency planning deals with the process of reducing water demand through a series of increasing restrictions on water use by municipal and industrial users. Establishing water use priorities in advance is essential for various water users to cope with difficult drought situations.

Water conservation is also promoted through the use of water-saving plumbing fixtures. Since 1978, Georgia law has required newly constructed and rehabilitated buildings to use water-saving showerheads, toilets, and faucets to help reduce routine water demand. Substantial reductions in per-home water use have been achieved since enactment of this law, which is also incorporated into the Georgia Building Code.

The water withdrawal permitting process does not include, except for reporting purposes, the withdrawal of water for agricultural uses. This is a significant factor in the water resources management strategy which needs to be addressed.

In 1972, when the Groundwater Use Act was passed, agriculture accounted for less than 5% of total statewide water usage. Therefore, agriculture was exempted from the Act. However, the recent widespread use of center pivot irrigation systems has increased the agricultural usage t more than 33% of the total. Statewide this usage has resulted in significant declines in the levels of major aquifers in South Georgia.

In 1977, the surface water withdrawal amendments to the Georgia Water Quality Control Act also exempted agricultural usage. It was believed at that time that agriculture would not interfere with municipal water supply needs. However, the droughts of 1981 and 1986 demonsrated that these withdrawals competed with municipal withdrawals in some cases, such as on the Alcovy River above Covington and the Flint River near Lovejoy.

In 1982, the General Assembly passed a bill requiring farmers to report estimated agricultural water usage. This bill has largely been ignored by farmers and only a very limited amount of information has been reported.

Many farmers are now recognizing the value and importance of being officially allocated a quantity of ground water to meet their needs. In addition, they realize the value of being able to obtain information from the State, based on correct water budget data, so they can make wiser decisions in locating and sizing future wells and irrigation equipment. It is anticipated that the farming community will soon encourage amendments to the water allocation laws to allow them to receive allocations and become part of the State's water management strategy.

Public Water System Supervision Program

The purpose of the Public Water System Supervision Program is to assure a high and safe quality of drinking water to the public. This program is managed by the Environmental Protection Division with the support of a yearly grant administered by the U.S. Environmental Protection Agency. The legal basis of the program is the Georgia Safe Drinking Water Act of 1977 and the Rules and Regulations for Safe Drinking Water promulgated pursuant to the Act.

There are 2740 public drinking water systems in Georgia. To ensure that the public water systems are operated in accordance with the Rules, EPD maintains a comprehensive regulatory program. Certain aspects of public water system management are closely related to the water resources of each community. For instance, each major public water system is required to receive a permit from EPD prior to operation. The permit is renewable every ten years and sets forth the operational and monitoring requirements necessary to insure the delivery of safe water. EPD also reviews and approves engineering plans and specifications for wells, water treatment plants, and water distribution systems prior to construction.

By overseeing not only water withdrawals but water systems and wastewater facilities as well, EPD is working with our local communities to provide adequate water sources, treatment and distribution, and pollution control. It is through this program that EPD determines if a community's water treatment and distribution system capacity is adequate for existing and future needs.

Emergency Water Shortage Plan

The Georgia Water Quality Control Act and Rules and Regulations for Water Quality Control authorize the Director of the Environmental Protection Division (EPD) to issue emergency orders to protect the health and safety of water supplies during emergency water shortage periods. The emergency water shortage plan was designed to provide a method to provide water for essential purposes while helping maintain some water for downstream uses during critical drought periods.

Since the demands on Georgia's water resources are significantly stressed during drought conditions, the protection of water supplies will be insured by institution of the water conservation plan required through the withdrawal permit process. The extent of water conservation measures and the actions taken by EPD depend upon the degree of the drought and the specific conditions affecting each local government.

The emergency water shortage plan consists of the following water steps to be implemented during emergency or drought periods:

Step I. Enforced Outside Water Use Restrictions

EPD will request or, if necessary order, a community to restrict outdoor water use to certain days or hours for all users. This will occur if a community exceeds 90% of its permitted water withdrawal amount or maximum safe production level of one day, if low pressure (less than 20 PSI) or loss of service is experienced, or if the steam flow below the water withdrawal is less than 1.2 times the stream's 7 day-10 year minimum (7Q10) flow. In addition to outdoor watering restrictions, other water conservation measures specific to a community may be adopted by the community or ordered by EPD.

Step II. Enforced Outside Water Use Bans

EPD will issue an emergency order to a community (unless the community voluntarily adopts the ban) stopping all outdoor use of water including lawn and garden watering and car washing. Businesses using high volumes of water such as car washes and nurseries may be put on significant reductions. This step will be implemented if Step I measures are not effective and if a community exceeds its permitted water withdrawl amount of maximum safe production level for one day, if low pressure (less than 20 PSI) or loss of service is experienced, or if the stream flow below the water intake is less than 0.5 times the stream's 7Q10 flow.

Step III. Water Use Ban for Non-Essential Purposes

EPD will issue an emergency order to a community (unless the community voluntarily adopts the rationing) rationing the use of water to essential purposes only. Essential services are health care, sanitation and cooking needs. Commercial and industrial uses will be restricted and outdoor water use will be banned. This will be implemented if Step II procedures fail to prevent loss of service or if extreme low stream flow conditions persist severely limiting the amount of water available.

The drought of 1986 tested the emergency water shortage plan. The Environmental Protection Division notified 103 communities using surface water and 350 using ground-water to restrict outdoor water usage (Step I). Of these, 29 communities adopted total outdoor water use bans (Step II). Fortunately, only 5 communities needed to ration water (Step III) by reducing industrial water usage. During the drought, the Division provided technical assistance to local supplemental water sources for 17 communities and awarded $250,300 in emergency grant funds to install the necessary facilities (wells, pumps, piping) to use these sources.

The 1986 drought confirmed the information in the Water Availability and Use Reports pertaining to water systems which were shown to have unreliable sources. The drought also served not only to identify streams with conflicts over the water usage (agriculture irrigation versus municipal drinking water) but also to emphasize the need for storage reservoirs capable of providing water during drought periods.

State Water Budget

Georgia's water budget is compiled in a series of reports on Water Availability and Use by river basin for the State. The Water Availability and Use Reports have been under preparation since 1982 and are now complete. As drafts of the reports have been completed, they have been distributed for public review and comment in the various river basins in the State.

The Water Availability and Use Reports have developed for the first time a comprehensive inventory of the State's water resources and uses made of those water resources, both from surface water and ground water. They provide the data base necessary for informed permitting decisions that help to meet the State's water demands while protecting the natural resource base.

By dividing each river basin into hydrologic units possessing similar characteristics, the Water Availability and Use Reports produce an accounting, or budget, of water naturally available at various points in a river basin, and the uses made of that water. Proceeding from the head-waters toward the mouth of each major river, the reports list significant withdrawals of water from the basin and against discharges back to the basin's streams. By summing the net effects of withdrawals against discharges and considering natural runoff contributions in each hydrologic unit, the amounts of water available for use are identified for both average and drought conditions. Using a technique developed by EPD staff, a measure of reliability for each surface water user called the Level-Of-Service Index (LOSI) is computed. The LOSI gives a convenient estimation of a given water system's current ability to meet drought demands.

A major function of the Water Availability and Use Reports is to identify areas in each river basin where water resources problems or conflicts occur, as well as where water supplies are plentiful. By projecting future population trends and their resultant water demands, the reports can identify areas of future water resource concern. It should be pointed out, however, that water resource capabilities are only one component of a water system, dealing with the adequacy of water supply sources. Another major concern, especially in areas of high growth, is the adequacy of water treatment and distribution capacities in the community's water system. Effective delivery of water to consumers can be jeopardized by inadequate source, withdrawal, treatment or distribution capacity.

Georgia's water budget indicates that most of south Georgia (below the Fall Line) has an abundant supply of ground-water sufficient to meet both current and future needs, if it is properly managed. To do so, the withdrawal of water for agricultural uses must be included in the water permitting and allocation program.

The ground-water in certain areas of Chatham County and Glynn County needs to be protected from further drawdown. The Environmental Protection Division has adopted ground-water management plans for both counties which promote water conservation; ban the installation of new wells (or increased withdrawals from existing wells) in the critical areas of Savannah and Brunswick; and provide for limited new wells in the outlying areas of Chatham and Glynn Counties. In addition, EPD is working with the United States Geologic Survey to develop a computer model of coastal Georgia to determine the optimal locations for wells to meet the future water needs of coastal Georgia.

North Georgia, north of the Fall Line, relies primarily on surface water to meet its water supply needs. Georgia's water budget and the 1986 drought demonstrated that the surface water sources for many communities are insufficient to meet current and future needs. To correct this deficiency, the Environmental Protection Division is recommending a system of water supply lakes which can also serve as public fishing lakes for north Georgia. Some major lakes are already in use (Lanier, Allatoon, West Point, Oconee, Clark's Hill, Hartwell). Smaller ones are still in the planning stages as discussed later in this summary document. Also, EPD has participated with the Corps of Engineers, APDC's and local governments to develop areawide water supply plans for Metropolitan Atlanta, several counties south of Metropolitan Atlanta and several counties in Northeast Georgia.

II.2 WATER PROBLEMS AND ISSUES OF THE STATE OF GEORGIA: PROBLEM GOALS AND PRIORITIES

BERND KAHN

Georgia has the full range of water problems commonly associated ith industrial and agricultural development in its geographical setting, ameliorated by generous rainfall and the efforts of a forward-looking state water management agency. The Environmental Resources Center (ERC), as the State Water Research Institute under the Water Resources Research Act of 1984 and earlier laws dating to the Act of 1964, functions to provide support for the water management agency through a network of research at universities and colleges in Georgia.

The average rainfall of approximately 50 inches per year is sufficiently distributed throughout the year and over all parts of the state so that normally water is plentiful. The rain maintains numerous large and small streams that originate in north Georgia and flow through the state to the Atlantic Ocean or the Gulf of Mexico, and recharges an enormous aquifer underlying south Georgia. Water users generally depend on streams and shallow wells in northern Georgia and on deep wells in southern Georgia. This water supply supports industrial and agricultural development throughout the state, and population growth with concentration in the Atlanta area.

A number of water quality, quantity, and management problems have developed with growth. Small streams in north Georgia have reached capacity for supplying water and receiving waste. Some deep wells in Georgia have dropping water levels, and some in coastal Georgia have salt-water intrusion. Surface runoff and resulting sedimentation have been a longstanding problem, and herbicide/pesticide/nutrient runoff has increased with intensified agriculture. Solid and toxic waste management is being recognized as a major problem with water pollution implications. The economics and technology of building and maintaining water and wastewater treatment and distribution facilities need consideration as Federal support decreases and guidelines become more demanding.

The state agency, the Georgia Department of Natural Resources, has addressed these problems by enforcing laws that control water quality and water use. As a result, surface water quality throughout the state has improved to meet standards, and industrial development is guided to locations where water remains available at the appropriate volumes. The agency has also identified the following priority issues, prompted by the problems associated with an extensive drought in 1986.

- plan regional reservoirs in north and central Georgia;
- implement a comprehensive ground water management program for both quality and availability;
- establish a modern hazardous waste facility;
- develop and implement a toxics management strategy

These efforts should go far toward managing water in Georgia for the foreseeable future.

II.3 A TAXONOMIC TREATMENT OF DYNAMIC PROGRAMMING MODELS OF WATER RESOURCES SYSTEMS

AUGUSTINE O. ESOGBUE

Abstract

This paper presents an overview of the various aspects of dynamic programming and the problem areas of water resources. The models which have appeared in the literature addressing the use of this problem solving tool in water resources systems are then reviewed and grouped using a taxonomic scheme developed for its analysis. This is summarized in tabular form and followed by a discussion of research needs and an extensive list of references.

Introduction: Problem Statement.

In discussing the origins and interconnections of dynamic programming and water resources, we pointed out that the two fields have contributed to the progress in the state of knowledge of each other. We observed, for example, that the water resources systems field has been a testing ground for some techniques and models of dynamic programming. Additionally, some of the problems encountered in solving water resources problems have led to the development of aspects of theory and computational solution of dynamic programming. For the field of water resources systems engineering and analysis, dynamic programming has enabled problems of certain structure and complexity to be handled in areas where other systems and optimization techniques had proven ineffective. This therefore has led to advances in our ability to analyze optimally the usually complex and multifaceted systems problems in water resources.

It was also stated that dynamic programming has not only become one of the most popular techniques from the standpoint of frequency of use but also from the perspective of the variety of problems addressed. The number and growth is staggering. In this paper, we wish to examine more critically and in depth our foregoing observations. We survey these applications not only with respect to their origins and genesis but considering their coverage. In other words, we seek to identify the types of water resources problems addressed, the dynamic programming techniques used - both the model and its computational solution, and the degree to which the proposed solution approach is appropriate or usable.

Finally, we hope to identify the trends and the manner in which authors have been influenced by one another. By developing a taxonomy, we hope to unify these sundry models and treat them in one framework. This could serve as an important reference source for users and future developers of dynamic programming based water resources models. Clearly, this is an ambitious task as was learned by Yakowitz [1]. Our work is a realization of an effort we reported in 1975, aided by Yakowitz's excellent review, and the continued explosive developments in the field to date.

The plan of the paper is as follows. We begin in Section 2 with a survey of the field of dynamic programming, both the theory and the computational approaches for realizing solutions to the functional equation. Clearly, it is impossible to present a complete treatment of dynamic programming in this paper. While we attempt to cover as many significant topics as possible, our focus is only on those that have impacted the field of water resources considerably. In Section 3, we identify and classify the various water resources problems discussed in the field. We next present a survey of the models of the use of dynamic programming in treating the identified problems. This is given in Section 4, the heart of the paper, as its length clearly shows. In Section 5, we present a scheme for a taxonomic classification of the issues encountered in the papers. The paper is concluded with a synthesis of our observations and findings including a summary of research needs as well as an extensive list of references. The reader is now fully prepared for the detailed subject and technique oriented models which appear in the remaining parts of this book.

Summary and Discussion of Research Needs

From the foregoing survey, it is obvious that water resources problems and the techniques of dynamic programming have been popular among researchers. Clearly, reservoir operation and design problems predominate. This is also reflected in the distribution of papers in the sections of this volume. In reservoir studies, the emphasis had been on operation but the design aspects and efforts to combine both have also appeared. Multi purpose and multi reservoir systems have been of interest. This is as it should be. However, the models have often been simplified considerably almost ad absordum. Large reservoir systems located on several different streams and converging or diverging at a delta in a basin, for example, have been decomposed and analyzed separately because of computational tractability. The result is that often times errors and inaccuracies are introduced in the process. This difficulty can now be circumvented or minimized by utilizing efficient nonserial dynamic programming algorithms available in current literature. As more efficient algorithms are developed, our ability to analyze more complex realistic systems will inevitably be enhanced.

Another issue is that for a long time, the most popular dynamic programming computational algorithm has been DDDP. Yakowitz has shown that differential dynamic programming, although difficult to implement, is by far more efficient. We have also shown that in the case of nonserial systems, our nonserial dynamic programming algorithms developed for various types of nonserial systems and complexities, are vastly superior. The hope is that optimal exploitation of these algorithms will be pursued to generate models of better fidelity, solve larger scale as well as more realistic problems and provide more accurate and less expensive solutions. Our capability to explore various policy issues should also expand.

We also note that, especially in reservoir systems, stochastically occurring problems had initially been approximated by their deterministic analogues primarily to ease computational burden. However, with developments in and better understanding of stochastic dynamic programming, algorithms for stochastic models have begun to crop up. Here again, adroit modeling and familiarity with the literature of stochastic dynamic programming can lead to more realistic and easily implementable models. In this regard, the papers by Sobel, Sharda and El Tayeh, Georgakakos, Read and

Boshier, Kitanides and Andricevic - all in this volume, represent important contributions to the literature.

The other popular water resources problem addressed is the area of sewer systems. Initially, the emphasis was on design with some layout profile given. As our ability to deal with more complex dynamic programming systems increased, the layout and design problem is being handled simultaneously as it should be. Again the principal technique used is DDDP - a tool which is familiar to the model developers. Further, the problem is treated by decomposition. We believe that as stated before, more efficient dynamic programming algorithms will be invoked so that large networks can be handled efficiently. Also both problems can be treated simultaneously without resorting to decomposition.

Our comments relate to three primary aspects. The first deals with the water resources problem areas that have not been modelled correctly or satisfactorily. Here, we are concerned with incorrect description of the problem as it occurs in real life settings. We are also concerned about erroneous dynamic programming formulation. Sometimes, the models are simplistic and over simplified. Other times, they are correct and realistic but very little regard is paid to the issue of computational efficiency. This results in difficulties when a practitioner, for example, wants to implement the model. It is simply too expensive. We have noticed also that the sensitivity analysis aspect of dynamic programming, one of its sterling properties, tends to be sublimated in these models. We expect to see some remedies which address these concerns.

A related problem is that of implementation and computational efficiency. Some of this concern has been touched on albeit tangentially in the previous paragraph. The temptation to employ algorithms familiar to an author, whether they are the most efficient available or not, should be resisted. An effort to keep abreast of the technology of problem solving via dynamic programming should be a profitable investment. Efforts to take advantage of the presence of various types of computing devices including the super computer and micro computers should be made. For example, Sugiyama's paper on this book shows how, by employing the proper solution algorithm, an otherwise expensive problem can be solved via an inexpensive device such as a programmable hand-held calculator.

Additionally, certain water resources problems such as reservoir operation, have proved to be a fertile ground for model developers, while various other areas have been shunned or treated as sacrosanct. Examples are irrigation, stream aeration, transbasin diversion, water quality especially nonpoint source pollution problems, etc. While these areas may be suitably and appropriately modeled via other techniques and sometimes very difficult to model, we believe that the principal reason for the paucity of attention given to them is due to our unfamiliarity with the potency of dynamic programming. For example, that water resources is typified by multiobjective, multicriteria decision making cannot be gainsaid, yet very few explicit treatments of this problem exist in the literature. The surrogate worth method described by Hall and Haimes is an attempt to deal with an aspect of this concern. Tauxe's paper in this volume considers this via multi objective dynamic programming. Labadie and Fontane also address it in their paper.

Finally, the developments in the area of computer hardware such as the arrival of the super computers, advances in computing technology and information processing such via parallel computing, efficient high level programs and data manipulation/transfer systems, all augur well for the eventual eradication of the curse of dimensionality in dynamic programming. This translates into the analyst's increased ability to model, solve and design water resources systems as they occur in their natural habitat.

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II.4. IDENTIFICATION OF DEMAND MODELS FROM NOISY OBSERVATIONS--AN APPLICATION TO WATER RESOURCES

LOV KUMAR KHER and SOROOSH SOROOSHIAN

Abstract

One of the major problems in systems planning is the identification of a demand model when all the independent and dependent variables are noisy. The existing methods generally used for noisy variables are associated with various problems, for example, nonidentifiability and unboundedness. An alternative model, the noise-in-variable model (NVM), is presented, which explicitly considers noise in the data for all the variables of the system. A mathematical programming-based solution algorithm is used to identify the NVM model. This algorithm gives bounds on both the model parameters and the noise covariance matrix. Here a solution range is obtained instead of the single poit estimate from the classical estimation theory. The problem of unboundedness is addressed by using prior information about the noise. The procedure is implemented for the water resources using real data. The NVM approach gives a more realistic picture of future water demands. Various demand values, obtained using the identified parameters' space, will correspond to a set of demand scenarios in which each scenario will have a different noise variance. Multiple step-ahead point forecasts for demand can be computed using the minimum noise variance system of the identified demand models.

Further, a suitable cost model can be indentified from noisy data using the same approach as outlined earlier. Finally, the point and cost models can be implemented in an integrated fashion to solve capacity expansion decision-making problems using dynamic programming procedures as given in Freidenfelds [1].

Introduction

In the real world, the future is uncertain, but not to a degree to obviate the benefits of long short-range planning or the use of mathematical models. Can we cope with it better than before with the new and improved modeling techniques that are available to us now? The obvious answer is yes. Dreyfus and Sen [2] comment: "If the wisdom of professional decision makers, forecasters, and planners indeed takes the analytical form, the computer implementation of mathematical models embodying their knowledge should be an invaluable aid to their activities." Many researchers have addressed the methodology for the analysis of empirical data for mathematical modeling. However, among these researchers, Kalman's recent work (Kalman [3], [4], [5]) presents a new improved direction towards the identification of mathematical models from real data. Kalman [3] raises an important question:

> "The dilemma is that we don't know whether there is a way, which mathematicians call natural or canonical, of defining models so that they depend only on the data and not on any external biases. Such biases may be introduced, often unintentionally and unknowingly, by the special procedures or algorithms employed in constructing a realization. In the vast majority of models which have

> arisen historically, such biases are indeed present and cannot be justified away. The problem is subtle. The solution requires a mathematical point of view which cannot be rendered into ordinary language with precision or intuitive meaning."

In particular, we focus our attention toward mathematical modeling problems for water resources systems. There are several important problems in planning for water resources systems, such as how much water should be used, where it will be needed, what purposes it will serve, when the demand for water will occur, and how much budget should be allocated to meet these demands. The actual water demand will depend on such time-dependent variables as population levels and distribution, per capita income, price of water, rainfall and temperature, technological development, consumer habits, and preferences. Developing relations between these variables and using them to estimate water demands under various conditions requires analytical approaches.

In most water management and/or planning studies, some best-guess demand function is specified by some growth rate rather than detailed year-by-year estimates (Dandy et al. [6]; Kindler and Russel [7]) In cases where detailed estimates are given, generally multiple regression or time-series methods are used (see e.g., Agthe and Billings [8]; Foster and Beattie [9]; Hansen and Narayanan [10]; and Maidment and Parzen [11]. Models based on these methods are known as error-in-equation models (EEM) which have an error term at the end of the equation, and the EEM define an inexact relationship among observable variables. Demand models developed using any of the above methods are based on the assumption that the data for all the independent variables are "exact" (i.e., data have no error). In real life, however, data are always "inexact" (i.e., noisy, uncertain), and lack of their consideration in the modeling process limits the usefulness of the results. Hanke and de Maré [12] have also made a similar observation about the noise in the data.

Without proper consideration of noise in independent variables, we can expect the resulting estimates to be biased and inconsistent and, therefore, produce inaccurate forecasts of future demands. For further discussion of the implications of some of these problems, see Hoodges and Moore [13]; Bard [14]; and Garber and Klepper [15].

To overcome the drawbacks of EEM models, some researchers (see e.g., Bard [14]; Mehra [16]; Garber and Klepper [15]; Kalman [4]; and Kher [17]) have examined the feasibility of developing models which consider noise in all the variables. In this case, the resulting water demand model will not be unique in the classical sense. Due to the consideration of noise in all the variables, a range for each model parameter is obtained rather than a point estimate by the classical estimation theory.

One class of existing models which incorporates errors in the independent variables is known as error-in-variable models (EVM). Unfortunately, the EVM are not very useful because, according to Kalman [4], all the model parameters cannot be estimated from the given behavioral relations. To overcome such a limitation, Kalman [4] has recently proposed an alternative to EVM which is based on "noisy realization theory". This procedure gives a bounded solution set when the data covariance matrix (Σ)

of all the variables is inverse positive (i.e., all entries of Σ^{-1} are positive real numbers). However, when Σ is not inverse positive, then the solution set will be unbounded if a single relationship for the demand is to be identified. Klepper and Leamer [18] have discussed determining a bounded solution set for the unbounded case by making the assumption that all the independent variables will have the same percentage of noise variance.

In this paper, the general background of a procedure is discussed for identifying a model which considers the noise structure in the inputs and produces a bounded solution set for a water demand model. The proposed approach extends the application of noisy realization theory introduced by Kalman [4, 5]. The name used to identify this class of model is the noise-in-variable model (NVM). A simple first-order lag dynamical model is used to incorporate time-dependent information. The NVM model explicity considers noise in the data for all the variables of the system. The solution procedure is developed so that the identification problem is transformed, using Cholesky-type factorization for the "true" component of the data covariance matrix, into a nonlinear programming algorithm which gives maximum and minimum bounds on both the model parameters and the noise covariance matrix. So, here we obtain a nonunique solution instead of a unique point estimate as obtained by classical estimation theory. For details about the mathematical problem formulation and solution procedure, see Kher [17] and Kher and Sorooshian [19].

The proposed procedure gives a bounded solution set for the identification of a linear relationship from the noisy data when the data covariance matrix is inverse positive. However, when it is not inverse positive, then the solution set for this will be unbounded. In this case, Kher [17] has assumed prior information about the noise covariance matrix (such as its upper/lower bound) for obtaining a bounded solution set. The use of such prior information also enables us to obtain a tighter parameter range for the NVM.

Finally, an example is presented using real data to identify a water demand model for the city of Tucson, Arizona. The solutions obtained by the proposed NVM approach are compared with the results when noise is not considered in the independent variables. Results are presented to demonstrate the usefulness and practical applicability of the proposed procedures.

Conclusions and Recommendations

Identification of demand models for water resources systems planning is the focus of this paper. A modeling procedure is presented which explicitly considers noise in all of the variables included in a chosen demand model.

A first-order lag dynamic noise-in-variable model (NVM) is formulated. This formulation attempts to identify a "true" relationship between the inputs and the outputs of the system. The procedure is such that we obtain both the model parameters and the noise variances from the known data statistic (i.e., data covariance matrix of all the variables) and some given behavioral relations. A mathematical programming solution procedure is developed in such a way that the original linear identification problem is transformed into a nonlinear programming problem. This procedure identifies a bounded solution set for a single linear demand model by making use of prior information about the noise covariance matrix. It should be noted that in the NVM, a range for each model parameter is obtained rather than a unique point estimate as obtained by classical estimation procedures. This implies that the "true" solution to a noisy identification problem lies within the convex polygon formed by the elementary regression vectors (ERV) of the data covariance matrix (Σ). In other words, any point within the range of each model parameter is a possible solution. At this point, it is necessary to point out that the range of each model parameter is also not unique because the bounds on each model parameter can vary with different lengths of data sets. Therefore, the selection of a proper data set also becomes an important factor.

These procedures are implemented to develop a water demand model or a "family of models" for the city of Tucson. These models are based on different combinations of variables, different lengths of data, and whether the model is static or dynamic. The variables used in these models are: water demand, income of a family, price of water, rainfall, temperature, and effective evapotranspiration.

In the first step of this procedure, all the possible models are analyzed, assuming that the data set is noise-free. This analysis gives ordinary least squares estimates and other statistical results. The second step consists of identifying a "family of models" for the given example by assuming that the data set is noisy. The "family of models" obtained by the model WTR is identified for the city of Tucson for the given data set. In this case, the data covariance matrix is inverse positive and hence the solution set is bounded. The tighter range for each model parameter is obtained by assuming that the variables income, price, and temperature have noise (e.g., ± measurement error) equal to 25, 15, and 20 percent, respectively. The identified model, once used for forecasting, will give us a range (a minimum and a maximum bound) where the future demand is expected to lie.

The mathematical programming-based solution procedure is found to be computationally efficient and fast. Another advantage of this proposed approach is that any dimensional problem can be addressed for the identification of a model for which real data are available. Some of the problems which are faced in this study are: (1) the model parameters are optimized individually and not simultaneously, thereby causing the problem of obtaining an optimum solution in a real sense for the noise-parameter space; (2) the assumption of an upper bound on the noise covariance matrix is quite significant for obtaining a bounded solution set; and (3) the selection of a proper length of data set is also important for obtaining the solution.

In this paper, several aspects of demand modeling are discussed in the context of noisy data. However, some work is underway to improve the decision-making proceses. With further improvements in the above items, the NVM approach to demand forecasting should be seriously considered as a tool in water resources systems planning.

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II.5. ON OPTIMAL PUMPING POLICIES FOR GROUND WATER MANAGEMENT

TOSHIO ODANAKA

Abstract

This paper is concerned with the optimal allocation over time of the resources which are in supply and are only partially renewable at a given point in time. A functional equation is obtained from a dynamic programming formulation of the problem. This functional equation is used to derive an optimal decision rule for resource use as a function of current supply. The results are applied to groundwater storage control separately and conjunctively. They are then tested empirically by comparison with a decision rule obtained by a detailed numerical method. A more general problem is next discussed. Finally, we solve a continuous version of the model in complete detail. The advantage of having a complete solution to the problem is that it is possible to determine turnpike horizon policies and to develop a practical method for ground water system operation. The stochastic case is also discussed.

Introduction

Water management, under conditions of uncertain supply and controlled demand, may be viewed as an inventory problem. The objective is to control the demand (withdrawal) in such a way that the expected value of net benefits at present value is maximized. This inventory control is of extreme importance for ground water systems management because its quantity in storage is often large in relation to the annual use rate. The inventory problem is similar to the models of surface reservoirs systems.

The supply of water which is available for possible capture is a random variable and thus the solution of the inventory problem requires an estimate of the probability distribution for this water supply. It is assumed that the probability distribution is known or that a good estimate is available from sources such as time series data.

The origin of the sequential decision model used dates back to Massé [1]. Some of the early pioneering works in the theory of inventory control of interest are those by Arrow et al. [2]. Bellman [1957] generalized the concepts of sequential decision processes and coined the term dynamic programming [3]. Odanaka studied the multistage inventory control problem using the technique of dynamic programming [4]. One of the first applications of modern sequential decision theory to water storage problems was, however, by Little [4].

In our study, the simplest water management problem is first considered; that is, the case of only underground water storage. A mathematical model is constructed which permits maximization of present value of expected net benefits for any length of planning horizon, under specified physical conditions of recharge, storage capacity, etc. (See O.R. Burt [6] for example).

The case of two storage facilities is next considered; that is, a single surface reservoir and one underground reservoir. The mathematical model formulated as a basis for quantitative analysis of this situation can be quite complex. The need for some simplification is correctly recognized by Buras and Hall [7]. Some approximation procedures are suggested. Most of the analysis will be readily understandable by first considering the single storage facility as background.

In the case of two storage facilities, we want to give a completely rigorous mathematical analysis to support our development. A functional equation is obtained from a dynamic programming formulation of the problem. This functional equation is used to derive an optimal decision rule for resource use as a function of current supply. The results are applied to ground water and surface reservoir storage control and then tested empirically by comparison with a decision rule obtained via some detailed numerical methods.

Finally, we solve in complete detail a continuous version of the model. The advantage of having a complete solution to the problem is that it is possible to determine turnpike horizon points or policies and to develop a practical ground water management protocol system.

Discussion

At first, using techniques of dynamic programming, the sequence of optimal policies is determined in terms of these expected future utilities. First the policy for the ground water, then the optimal policies for the surface and the ground water, can be determined. The advantage of using dynamic programming is that the structure of the optimal policy is understood. That is, in place of determining the optimal sequence of decisions from some fixed state of the system, we wish to determine the optimal decision to be made at any state of the system.

Secondly, we solved a continuous version of the model in complete detail, using the nonlinear boundary value problem. One advantage of having a complete solution to the problem is that it is possible to determine turnpike horizon points. These correspond to zeros of the adjoint function, and have the property that if they are known exactly, then pumping plan which is optimal up to the next horizon point also forms parts of the overall optimal plan. A second advantage of having the complete solution available is that it is possible to develop a practical ground water system which intermingles a prediction procedure with the solution procedure so that a comparison between predicted and actual ground water levels can be made continuously. Whenever the discrepancy between these two becomes sufficiently large, the model suggests proper actions to be taken.

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PART THREE

MULTIOBJECTIVE-MULTIPURPOSE WATER RESOURCE SYSTEMS

PART III: MULTIOBJECTIVE-MULTIPUPOSE WATER RESOURCE SYSTEMS

III.1 MULTI-OBJECTIVE DYNAMIC PROGRAMMING IN WATER RESOURCES

GEORGE W. TAUXE

Abstract

While Dynamic Programming is generally construed to be a single objective process, the introduction of additional state variables transforms it into a powerful multi-objective optimization technique. The beauty of this method is its capability to develop the entire pareto optimal set with just one pass. In this paper two applications will be presented. The first deals with continuous functions and the second deals with a discretized reservoir problem.

Introduction

Dynamic Programming is classically thought to be a single objective optimization technique, and as a result has only seen limited application to multiobjective problems. This paper describes Multiobjective Dynamic Programming (MODP) and then presents two applications: the first to a three objective problem with continuous functions after Reid and Vemuri [1,2] and the second a two objective reservoir problem [3] which must be discretized to solve.

One of the attractive features of Multiobjective Dynamic Programming is its capability of generating the non-inferior solution set as well as trade-off ratios between all objectives. Furthermore, once one of the non-inferior solutions has been selected by a decision maker, the entire policy that provided those levels of the objectives can easily be found using a traceback.

Let the multiobjective problem be defined to be

$$\min \{f_1 (X), f_2 (X), \ldots, f_i (X), \ldots, f_n (X)\} \tag{1}$$

subject to

$$g_k(X) \le \hat{G}_k \qquad k = 1, 2, \ldots, m$$

where X is an N-dimensional vector of decision variables; $f_i(X)$, i=1, 2,..., n, are n objective-functions and $g_k(X)$, k=1, 2, ..., m, are m constraint functions, where G_k is the limiting resource, and all functions may be non-linear in X. Problems of this form are abundant in the literature [4,5,6] with many approaches to solutions presented.

The MODP approach can best be characterized as being of the constraint approach where all but one of the objectives are treated as constraints. Thus the problem becomes

$$\min f_1(X) \tag{2}$$

subject to

$$f_1(X) \leq \epsilon_i \qquad i = 2, 3, \ldots, n$$

$$g_k(X) \leq G_k \qquad k = 1, 2, \ldots, m$$

where ϵ_1 are acceptable target levels of the n-1 objectives. These target levels must then be parametrically varied, each change necessitating a complete solution to (2), in order to find the non-inferior solution set. Insight into the problem as well as interaction with a decision maker can reduce the number of times that a complete solution to (2) need be obtained. One such method is the Surrogate Worth Trade-Off Method (SWT) [7,8].

The SWT method basically entails finding several solutions to (2), usually with the aid of a digital computer, and from these solutions the trade-off ratios, (essentially LaGrange Multipliers between objectives) are determined. Next a decision maker is presented with this information in order to articulate preferences. Next, more computer solutions are obtained to (2) with different ϵ_i reflecting the decisionmaker's performances and the process is repeated with the decision maker until he is no longer able to find a more preferred solution.

MODP has two distinct advantages over most techniques that are used to solve problems formulated using the constraint approach. First, the entire non-inferior solution set is obtained in one computer run, and second, the trade-off ratios are a by product of the MODP solution. Thus, a method, such as the SWT can be applied without having to return repeatedly to a computer for more updated information.

Multiobjective Dynamic Programming has the same properties as conventional Dynamic Programming, [9] regarding separability, convexity and continuity. It is, however, slightly more restrictive on the properties of the objective functions that are transformed into the constraint form. It is more difficult to treat min-max objectives as constraints and thus if one of the objectives is of this form, it should be selected as f_1. Functions must be monotonic and generally additive. These restrictions are not considered a serious limitation in the water resources field as objectives of such form are common.

Conclusions

Multi-Objective Dynamic Programming has been presented as a technique for quantitatively analyzing a variety of water resources problems involving non-commensurable objectives. The technique makes possible the analysis of objectives that may not be handled as easily or accurately with other optimization methods. In application, the MODP problem formulation is straightforward and the problem solution is computationally feasible. Although MODP adds one additional dimension to the state space for each additional secondary objective, it generally adds fewer decision variables than required by other techniques.

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III.2 OBJECTIVE-SPACE DYNAMIC PROGRAMMING APPROACH TO MULTIDIMENSIONAL PROBLEMS IN WATER RESOURCES

JOHN W. LABADIE and DARRELL G. FONTANE

Abstract

The "curse of dimensionality" continues to represent the greatest obstacle to full application of dynamic programming to complex sequential decision problems in water resources planning and management. A new approach to solving high dimensional problems is presented which conditions solutions on the one-dimensional objective-space rather than the high dimensional state-space. Sufficient conditions for global optimality are presented which are based on certain uniqueness requirements in the optimization. Aside from specification of the countability of the finite subset of decision variables, no other assumptions on problem structure or functional characteristics are necessary, including differentiability, convexity, or even continuity. Case studies in optimal reservoir operations and irrigation scheduling are presented to demonstrate successful application of objective-space dynamic programming to problems involving up to a 30-dimensional state-space.

Introduction

Dynamic programming is a powerful and versatile tool for solving a wide range of sequential decision problems in water resources. The technical literature abounds in an enormous variety of applications of discrete dynamic programming to water resource systems planning, design and operations. Labadie [1] has compiled several applications with emphasis on water resources management and Yakowitz [2] has summarized a large number of studies which demonstrate the flexibility and robustness of dynamc programming in attacking highly diverse problems.

The popularity of dynamic programming arises from a number of important advantages that it holds over many other mathematical programming techniques. These include: (i) efficient enumeration for sequential decision problems defined over discrete or integral decision sets; (ii) modest (approximately linear) increase in computational effort as a function of the number of stages in the problem, while most other methods display a geometric increase; (iii) attainment of globally optimal solutions (in a discrete sense) in the presence of functionally nonlinearity, nonconvexity, and even discontinuity; (iv) exploitation of state-space and policy or decision-space constraints as a means of actually alleviating the computational burden rather than aggravating it as in their optimization methods; (v) provision of flexible feedback or closed-loop decision policies as a byproduct of the recursive calculations, whereas most other methods produce open loop policies only; (vi) particular facility with stochastic optimization problems and direct inclusion of conditional risk constraints in the optimization problem (Sniedovich [3]). The reader is referred to Dreyfus and Law [4] and Cooper and Cooper [5] for more complete discussion of the characteristics and advantages of discrete dynamic programming.

In spite of these advantages, the "curse of dimensionality," Bellman [6] continues to be the primary obstacle to full application of dynamic programming to realistic problem formulations in water resources. The computer storage and processing requirements of dynamic programming increase dramatically with the state-space dimension, where problems in excess of three state variables are normally considered computationally infeasible. These difficulties have been encountered by a number of researchers involved in solving large dimensional dynamic programming problems in water resources such as Cohen [7], Pereira and Pinto [8], and Grygier and Stedinger [9].

A number of techniques have been proposed for ameliorating the dimensionality problems associated with dynamic programming. A compendium of these methodologies provided by Morin [10] is still an excellent reference source, and includes technologies such as:

1. fathoming
2. reaching procedures
3. approximation techniques
4. nearest neighbor techniques

A variety of other methods have also been employed for circumventing the dimensionality problem, such as use of Lagrange multipliers [see Rossman [11] for joint application of generalized duality theory and dynamic programmming in water resources], state-space decomposition methods, minimum state representations, and efficient data management structures. Morin and Esogbue [12] developed a method for solving a particular class of large dimensional dynamic programming problems where the objective function is composed of step functions. They prove that in this case, the dynamic programming optimal value or return function will also be a discontinuous step function. Identification of the points of disscontinuity enables a drastic reduction in the number of points that need to be evaluated in the state-space. This approach appears to be particularly well-suited to large-scale capacity expansion problems in water resources.

The major difficulty with popular methods employed thus far is that they are either still quite sensitive to the dimensionality problem, although not to as great an extent, or rely heavily on heuristics and exploitation of special problem structures. The danger in the various approximation methods is that the original problem is not really being solved, but rather one which is approximate to it in varying degrees of accuracy.

Labadie, et al. [13] developed a new category of techniques for solving high dimensional dynamic programming problems that condition optimal solutions on the one dimensional objective-space rather than the multi-dimensional state-space. In this approach, a one dimensional dynamic programming formulation in objective-space replaces a high dimensional dynamic programming problem involving the usual discretization of the state-space. Cooper [14] developed a techniques which uses objective-space concepts which is applicable to a certain class of multidimensional resource allocation problems. The method is referred to as a "hypersurface search technique" which, for maximization problems, involves stage-wise selection of discrete, initally infasible objective values which converge non-monotonically from above to the greatest feasible lower bound in a finite number of steps. Tauxe, et al. [15] have also employed objective-space concepts in dynamic programming for solving multiobjective problems in water resources, but have conditioned solution on the state-space as well. This, unfortunately, results in further intensification of the dimensionality problem. Becker and Yeh [16] employed a technique similar in concept to objective-space dynamic programming, but further comparative studies by Grygier and Stedinger [9] have shown that this method results in suboptimal solutions.

Sufficient conditions for global optimality of objective-space dynamic programming solutions are presented. These conditions are based only on certain uniqueness requirements which are believed to be applicable to a large class of multidimensional problems in water resources. No other assumptions about problem structure are necessary. However, without the uniqueness requirements, optimality cannot be guaranteed. The applicability of objective-space dynamic programming is demonstrated through two case studies involving complex problems in reservoir operations for water quality management and irrigation scheduling. In spite of these applications being characterized by high dimensional state-spaces involving up to 30 state variables, they have been successfully solved with this approach.

Results

A Lagrange multiplier was added to irrigation cost in increments of 0, 4, 10, and 20 $/ha-cm in order to reflect what were defined, respectively, as unlimited, slight, moderate, and severe limitations on total seasonal water availability. The final results of the objective-space optimization to show the tradeoff between total amount of water used and the total net return resulting from the various Lagrange multiplier values is presented (Figure 8.). In addition, one run was made with the objective of maximizing crop grain yield only with no economic considerations or water limitations. It can be seen that the maximum yield case required 45% more water than the maximum net return case under no water limitation, with the latter providing slightly more net return. These results imply that the typical farm objectives of maximizing crop yield may actually be giving the farmer less net return while placing heavy pressure on existing water supplies.

Table I gives the optimal open-loop decision policies for the two extreme water supply scenarios. As alluded to previously, it is possible to obtain limited feedback decision policies conditioned on the system state using the objective-space approach, but such policies were not derived for this study. It is difficult to ascertain a consistent pattern in the optimal policies. This suggests that it might be best to implement the objective-space dynamic programming model on a microcomputer for daily or weekly runs in the field in order to respond to sporadic rainfall events and highly variable evapotranspiration conditions.

TABLE I. Optimal management decisions for the two extreme seasonal water supply scenarios, 10 day stages starting June 1. (Martin et al. [18])

	Depth per Application, cm		Allowable Depletion, %		Irrigation Policy	
Stage Limit	No Limit	Severe Limit	No Limit	Severe Limit	No Limit	Severe
1						
2	3	2	40	50	1	1
3		3		50		2
4						
5	2	2	60	60	3	2
6	2	2	40	70	3	2
7	3		60		2	
8	3		50		1	
9	3		60		3	
10						

An indication of how the model would allocate water between the various irrigated areas under the center pivot is presented (Figure 9). A critical examination of that Figure shows that the model turns off the end run completely during conditions of severe water limitation.

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PART FOUR

LARGE SCALE WATER SYSTEMS: MODELING AND SOLUTION APPROACHES

PART IV. LARGE SCALE WATER SYSTEMS: MODELING AND SOLUTION APPROACHES

IV.1. KNOWLEDGE BASED DYNAMIC PROGRAMMING FOR WATER RESOURCES MANAGEMENT

OSMAN COSKUNOGLU

Abstract

Conventional optimization models become inapplicable to those problems that lack structure. A problem may become unstructured either because of the ambiguity in the goal structure, or because of the incomplete (or analytically untractable) knowledge on cause/effect relationships. However, the human problem solving process, albeit limited, can still accomplish results in unstructured problem situations. This observation can partially be ascribed to the richness of the individual's procedural as well as substantive knowledge within the problem domain. Integrating such a knowledge base into optimization models also improves their effectiveness. This assertion is demonstrated for dynamic programming in the context of water resources management. A declarative form of knowledge representation using first order predicate logic is proposed as an effective way of encapsulating technical knowledge and qualitative constraints. The programming language PROLOG permits such a representation to be executed directly. The resulting knowledge-base can then be integrated with a dynamic programming procedure, whereas the latter might have been coded in a computationally efficient code like Pascal.

Introduction

One of the earliest application areas for the dynamic programming (DP) approach is the water resources management field [1]. For over a quarter century, the field has remained a popular application are for mathematical optimization techniques, including DP. New algorithms, formulations, and computer implementations have flourished. The impedus of these efforts has been threefold; it has served to: improve the efficiency of solution algorithms, enhance the relevance of the models through refined formulations, and boost the appeal to users by developing friendly and interactive computer interface systems.

The purpose of this paper is along a somewhat different line. The emphasis is on increasing the effectiveness of DP as an optimization approach; that is, increasing the range of decision problems in the water resources fields for which DP can successfully be implemented.

When and why do mathematical decision models fail to live up to their purpose of aiding human decision-making processes? The Operations Research/Management Science (OR/MS) literature [2,3], as well as water resources literature [4], provide answers for the "when" part of the question more conclusively than the "why" portion. Mathematical models are successfully utilized when the decision problem is a structured one; that is, when the objective, the data, and the constraints can be prespecified unambiguously. The utility of such models diminishes when the problem becomes unstructured. In latter cases, however, human beings can still achieve results without using formal models. In understanding the reasons behind this simple, yet crucial, observation, the OR/MS or water resources literature provides little guidance other than some ill-defined human traits, such as experience, intuition, gut feeling, hunch, and so forth.

It is the thesis of this paper that knowledge is the major power source of human problem-solving and decision-making activities. Conventional mathematical optimization techniques, reflect the structured and orderly domain for which they were developed. For a given input there is a single and fixed computational path which produces an output. In contrast, human beings are equipped with an armory of overlapping techniques, hence computatational paths, for handling a problem. If an individual forgets one technique or finds a technique unsatisfactory, s/he can still strive towards a satisfying solution, albeit non-optimal. The richness, pertinence, and redundancy of the knowledge possessed by humans seems to be one important reason behind their effectiveness (not necessarily effeciency or optimality) in achieving results when analytical methods fail.

The foregoing conclusion was recognized in the Artificial Intelligence (AI) arena during the late 1960's. Earlier, the focus of AI researchers was exclusively on search techniques in their quest for developing intelligent programs that can be used for general purpose as well as being powerful. Later, these general problem-solvers were recognized as being too weak for use as the basis for building high-performance systems. Instead, programs with rich domain-specific knowledge, even in poor in method, proved to be more powerful in problem solving [5].

In a similar vein, the main thrust of this paper is to investigate the role of knowledge in optimization models. Specifically, the following question is investigated: Is it possible to increase the effectiveness, hence, the range of application of dynamic programming (DP) in water resources management by integrating this approach with a domain-specific knowledge base?

Concluding Remarks

This paper dealt in general with a number of issues evolving around the decision-making process and the role of decision models. More specifically, the main focus was on improving the effectiveness of dynamic programming, as a problem solving approach, in the domain of water resources management problems.

One issue that has gained much attention recently is the role of human cognitive aspects in decision-making, and its implications to decision modeling. On the one hand, it has been shown that individuals are seriously flawed in their decision-making activities, on the other hand it is well known that individuals can handle problems that are prohibitively complex for computerized models. This human vs. model dichotomy, however, is superficial. This paper's position is that a model's effectiveness can be enhanced through incorporating the knowledge (whether heuristic or factual) of the managers in the problem domain. Such an endeavor can also ease the tension between the models and users. It is often stated that the latter's objections to models include two claims: "models are too complex to be useful" and "models are not useful because they exclude many important factors." These ostensibly contradictory arguments are actually very revealing. The hypothesis of this paper is that the analyst developing models and algorithms may utilize his or her procedural knowledge to the limits in excruciating details while leaving out the substantive (descriptive) knowledge of the manager operating within the problem domain.

In addition to developing a symbiosis between the human problem solver and the model, incorporating knowledge into the latter renders the model more effective. That is, many problems which lack the analytical structure that is requisite for the mathematical models, can effectively be handled by a knowledge augmented model. Furthermore, coding the knowledge in a declarative form, independent from the procedural aspects of the model, can alleviate inflexibility and opaqueness of the models. Relatively flexible structure of a dynamic programming formulation appears to more readily allow knowledge-model integration. These arguments are further demonstrated in a forthcoming paper which also includes a specific application of knowledge-base (in PROLOG) augmented dynamic programming (in Pascal) to a replacement problem.

In the water resources area, the past construction era has been replaced, at least in the U.S.A., by the current management era. Consequently, an increased focus on optimizing the operation of existing projects to meet increasing demands can be expected. Significance of developing knowledge-based systems to this end has already been recognized [32]. This paper attempts to put the knowledge-based optimization models to the research agenda.

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IV.2 DYNAMIC PROGRAMMING AND NON-SEPARABLE WATER RESOURCES PROBLEMS

MOSHE SNIEDOVICH

Abstract

A solution strategy designed for certain types of non-separable dynamic programming problems is proposed. The strategy is demonstrated through its treatment of a water resources problem which in terms of a dynamic programming formulation is rendered non-separable due to economies of scale factors. The merit of the proposed strategy is in its ability to deal effectively with problem formulations that faithfully depict those real-world features that are behind the non-separability of the objective function.

Introduction

In an extensive survey of dynamic programming applications in water resources, Yakowitz [1, p. 673] pointed out the following:

> " An unmistakable conclusion is that water resources problems serve as an excellent impetus and laboratory for dynamic programming developments; conversely, progress in making dynamic programming applications in water resources economically viable depends on further advances in theoretical and numerical aspects of dynamic programming. At the present time the influence of dynamic programming on water resource practice is modest. Attempts will be made in this survey to point out where further mathematical modelling efforts are needed...".

Not surprisingly, one of the issues singled out by him in this connection, obviously, on account of its far-reaching implications for the application of dynamic programming techniques in water resources management, was the Curse of Dimensionality. Yet, for all the advances in computational methods since the survey's publication, not a single breakthrough has been achieved on this front to unfetter dynamic programming applications from the Curse of Dimensionality.

Indeed, the Curse of Dimensionality remains the irksome sore point it has always been in dynamic programming, thus continuing to present the single most serious impediment to the use of dynamic programming in the solution of real-world problems, water resources problems included.

Therefore, it is our objective in this paper to examine, in detail, one of the manifestations of the Curse of Dimensionality's hampering a conventional use of dynamic programming, and to propose an alternative solution strategy for problems thus affected. And to be precise, we want to show how problems whose non-separable objective functions make them potential prey to the Curse of Dimensionality, can be handled effectively by a strategy fusing dynamic programming and c-programming techniques.

Our discussions therefore proceeds as follows. We begin with a definition of a prototype dynamic programming problem and show that in cases where the pertinent objective function is rendered non-separable, the problem in question threattens to fall victim to the Curse of Dimensionality. We then go on to describe in very broad terms the sort of tactics that can be deployed in such situations to counteract the difficulties brought on by the non-separability of the objective function. This leads to an outlining of the c-programming method ([2]-[6]) where we sketch its essential ingredients and explain the position that it takes vis-a-vis difficult optimization problems such as the above. Following that, we consider a prototype separable c-programming problem and we identify the stock elements required for the design of algorithms for problems of this type. We then take up again the non-separable dynamic programming problem defined at the outset and we discuss some of the issues bearing on the use of c-programming techniques in the solution of problems of this format. We end with a numeric example involving a problem that economies of scale factors render non-separable and we demonstrate how a c-programming algorithm assists in its solution.

Summary

We have shown that c-programming offers the very machinery required to handle certain types of problems whose objective functions are rendered non-separable under the terms of a standard dynamic programming formulation. Considering how often in the analysis of real-world water resources problems the analyst encounters objective functions of this type, c-programming techniques clearly provide the analyst with a potent tool. Particularly because they invite a formulation that remains true to the real-world attributes of water resources problems.

Although it is somewhat premature at this stage to pass final judgement on the efficiency of c-programming algorithms, preliminary experiments indicate that they perform surprisingly well, especially in cases where the decision space is discrete. This is perhaps due to the fact that these algorithms operate essentially on the extreme points of the convex hull of u(X). Whatever the case, it should prove interesting to examine whether the performance of these algorithms can be further enhanced by allowing them to exploit, in any given case, the peculiar features of the decision space and the objective funciton in quesiton.

And finally, by its very nature c-programming has the ability to join forces with any optimization method capable of handling its parametric problem. Owing to its vulnerability to the Curse of Dimensionality, dynamic programming seems to be a prime candidate for the collaboration with c-programming.

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IV.3. CLOSED-LOOP CONTROL, BALANCING, AND MODEL REDUCTION OF LARGE SCALE WATER RESOURCE SYSTEMS

JOSE A. RAMOS

Abstract

A new approach for dimensionally reducing large water resource systems is presented. The approach is based on the concepts of closed-loop balancing and linear-quadratic-gaussian (LQG) methodology. We start by solving a general, discrete-time, LQG optimal control problem via dynamic programming. Its solution, by virtue of the separation principle, yields a pair of Riccati equations, one for the deterministic controller and the other for the stochastic observer. By transforming this pair of equations to a new coordinate system where costs and uncertainties of individual state components are matched, a balanced model is obtained. Then by deleting the state components that are least uncertain and at the same time contribute least to the cost function, one obtains the reduced-order model. The derivations are carried out for a typical multireservoir system operating under flood conditions.

Introduction

Dynamic programming (DP) has long been recognized as a powerful optimization tool for solving a large class of sequential decision problems encountered in water resources. The literature on DP applications to water resources problems is quite extensive and has recently been surveyed by Yakowitz [1]. Other survey articles of relevant interest are given in Ramos and Rao [2] and Yeh [3]. Much of the research on DP has concentrated on developing computationally efficient algorithms to overcome the "curse of dimensionality" a computational barrier often found in multidimensional problems (see Morin [4] for an exposition on computational advances in DP). This, however, is not a criticism of DP but often a result of difficulties inherent in the problem at hand. Nevertheless, efficient algorithms have been developed and successfully applied to a gamut of problems in water resources.

In multireservoir operation studies, for instance, the aim has been placed at finding optimal operating rules for reservoir systems arranged in arbitrary topological order, while satisfying various system, demand and operating constraints at minimum operating costs. In general, this problem can be formulated at a nonlinear stochastic optimal control problem where the stochasticity comes from the unknown streamflows and demands. In addition, the temporal evolution of the system allows a natural stagewise decomposition of the problem, which makes DP a very attractive solution strategy.

Most reservoir operation studies in the past have dealt with the problem of specifying contract levels and prices for planning the long-term operation of the system. Short-term operation, on the other hand, makes use of the latest hydrologic information about the system in order to implement decisions in real-time. Such is the case for systems operating under flood conditions, where latest weather and streamflow forecasts are instrumental in determining the immediate releases from the reservoirs. Recent studies have shown that the use of hydrologic information in real-time can improve reservoir operating policies (Becker and Yeh [5]; Bras et al. [6]; Stedinger et al. [7]; Houck [8]). However, in going from long to short-term operation, the system is more dependent on its initial conditions and on the dynamics of the hydrologic processes driving the system. Necessarily then, for the real-time short-term reservoir operation problem, the DP model has to account for these process dynamics by augmenting the state-spce (Wasimi and Kitanidis [9]). The solution to this problem via stochastic dynamic programming (SDP) requires a great deal of computational effort and is, therefore, practically infeasible.

Recently, Wasimi and Kitanidis [9] have formulated the above problem as a linear-quadratic-Gaussian (LQG) optimal control problem. Here, the multi-reservoir system along with the driving hydrologic processes are represented by a <u>linear</u> state-space model driven by <u>Gaussian</u> noises and a performance criterion which is a <u>quadratic</u> function of the state and input vectors, hence, the acronym LQG. The advantage of using such approach is that the real-time short-term reservoir operation problem can be solved in closed-form. Moreover, the solution, by virtue of the separation principle (Athans [10]), is separated into a deterministic linear-quadratic (LQ) optimal control problem and a state estimation problem. The conditions under which this separation is possible for reservoir systems has been recently studied in Kidanidis [11].

The heart of the LQG problem is the solution to a pair of Riccati equations, one for the controller and the other for the estimator. However, with the increasing interest in microcomputer applications and the development of expert systems (Houck [8]), where computer storage is a constraint, the numerical solution to these equations can be computationally prohibitive for large scale systems. The solution then calls for an approximate or reduced-order model.

Reduced-order state-space models for streamflow forecasting have been recently studied by Goldstein and Larimore [12] and Wasimi and Kitanidis [9]. More recently, Ramos [13] recognized this estimation problem as a stochastic realization problem and gave directions for model reduction as well as general approaches for solution. However, the problem of simultaneously building reduced-order state estimators and controllers has not been studied in the water resources literature, although the concept is now well established in the control engineering literature (Verriest [14,15]; Jonckheere and Silverman [16]). This paper concentrates on deriving reduced-order LQG models for water resources applications. The ideas presented here are an extension from the works of Verriest [14,15] and Ramos [13].

In Section 2, the real-time short-term reservoir operation problem is formulated as a discrete-time LQG tracking problem via DP and the separation principle, which allows the solution to be implemented as a separate controller and a state estimator. Section 4 contains a brief description of the ideas behind closed-loop balancing and model reduction. Finally, in Section 5, the implications of reducing large scale water resource systems are discussed.

Discussion

The main objective of this paper has been the design of reduced-order models for short-term real-time control of large scale water resource systems. The material plays the role of a tutorial paper in the subject and should be useful to researchers in all areas of water resources where linear systems theory can be applied.

The computational effort required to implement current feedback control policies is almost proportional to the square of the state vector dimension. Thus, the application of existing design procedures to large scale water resource systems constitute an excessive burden, particularly from an implementation point-of-view. Resorting to reduced-order models, which are some form of model aggregation, will then lead to a great deal of flexibility in the design but at the expense of performing suboptimally. For a good approximation, however, the degree of suboptimality should be very small. It should be kept in mind however, that when dealing with physical systems, the balancing transformation and model reduction operation map the physical state vector into a coordinate system where the reduced state vector has no physical meaning. This bears no loss of generality since the control vector retains its physical properties. While the physical states, if needed, can be approximately recovered by applying the inverse balancing transformation. Ramos [13] has studied the forecasting aspects of reduced-order streamflow models, and found that for size reductions as large as 50%, the reduced-order models performed as good as the full-order models. The author is currently investigating the numerical implementation of reduced-order controllers, the results of whch will be reported elsewhere.

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PART FIVE

WATER QUALITY AND WASTE TREATMENT SYSTEMS

PART V: WATER QUALITY AND WASTE TREATMENT SYSTEMS

V.I. IMPROVING WATER QUALITY BY OPTIMAL AERATION CONTROL VIA DYNAMIC PROGRAMMING

HIROSHI SUGIYAMA

Abstract

The problem of improving water quality via aeration control at certain fixed points of a slow river stream is addressed in this paper. The biochemical oxygen demand (BOD) and dissolved oxygen (DO) at time t are denoted by B(t) and D(t) respectively and we consider (B(t),D(t)) as the system state. Criterion function J(u) is defined by an integral over a specified time interval, where the integrand is weighted sum of squares of B(t), DO deficit, and control u(t). By minimizing J(u) via dynamic programming (DP) subject to a set of differential equations relating the system state and control u(t), we wish to obtain the optimal aeration control u*(t) numerically, starting from a specified state (B(o)<D(o)). By the mathematical formulation stated above, we are able to achieve objectives of decreasing BOD level and increasing DO level simultaneously, taking aeration cost into our account. In order to solve this problem in a feasible way, we discretized our process allowing t to take on discrete values 0, Δ, 2Δ, ... Then, replacing u(t) by $u_0, u_1, u_2, \ldots$ and solving our differential equations successively by step-by-step method, our discretized DP formulation is set up for minimizing the value of discretized criterion function J_n corresponding to the criterion functional J(u). An efficient and feasible policy is devised for solving these DP equations and practical solution algorithm is obtained. Thus computations required can be readily performed even via hand held programmable calculators. Finally, application of Box's hill-climbing method is first exemplified in our simple examples for obtaining approximate minimum value of our DP return functions fairly accurately, reducing the dimension of DP computations effectively. The author considers that all the methods proposed in this paper are viable and conducive to our practical purposes.

Discussions and Conclusions

It is certain that there are a number of ways of computing the values of $f_n(B(o),D(o))$, together with the incidental aeration control rates $\{u_i^*\}$(i = 0,1,2,....,n), for the larger n, combining the values of $f_2(\ldots)$, $f_3(\ldots)$, $f_4(\ldots)$, ..., i.e. the values of $f_n(C_1,C_2)$ for the smaller n, easily obtainable by the methods we have shown in this paper, using many ways of recurrence relationships due to the principle of optimality of dynamic-programming. We believe that in general a dynamic programming formulation can usually be developed but its numerical solution is difficult. The usual problem is the one frequently articulated as the curse of dimensionalty - a problem which occurs even with a large scale computing machinery. But, in this paper, the author devised feasible solving scheme free from the curse of dimensionality and yet extremely efficient for practical purposes. This is particularly the case with the optimal aeration problem treated in this paper.

Dr. Richard Bellman emphasized, throughout his life, the increasing importance of using the large scale of digital computers in solving dynamic programming problems numerically. After his epochmaking discovery of the principal of optimality, he thought of storing numerical values of return functions at a considerable number of discretized grid points in order to find out the optimal path, i.e. the maximum or the minimum values of return functions at the various stages. We consider it important to solve dynamic programming problems in a practical way, even by approximate solutions, by minicomputers, or even by programmable hand held computers like HP 67 used in this paper.

The form of our criterion functional was quadratic. This fact was the incentive of overcoming the difficulties by our approaches discussed above.

Our feasible solutions, which might be called "suboptimal solutions" to our dynamic programming formulation, turned out to be very efficient, considering the numerical examples shown in this paper.

As mentioned in the foregoing sections, DP solutions are very useful for setting the aeration rates at the beginning stages of aeration control to start with, based upon the results of $f_2(10,3)$, or $f_3(10,3)$. Though, these aeration rates seem would otherwise be difficult to assume intuitively.

As Dr. Richard Bellman stressed in his paper [1], "most functionals are fairly flat" in nature learning from many years of Rayleigh-Ritz-Galerkin methods, and thus, the author considers that the subsequent aeration rates are not required to be so precise.

Based on our experiences it is not necessary to compute $f_n(10,3)$ for large n, say $f_{20}(10,3)$ as well as the associated aeration rates $\{u_i^*\}$, i = 0, 1, 2, ...,19, for instance.

Dr. Bellman emphasized the future importance of applying the methods of stochastic approximation for facilitating the computation of solutions to dynamic programming problems. We have shown and suggested the usefulness of hillclimbing method due to G.E.P. Box in this paper for computing numerical solutions to the optimal control problems formulated via dynamic programming.

We emphasized the usefulness and the importance of applying the Kiefer-Wolfowitz stochastic approximation with added artificial noise for locating the global maximum or global minimum in our search region. Thus, we equally must emphasize the combined use of Box's type hillclimbing method and the above type of stochastic approximation methods to be more useful for the numerical computation of DP solutions, because of the slow convergence of stochastic approximation processes.

As described in Hullett's paper [2], the minimization problem of quadratic criterion functional subject to a set of differential equations is already solved.

This is an optimization problem in Hilbert space, and the optimal feedback control is known to be expressed by linear operator which is the solution of infinite dimensional Ricatti equation with certain terminal condition. In this context, the optimal control is already obtained, but on the contrary tremendous effort is required in order to obtain concrete numerical solutions for practical applications, starting from apparently simple expression of the optimal feedback control stated above.

Pontryagin's maximum (or, minimum) principles, the necessary conditions thereof, are also considered to be too mathematical and rather complex for practical applications, particularly for aeration control problems.

Thus, we feel that dynamic programming is the most practical and useful technique for our aeration control problems, because it is simple in its formulation and useful for our aeration control of water quality.

In this paper, we discussed aeration control approach for improving water quality based upon the number of parameter values specified precisely. In the actual situations however, such parameter values are not known in advance. We know that there exist no such precise values nor constant values for an actual river water, and thus, only rough estimates of parameter values are sufficient for the efficient water quality aeration control, since any mathematical methods of optimization offers us only good suggestions or ideas for practical purposes. Thus our "optimal solutions" must be robust for the set of parameter values.

Finally, it is most important for us to be aware of all the available technical strategies, local and global, for improving water quality if needed. One should thus not be confined to an aeration technique with introduced aerobiotic micro-organisms.

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V.2. A VARIABLE STATE-SPACE DYNAMIC PROGRAMMING MODEL FOR OPTIMIZING INDUSTRIAL WASTE TREATMENT SEQUENCES

J. H. ELLIS

Abstract

A stochastic methodology is described for identifying cost-effective treatment sequences for a centralized liquid industrial waste treatment facility. The dynamic programming (DP) optimization model delineates those sequences of unit treatment processes which will produce an acceptable effluent quality, given probabilistically-generated influent waste regimes. Considerable flexibility is embedded in the methodology through allowing user-determined options such as waste characterizations, unit processes for consideration, performance functions for the processes, probabilistic descriptions for the influent wastes, and others. From a DP viewpoint the model is somewhat atypical in that it possesses a state-space which varies by stage and furthermore the number of stages required in any given application is unknown a'priori.

Introduction

The design of centralized hazardous waste treatment systems can be improved through proper consideration of system uncertainties. Important elements of uncertainty are related to the prediction of influent waste flows and contaminant strengths which in turn impact on the sequencing of unit treatment processes. Additional uncertainty is associated with the assessment of treatment efficiencies of individual processes as functions of influent waste characteristics, (i.e., composition, strength and volume). Criteria to be used to select individual (unit) treatment processes and their sequencing for a centralized facility are far from obvious. Successful treatment can be accomplished thrugh the use of more or less conventional means of selecting processes and process sequences, but this may not yield an optimally cost-effective design [1]. Moreoever, optimization of individual process design does not guarantee optimality of the entire process sequence. These considerations become even more complicated if variability in influent waste strengths, compositions, volumes, etc., is addressed. Although the selection of optimal treatment sequences has been investigated previously (e.g., see [1], [2], [3], [4], [5]), the above-noted concerns remain unresolved.

The purpose of this paper is to develop a methodology for stochastic optimization of LIW treatment sequences which, in view of the previously-discussed design considerations, possesses the following attributes:

i) objective selection of unit treatment process sequences based on cost-effectiveness, for the purpose of generating least-cost configurations;

ii) variability in influent contaminant concentrations incorporated into the model through the use of probabilistic representations of waste strength, (as opposed to simply using expected-values); and,

iii) ability to accommodate the joint treatment of several waste streams with stream-specific compositions.

Conclusions

The stochastic optimization/simulation methodology is a useful tool for delineating least-cost liquid industrial waste treatment sequences. An important feature of the model is the characterization of influent contaminant concentrations by lognormal probability density functions, with influent waste streams generated by a Monte Carlo technique. Interdependencies between contaminants can be preserved in the generated influent realizations given estimates of their correlation structure.

Another important aspect of the methodology is automatic, objective evaluation and selection of extensive arrays of treatment sequences. The use of influent screens accomplishes this task through the creation of a stage-specific, variable state-space DP structure.

Depending upon application-specific boundary conditions and transition functions, the stochastic optimization exercise may yield acceptable final treatment configurations or alternatively, serve as a preliminary screening device. As a screening device, the optimization analyses identifying unit processes with desirable cost-effectiveness attributes. For this type of result, subsequent iterative analyses involving stochastic simulation are needed to generate acceptable treatment configurations.

Numerous opportunities exist for enhancing the utility of the methodology through more detailed, comprehensive representations of model input and certain critical model components. Of particular note is the fact that unit treatment process removal efficiencies are generally not constant, as was assumed in this study. The consideration of removal efficiency variation, perhaps as a function of waste strength and flow for example, represents a logical next step in this modelling approach. This extension of the methodology could then more realistically depict the fact that variation in removal efficiencies modifies the form of the original waste contaminant probability density functions.

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PART SIX

WATER SUPPLY AND DISTRIBUTION SYSTEMS

PART VI. WATER SUPPLY AND DISTRIBUTION SYSTEMS

VI.1 DYNAMIC PROGRAMMING FOR OPTIMIZED CONTROL OF WATER SUPPLY AND DISTRIBUTION SYSTEMS

B. COULBECK

Abstract

The article introduces the general problems of least cost control of water supply and distribution systems, and their solutions based on dynamic programming techniques. A description is given of the hydraulic operation of typical systems and components together with an evaluation of operating cost factors. The resulting mathematical formulation is then presented as a general dynamic optimization problem and forward dynamic programming solutions are developed for specific single reservoir systems. Simplifications are incorporated to cater for practical requirements and a resulting scheme is illustrated by evaluation of optimal schedules for an actual system. Finally, the solution methods are extended to cover compatible multireservoir systems.

Introduction

In common with executives of other public utilities, managers of water supply and distribution systems are now seeking to implement overall automatic control in order to achieve more efficient operation of systems of everincreasing complexities and costs. Existing technology has loog been capable of providing computerized hardware for measurements and control; however, computer software, in the form of program algorithms, is not in such an advanced state that effective on-line control can be achieved, and additional research is required in this area.

An an initial step towards improved control, many authorities are now completing installation of systems for computerized monitoring with limited control features. The current work forms part of continuing collaboration with various UK water authorities to devise and present computer algorithms suitable for on-line control of complete water distribution systems.

Of major importance in the control schemes is the concept of optimization of operation, which attempts to achieve lowest operating costs consistent with providing a satisfactory service to customers. It has been shown [1, 2, 3] that the project is very complex involving control of large-scale non-linear dynamic systems subject to unkwown disturbances.

The optimization methods must cater for high state and control dimensionality, with further complications of highly non-linear performance indices, and must incorporate both continuous and discrete controls.

Distribution networks consist of large numbers of interconnecting pipes with occasional control valves, both of which have a non-linear relationship between flow and head loss. Reservoirs are connected at strategic points throughout the network to provide storage capability and maintain required pressure levels. Individual consumer demands occur at distributed points throughout the network but, since there is usually minimal monitoring it may only be possible to estimate the total demand from measurements of pump flows and reservoir levels. In many regions boreholds are a typical source of water supply, with pumping to the network via pump stations using parallel combinations of fixed and variable speed pumps. Booster pumps, together with control valves, are normally used for transfer of water between reservoirs of differing pressure zones. In both cases the pump flows are influenced by the reservoir level and the resultant costs are dependent upon electricity unit and demand charges.

Since water networks contain storage, the optimization problem reduces to minimization of electricity and associated costs for the complete network over the entire control period. This requires the control of pumping and storage while catering for consumer demands and maintaining desired reservoir levels. Consequently the successful application of optimization methods depends significantly upon the formulation of simplified dynamic models for rapid and repeated evaluation of the effects of control strategies upon the network operation. In addition, a prediction scheme is required which will provide a forecast of consumer demands for the complete control period.

It is essential to ensure that theoretical developments are applicable to actual systems and meet all operational constraints. However, to avoid unnecessary experimental manipulation of operational systems, system analysis and initial validation of results must rely upon accurate simulation methods. In this article particular consideration is given to development of operation and costs in a suitable form for treatment by forward dynamic programming. This optimization technique is illustrated by application to one single reservoir supplied by fixed speed pumps and another single reservoir system supplied by a combination of fixed and variable speed pumps. For extension of the basic technique to cover multi-reservoir systems it is necessary to devise methods to alleviate the attendant dimensionality problems. Two restricted classes of multi-reservoir systems are considered with a solution for one case obtained using successive approximations [4] and a proposal for the other case using state increment dynamic programming [5].

Summary

Optimization of water distribution systems presents a very complex problem, when all operating factors have to be taken into account, and no entirely satisfactory solution methods are currently available. In order to determine possible solution techniques which will cater for some of the requirements, it is necessary to simplify the problem. By adopting a compromise between accuracy and feasibility, hydraulic and cost models can be formulated which are sufficiently representative for operational control purposes but which allow for optimization by efficient computational methods. These particular formulations have allowed development of two flexible computational modules for optimizing some typical one-dimensional water supply systems. Both the algorithms use dynamic programming techniques and one of them has been programmed for interactive use on a minicomputer. The validity of the results has been demonstrated by applying the generated least-cost pumping schedules to actual operating systems.

Additional simplifications are required for multidimensional systems which usually rely upon decomposition methods. For a parallel connected class of systems useful results can be obtained by structural decomposition, which leads to a dynamic source optimization problem and a static network control problem. Further decomposition, using the dynamic programming method of successive approximations, then allows each of the source supplies to be optimized using one of the previously developed computational modules. A series connected class of systems with continuous controls can take advantage of the computational efficiencies offered by state increment dynamic programming. This method extends the applicability of the corresponding one-dimensional module to series-connected multidimensional systems.

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VI.2. OPTIMAL DESIGN OF LARGE COMPLEX WATER RESOURCES CONVEYANCE SYSTEMS VIA NONSERIAL DYNAMIC PROGRAMMING

A. O. ESOGBUE and CHAE YOUNG LEE

Introduction

Water resources planning is a multi-faceted multi-staged, continuous process which occurs at several levels and in various locations. At the state, regional and even local levels the systems under consideration are more often than not large scale in nature. That is, planning whether for design, operation or maintenance relates to a system of units rather than a single unit. Thus, cost effectiveness considerations require the treatment of all systems units as a whole. In general, in such large scale systems, the number of variables and alternatives that must be considered forces the planner or analyst using classical approaches favored by practicing engineers to eliminate a large number of possible alternatives. This is done in order to focus on the few that are considered most promising. Only very few experienced engineers can use such a trial and error approach in combination with good judgement to produce cost-effective designs, most of the time, in the usual time and resource constrained design environment. The use of mathematically reliable models, especially those that can be automated has tended to minimize the problems inherent in traditional practices.

As documented in the literature, systems and optimization based approaches have become a useful tool of the modern design engineer [1], dynamic programming has become a very attractive modeling and design tool. However, because of the well known but perhaps somewhat exaggerated problem of dimensionality, its utility to the practicing engineer has been quite limited. Various authors and model developers have sought approaches to circumvent this problem. Unfortunately, the casualty is usually the problem. Oversimplification and sometimes sensible decomposition methods have been advocated. We have erstwhile postulated that these problems can only be eliminated or more realistically ameliorated when large computers of the super variety, efficient algorithms geared towards memory reduction, parallel computing and above all adroit problem formulation which ad initio requiers a minimal number of state variables are efficiently utilized to address a given problem. Some of the foregoing prerequisites are beginning to be made available to the systems designer.

Our principal contribution is in the area of modeling and computational technology, but specifically nonserial dynamic programming. The purpose is to show how a problem which naturally occurs as a nonserial system but which has hitherto been approximated as a classical serial dynamic program can be directly assaulted via nonserial dynamic programming. This approach naturally minimizes approximation errors and, ipso facto, increases accuracy of results. Most of all, it benefits from the global optimality characteristic of classical dynamic programming.

Discussion of Results

Now by applying the multi-converging branch algorithm developed in the paper via the functional equation at each stage) we optimize the system from manhole 1 though manhole 9 in the main stream. The optimal return of each branch is computed and combined to the main system at the corresponding junction manhole. Table 2 illustrates the computational results for the problem. At each stage, 11 discretizations were used for the input elevations of each pipe. The physical data and cost functions given in [2] were used to determine the optimal diameter and the slope of each sewer pipe. The optimal solution is obtained with the outlet elevation of the system to be at 435 feet. Due to the several different assumptions and constraints used, the upstream and downstream elevations of the pipes are slightly different from the solution given by Mays and Yen.

The computational complexity (both space and time complexity) of the two approaches, howevr, differed by more than 75%. The multi-converging branch algorithm required 19723 elementary operations with 11 discretizations of the state variables. See Esogbue and Warsi [3] for computational complexity analysis of converging branch systems. For comparative purposes, consider the discrete differential dynamic programming approach which uses 5 discretizations at each stage in each iteration. The recursive equations would require three additions and one comparison at each junction and two additions and one comparison at all other stages. The total number of operations results in 34925, an astronomically higher number than our nonserial dynamic programming approach. The computer time requirement of the two approaches were also examined. The multi-converging branch approach required a total processing time (compilation time + execution time) 20.5 CPU seconds (CYBER 855) while the discrete differential dynamic programming approach required 28.2 ~ 43.3 CPU seconds (IBM 360.75). The minimum cost solution indeed involved eleven iterations and a total processing time of 43.3 seconds for the DDDP approach while the inefficient DP approach took 113.7 seconds.

From the above results we conclude that the computational demands of the multi-converging branch algorithm is much less than the discrete differential dynamic programming approach, which is currently used in practice. Further, the computational superiority of our algorithm becomes more impressive when solving higher dimensional (more branches and nodes per branch and main chain) and more complex (the structure of convergence) systems. Finally, global optimality is assured in all cases and the application is not restricted to special cost functions nor specially structured hydraulic systems as in the discrete deterministic dynamic programming model.

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PART SEVEN

STOCHASTIC RESERVOIR OPERATION MODELS

PART VII: STOCHASTIC RESERVOIR OPERATION MODELS

VII.1. ACCURACY OF THE FIRST-ORDER APPROXIMATION TO THE STOCHASTIC OPTIMAL CONTROL OF RESERVOIRS

P. K. KITANIDIS and R. ANDRICEVIC

Abstract

Optimization of the operation of a multireservoir system may be formulated as a stochastic optimal control problem which can often be solved through stochastic dynamic programming. This paper describes the application of a new approximate method which can be used for the solution of problems with many state and control variables. The optimal solution is given by the solution of the deterministic feedback control plus a caution (or hedging) term. The caution term is analytically approximated by the leading term of an asymptotic expansion obtained by assuming that the variances of the random inputs are small. The developed approximation makes use of the first two statistical moments of the random inputs and of the first three derivatives of cost functions. Its computational requirements do not exhibit the exponential growth exhibited by discrete DP. It can be used as an approximate solution to problems for which it is not feasible to use classical discrete stochastic dynamic programming. The paper presents an evaluation of the method through Monte Carlo simulations. A comparison with the exact solution and with deterministic feedback control is very encouraging, showing that the new method gives near optimal results even when the "small-perturbation" assumption is only approximately met and that it is superior to deterministic feedback control.

Introduction

In a previous paper [1] a small-perturbation approximation was proposed for the solution of a class of explicit stochastic optimization (or stochastic optimal control) problems. The developed methodology was named First-Order Approximation (FOA). The approach decomposes the problem into two parts: In the first one the deterministic feedback solution is obtained and in the second one stochasticity is accounted for using analytical small-perturbation techniques.

The purpose of this paper is to illustrate the applicability and potential advantages of FOA in the stochastic optimal control of reservoir systems. FOA is compared through Monte Carlo simulations with the two most commonly used methods: deterministic feedback control (DFC), and discrete stochastic dynamic programming (DSDP). In the following section the problem is mathematically formulated and the recently proposed FOA method of calculating optimal controls is reviewed. Numerical examples and conclusions are given in the last three sections.

Discussion and Conclusions

The problem of optimizing the real-time operation of complex reservoir systems with uncertain inflows is very difficult and no practical general method of solution is currently available. The applicability of discrete stochastic dynamic programming is limited by the dimensionality curse to problems simpler than many cases of practical interest. As a result, methods which separate the stochastic optimization problem into a stochastic estimation and a deterministic optimization part are recently commanding much attention. First, the estimation problem is solved and then some of its results, such as the best predictions, are used as known inputs in deterministic optimization. There are, of course, systems for which estimation and control may be solved separately without loss of optimality. The best known representative of such systems, which are called certainty equivalent, is the class of LQG systems (Linear transition equation, Quadratic cost function, and Gaussian inputs).

In some of the most important problems of reservoir operation, however, it is not possible to neglect the interaction between estimation and optimization. These are cases for which there is significant need for "caution" or "hedging." First-order approximation is a new approximate method developed for the solution of some stochastic optimization problems for which caution is important. An important advantage of this method is that its analytical nature allows us to develop a better grasp of the essential features of caution-affected stochastic optimal control problem. Thus, it illustrates that the caution effect is conditional on the presence of forecasting uncertainty but also depends on system characteristics, such as the shape of cost functions and constraints.

This paper has presented the results of Monte Carlo simulations in which the performance of the first-order analysis was compared with the performance of deterministic feedback control (which assumes certainty equivalence) and, in one of the two cases, discrete stochastic dynamic programming. Attention was limited to two caution-affected stochastic optimization problems, one scalar and one multistage. The results illustrate the superiority of FOA, which accounts for caution albeit approximately, over the deterministic feedback solution which implicitly assumes certainty equivalence. This superiority is both in terms of average cost of operation and improved consistency in performance from one possible realization of inflows to another.

Comparison with the exact solution, closely approximated through stochastic dynamic programming with a very fine discretization grid, indicates that the analytical solution is nearly optimal for a wide range of the values of the variance of forecasting uncertainty. However, an advantage of the analytical solution is that its applicability is not limited to problems with few state variables. This has been illustrated by presenting a case with six state variables, a case beyond the range of applicability of conventional discrete stochastic dynamic programming. Thus, the analytical approach can be applied to problems of practical significance as an alternative to deterministic feedback control.

Although limited to two particular cases, the extensive Monte Carlo simulations presented in this paper confirm the usefulness of FOA analysis in obtaining near-optimal solutions to caution-affected stochastic optimal control problems. Thus, they illustrate the robustness of the small-perturbation approximation made in the derivation of the analytical solution. In fact, the most interesting results of this study may be that as the forecasting uncertainty increases, so does the superiority in performance of the first-order analysis solution over the deterministic feedback control.

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VII.2. A DUAL APPROACH TO STOCHASTIC DYNAMIC PROGRAMMING FOR RESERVOIR RELEASE SCHEDULING

E. G. READ

Abstract

In a mixed hydro thermal power system, optimal reservoir operating rules may be summarised by a set of "guidelines" which can be developed by a backwards recursion equivalent to conventional SDP. Because it uses a dual-based discretisation which directly reflects the structure of decision-making, this method is more accurate and yields significant insights. It will also be faster for problems with a sufficiently compact set of guidelines and has been used to develop a module which produces operating rules for twin reservoir problems with over a thousand stages, as part of a long term simulation package.

Introduction

Read and Boshier [1] describe an iterative technique based on marginalistic Stochastic Dynamic Programming (SDP) which has been used for some years now to optimise operating rules for New Zealand's hydro reservoirs over an annual time horizon. More recently Baker and Daellenbach [2] investigated long term coal stockpiling strategies, using a two reservoir SDP model to develop quarterly hydro reservoir operating rules over a 15 year time horizon, then simulating system operating using these.

A similar philosophy has been adoped for the much more detailed expansion planning model of [3], which simulates optimal management of up to 50 historical inflow sequences using a weekly time step over a 30 year horizon, assuming reservoir operating rules optimised by the model developed here. Since this simulation must reflect the way in which the system is really operated, strict accuracy may not be necessary and there is no point pursuing accuracy beyond that of current scheduling models. But it is important that the comparisons between plans are not distorted by the reservoir operating rules being better for one plan than another. Thus heuristic rules were discarded in favour of an optimisation which would automatically adjust to changes in the system. To be realistic the stochastic nature of the inflows must be modelled (see [1]), and the decision period should be no longer than one month. The power system is briefly described in [1], but an important feature not modelled there is that the transmission link between the pure hydro South Island system and the mixed hydro/thermal North Island system contrains operations significantly. Since the expansion of inter-island transmission capacity, and the balance of supply in the two islands, are major long term planning issues, it is crucial that the North and South Island reservoirs be modelled separately.

Since the model must be run as part of a larger package which is in constant use, computational efficiency was a major concern. Although a two reservoir version of the model in [1] is used for weekly scheduling over an annual time horizon, it would be computationally out of the question to run this model regularly over a 30 year time horizon. The model of [2] could have provided approximate (quarterly) rules in about 60 seconds cpu on the IBM 3033 used for this project. But a significantly faster and more accurate program was developed using a combination of strategies. These include the efficient separation of the uncertainty and decision phases and the use of precomputed system schedules, as explained in the next Section. But the major conceptual change is the modification of SDP so that, instead of searching for an optimal release pair corresponding to each storage pair, the optimal decision rules for the beginning of a period are constructed directly from those for the end of that period. This approach is developed first for a single reservoir deterministic model, then extended to handle two reservoirs under uncertainty.

DP is ideally suited to single reservoir problems, but the "curse of dimensionality" has made it difficult to apply to realistic multi-reservoir systems, particularly under uncertainty. Although ignored here the dimensionality of many SDP models for reservoir optimisation is further increased by the need to model serial correlation using Markov chains as in [4]. Yeh [5] and Yakowitz [6] review many developments designed to reduce these computational problems, but concluding that methods which do not require discretisation of the state space show considerable promise. Labadie and Fontane [7] show that multi-dimensional deterministic problems can be solved by disretising the objective function space instead, as long as a more-or-less unique decision can be associated with each objective function value at each stage. Our problem does not satisfy this condition, and instead we exploit the piece-wise quadratic nature of the DP value function to construct an optimal release policy for the whole state space. Our method is also related to that of Gal [8] who applied "parameter estimation" to develop approximations to the optimal value functions for a stochastic multi-reservoir problem, and to "Constrained Differential DP" [5], which works with a locally valid quadratic approximation to the value function to find an optimal storage trajectory for a deterministic problem.

Conclusions

Apart from the insights it yields into the nature of reservoir operation, the technique developed here should be more accurate than traditional SDP using the same number of grid points. Moreover it is more efficient for the deterministic case, and also for the stochastic case unless the overhead involved in performing the required "uncertainty adjustment" outweighs the savings made in the "optimisation" phase. Although we did not model current inflows as an extra dimension, our method should be able to handle this particular kind of multi-dimensionality with relative ease, because the number of decision alternatives does not increase.

In general the method shows promise for problems where the primal state space is large, but the decision rules can be expressed relatively compactly, reflecting the fact that decisions are determined by relatively few critical values and relationships between the dual variables. (For example an inventory problem with a linear production/consumption technology at each stage.) For such problems the decision rules can be expressed by "guidelines" analogous to those used here and the augmentation performs the optimisation required at each stage efficiently and with complete accuracy.

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VII.3. AN ADAPTIVE CONTROL MODEL FOR SINGLE RESERVOIR OPERATION

R. SHARDA and M. A. EL-TAYEB

Abstract

This paper presents an extension of the adaptive control approach to single reservoir operation planning problems characterized by random inflows and discrete state and control variables. The model allows a decision maker to modify the release decisions not only on the basis of realized values of inflows but also on the basis of the past performance of the decision maker in attaining the target. Bayesian densities are used to capture continuously updated information. A dynamic programming formulation is presented which involves a large state space. The implementation of the model is made possible by decomposing the problem into smaller problems and discretizing some state variables. A post-optimality analysis is performed to ensure the optimality of the solution. The practical feasibility of the approach is demonstrated by taking data for a single reservoir out of a system and comparing the results of this model with two other models.

Introduction

Many techniques have been developed and applied to determine the optimum operation and regulation rules for different water resource systems. A great deal of literature focuses on deterministic linear, nonlinear and dynamic programming. The methods introduced by Chu and Yeh [1], and Roefs and Bodin [2] are based on the assumption of certain future inflows. However, a long-standing problem in reservoir operation and regulation is the risk involved due to the stochastic nature of the inflows and the value of information needed to reduce this risk. This issue has been considered via several approaches. An early approach to the stochastic nature of reservoir inflows was represented with explicit stochastic optimization methods such as chance-constrained programming [Eisel (3)], stochastic programming [Prékopa (4)], and stochastic dynamic programming [Askew (5)]. These methods basically use the expected value in the objective function and the probability distribution in inflows in the constraints. Uncertainty associated with finite sample size has been dealt with in Bayesian decision approaches [Davis et al. (6), value of information approaches [Close and Beard (7)], and various analytical probability models [Lloyd (8)].

In this paper we extend the two-state adaptive control approach in Bellman [9] and Kushner [10] to a more general multiple-states system, in particular a reservoir operation problem. This approach takes into account the probability distribution of inflows and continuously updated Bayesian densities which are derived from the system's past behavior. Incorporation of these two densities is likely to enhance the reliability of the final solution. Pekelman and Rausser [11] provide a survey of the methods and applications of adaptive control. To the best of our knowledge this is one of the first attempts to apply adaptive control to reservoir operation.

In the next section an adaptive control formulation of a single reservoir operation is presented. We then describe an approach to solving the problem. For the purpose of illustration we take a reservoir operated by the Tennessee Valley Authority.

Conclusions

The model presented above was able to expand the application of the adaptive control approach to a class of reservoir operation problems. The model allows a decision maker to modify his decisions on the basis of not only the updated information on random inflows, but also on the basis of the past performance in terms of attaining the targets. The formulation accommodates a large state space. The practical feasibility of this approach was demonstrated by applying a discretization and decomposition process to a release decision problem for a single reservoir. The ex post results show that this approach would have done at least as well or better than a deterministic approach or another stochastic approach. The model does not require any assumptions about the probability distribution of inflows, in contrast to some other models. The ability to modify decisions on the basis of past performance should make the model attractive for actual applications. An extension of the model to a multiple reservoir system is possible, but further improvements in the computation algorithm would have to be made to accomodate the astronomically large state space. The decomposition and discretization steps used here do make it practical.

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VII.4. A MULTI-RESERVOIR MODEL WITH A MYOPIC OPTIMUM

M. J. SOBEL

Abstract

A dynamic model with four reservoirs, autocorrelated inflows, and significant flow times between reservoirs is shown to possess a myopic optimum. If the model is solved as a dynamic program, it has eight state variables. The myopic approach consists of solving four static (one-period) scalar optimization problems which yield the solution of the dynamic program.

Introduction

The origins of dynamic programming are rooted partly in the development of dynamic reservoir optimization models [1]. The generic problem is to decide how much water to discharge, as time passes, in order to optimize an objective. The "curse of dimensionality" [2] has bedeviled the prospect of utilizing dynamic control models to solve real problems. That is, the "state variable" becomes a vector whose dimension grows with the number of reservoirs in the river basis, the number of layers modeled in the reservoir, and other attributes.

The curse has been exorcised in some cases. Highly structured multi-echelon inventory models [3] comprise one class of examples. Although inventory and reservoir models are closely related [4], simple solved multi-echelon inventory models correspond to bizarre reservoir models. For references to other approaches which accelerate and simplify the solution of large dynamic programming problems, see [5, pp. 302-305].

The curse of dimensionality can be exorcised from some dynamic programs by replacing them with static programs. In other cases, the curse is exorcised by recognizing that the same action is optimal in every state. The former approach was introduced first in inventory theory [6] and then developed for more general applicability [7]. The mathematical foundations of the latter approach were explored more recently [8]. The methods utilized in this paper are found in [9] which draws on both approaches.

Section 2 presents a model of a river basin which has four reservoirs, autocorrelated inflows, and delays for upstream discharges to reach down stream reservoirs. The model is manipulated in Section 3 to elicit its affine structure. Section 4 summarizes the "myopic affine" approach in [9], and utilizes that approach in Section 5. As a consequence, a dynamic program with eight state variables and four decision decision variables can be solved by optimizing four scaler one period problems. Section 6 briefly suggests some generalizations. The assumptions in the model, its applicability, and this paper's results are summarized in Section 7.

Summary

The model in this paper describes a river basin with tributaries, possibly several reservoirs on a tributary, and autocorrelated inflows. The decisions are the reservoir discharges; the benefits and costs derive from reservoir levels and discharges. The essential assumptions (and restrictions) are (i) the benefit and cost of a discharge are proportional to the quantity discharged, and (ii) the overflow effects of finite reservoir capacity are ignored. It follows from (ii) that the model should not be used for an application where flood management is a consideration.

Under the model assumptions, the usual dynamic programming formulation would have a "state variable" which is a vector with many components. For a wide range of initial conditions, it is shown that the dynamic program can be solved by optimizing a one-period model. This one-period model decomposes to scalar one-period models if the net benefit of reservoir storage is the sum of the benefits attributable to each reservoir's storage level.

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VII.5. EXTENDED LINEAR QUADRATIC GAUSSIAN CONTROL FOR THE REAL TIME OPERATION OF RESERVOIR SYSTEMS

A. P. GEORGAKAKOS

Abstract

The Extended Linear Quadratic Gaussian (ELQG) control method [1] is discussed and tested in the control of a single reservoir. The results indicate that the method is reliable, computationally efficient, and compares favorably with traditional reservoir operation schemes. ELQG is well suited for real-time reservoir control as well as for developing policy-making guidelines.

Introduction

The operation of a single reservoir has been a topic of extensive and fruitful research. Comparatively, the Markov-chain Stochastic Dynamic Programming has been the most comprehensive formulation [2,3,4,5,6]. Successful extensions to account for reliability constraints or forecasted information in real time have also been reported in [7,8,9,10,11,12,13]. However, the use of this formulation for multireservoir systems is seriously limited due to "dimensionality" problems.

In an effort to overcome this limitation, recent developments have moved away from this traditional approach and toward analytical reservoir operation schemes [14,15,16].

This paper reports computational experience with the Extended Linear Quadratic Gaussian (ELQG) control method [16] and compares this method's performance with that of some traditional formulations. The case study concerns the control of the High Aswan Dam in Egypt for which some interesting policy-making conclusions are also drawn.

Conclusions

The ELQC control method was tested in several computational experiments for the control of the High Aswan Dam. The problem was to maximize expected energy generation subject to release and storage reliability constraints imposed from operational requirements (water supply and flood control objectives). The method displayed reliability and computational efficiency even for very long control horizons. Control constraints were accounted for within a few iterations (5 or 6), while the handling of storage reliability constraints, although satisfactory overall, was less efficient. ELQC was also compared favorably with models of the Markov-Chain Stochastic D.P. philosophy in simulation experiments. Some interesting policy making issues for the HAD operation were discussed, and a potentially attractive tradeoff between energy losses and evaporation gains was identified.

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PART EIGHT

FLOOD CONTROL AMD MANAGEMENT

PART VIII: FLOOD CONTROL AND MANAGEMENT

VIII.1. DYNAMIC PROGRAMMING FOR FLOOD CONTROL PLANNING: THE OPTIMAL MIX OF ADJUSTMENTS TO FLOODS

T. L. MORIN, W. L. MEIER, JR., AND K. S. NAGARAJ

Abstract

Despite substantial expenditures on flood protection structures, flood damages continue to increase. It has been observed that structural measures, such as dams, levees and channel improvements, often provide a false sense of security to existing and potential floodplain occupants and, as such, may actually result in increased flood damages, contrary to their intended purpose. This realization among others has led to an increasing awareness of and interest in the role of nonstructural measures, such as floodplain zoning, land use allocation, insurance, and warning, as an important and integral part of any overall flood damage mitigation program. However, determining an "optimal" mix of adjustments is very difficult as a consequence of both the interdependence between the structural and nonstructural measures and its inherent computational complexity that is the result of the multitude of feasible combinations of structural and nonstructural measures which must be considered over time and space. This paper develops a Dynamic Programming (DP) algorithm for the solution of the optimal mix of adjustments problem by recognizing that the overall problem has an underlying sequencing nature that bears distinct similarities to the sequencing approaches used in electric generation planning problems. Specifically, we adapt Erlenkotter and Rogers [1] dynamic progrmaming approach to the optimal mix of adjustments problem. Computational refinements, data requirements, and implementation details are also discussed and details of an application to a real-world problem are given.

Introduction

Floods are the most widespread geophysical hazard in the United States and they account for greater average annual property losses than any other single geophysical hazard [2]. Moreover, despite substantial expenditures for flood control measures, flood damages continue to increase [3]). Specifically, the total annual national flood damages have been increasing by about 4 percent annually in real dollars during this century and there are indications that this rate has accelerated to the 6 to 7 percent range during the last decade [4]. The dollar value of these losses is truly staggering -- the total annual flood damages were $3.4 billion in 1975 and it has been estimated [88] that even with improved flood stream management, damages will exceed $4.3 billion (measured in 1975 dollars) by the year 2000. Without such improvements in flood plain management, the damages could approach $6 billion (in 1975 dollars) by the year 2000. In Indiana alone the annual flood damages for 1980 were $128 million (measured in 1978 dollars) [5].

The magnitude of problem prompted Congress to instruct the National Science Foundation to conduct a flood hazard mitigation study during fiscal year 1980 (House Report 96:91). NSF concluded that [4, p.1], "Innovative approaches and increased attention to flood problems nationwide are required if the United States is to arrest, much less reverse, rising flood losses and the social and economic burden they place on the people and the nation's tax-supported flood-relief institutions". This paper discusses one such innovative approach -- the development of a Dynamic Programming (DP) algorithm for the determination of an optimal mix of adjustments to floods.

The mix of adjustments to floods involves both structural and non-structural measures. The structural (protective) measures for flood control typically include levees, floodwalls, channel improvements, and storage reservoirs. The nonstructural measures for flood control typically include land use control and management (i.e., floodplain zoning, outright purchase of portions of the floodplain, and land use conversion), flood-proofing, warning and evacuation, relief and rehabilitation, and flood insurance. A recent analysis [2, p. 103] of the net benefits of various measures as a function of the magnitude of the catastrophe is presented graphically in Figure 1 -- see also [6].

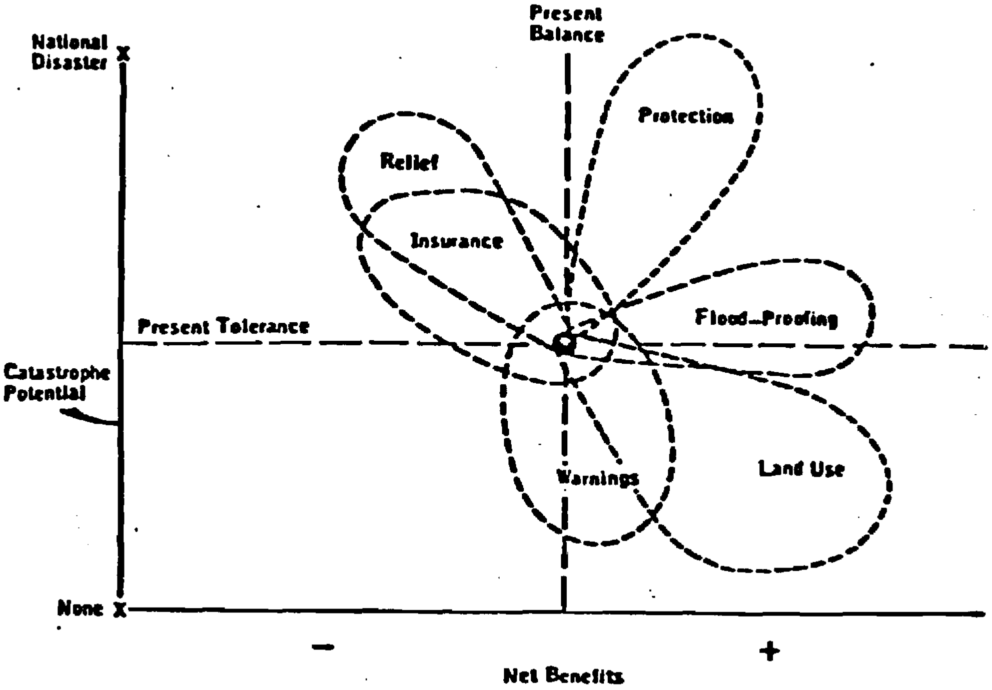

FIG. 1. Trends and limits of adjustments to floods [115].

Reliance has historically been placed on structural measures for flood control. However, it has been observed that structural measures often provide a false sense of security to existing and potential floodplain occupants and, as such, may actually result in increased flood damages, contrary to their intended purpose. That is, the potential benefits from structural flood control measures are often lost through subsequent unwise development in the areas presumed to be protected [4]. A tragic example of this was the over-topping of the Valont Dam in Veneto Province, Italy on October 9, 1963, which was caused by a massive rockslide (see Jansen [7]).

It resulted in the almost total destruction of the floodplain below and the deaths of 2600 flood-plain occupants. Such events and realizations have led to an increasing awareness and interest in the role of nonstructural measures as an important and integral part of any overall flood damage mitigation program -- for example see [8, 9, 6]. Furthermore, the age-old hope for complete protection from floods has given way to the realization that a more realistic and viable goal is the mitigation of flood damages [4]. In fact, the NSF study concluded [4, p. 214] that, "Flood hazard mitigation strategies can be effective only if they reflect mixes of alternative structural and nonstructural approaches appropriate to the circumstances. Much more work needs to be done on improving methods of planning for different aspects of flood hazard mitigation". This is precisely the issue addressed in the paper.

The paper is organized in the following manner. In §2 we review the relevant literature on previous approaches to flood control planning and related problems and outline our approach to the problem. The lack of viable planning methodologies is a consequence of the highly complicated nature of the problem and its inherent computational complexity that result, respectively, from the interdependence between the structural and nonstructural measures and from the multitude of feasible combinations of structural and nonstructural measures that must be considered over time and space. These factors have contributed to the fact that, although planning methods for problems involving only structural [10] and nonstructural [11] measures have been developed, the optimum mix of adjustment problem has yet to be satisfactorily resolved. We present a general formulation of the optimal mix of adjustments problem in §3 and develop a Dynamic Programming (DP) solution algorithm for its solution in §4. Computational refinements, data requirements and implementation details are also discussed and the results of an application to a real-world problem are presented in §4. The paper concludes with a discussion in §5.

Discussion

We presented a very general model for the Optimal Mix of Adjustments Problem and showed that this model fits naturally into a dynamic programming framework. This model is general enough to include numerous different types of damage functions. Furthermore, we proved that if the damage functions satisfy some reasonable and fairly mild conditions, then dynamic programming provides an exact solution algorithm. We discussed different ways of implementing the algorithm to account for and exploit properties of the different methods of estimating damage functions. Finally, we addressed issues of computational efficiency and pointed out various improvements which could be incorporated into the solution algorithm.

We next consider applications. A specific application of our solution approach was discussed in §4. In particular we indicated how our approach can be easily implemented even using hand-calculations. That is, the computational requirements were modest compared to the alternate DP solution approach originally used by Cortes-Rivera [12] to solve this problem. We also note that the effects of interdependence between the structural and nonstructural measures has been addressed qualitatively [2,6], as depicted in Figures 1 and 2, and that data exist for specific applications--see [12,13] for example. However, to date there appear to be no readily available *general* quantitative methods (except for the approach we described in Appendix B of [14]) for estimating the damage functions that comprehensively evaluate interactions among the structural and nonstructural measures. Thus, one might critically ask if our model imposes excessives information requirements on the user when it requires such damage functions to be constructed. The answer, of course, is that if detailed quantitative decision making support is required, then it is essential that these damage functions be specified. In such cases we recommend our approach for constructing comprehensive damage functions described in [14]. However, if less detail is required, then it may be more reasonable to aggregate the effects of the nonstructural measures either in the constraints or in the damage function and explicitly consider only the structural measures as decision variables. One could then use DI [15,10] to determine the sequencing of the structural masures. Once the sequencing has been determined, it may then be possible to assign different levels of the nonstructural measures using the decision maker's *qualitative* understanding of the effects of the nonstructural measures. However, not only would such an approach be heuristic, but it also would completely neglect interdependencies and interactions among the measures. We would, therefore, recommend our general model and DP algorithm for all except the most preliminary (or purely qualitative) phases of planning.

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PART NINE

SUCCESSFUL APPLICATIONS: RESERVOIR AND HYDROPOWER MANAGEMENT

PART IX. SUCCESSFUL APPLICATIONS: RESERVOIR AND HYDROPOWER MANAGEMENT

IX.1. BIASES IN STOCHASTIC RESERVOIR SCHEDULING MODELS

E. G. READ and J. F. BOSHIER

Abstract

The New Zealand power system is currently operated using guidelines produced by a model which combines marginalistic Stochastic Dynamic Programming with forward simulation. This approach was selected after a comparative test confirmed theoretical predictions that other approaches to modelling uncertainty would bias the solution towards unduly high or low releases. The results of this study are presented, the reasons for the effect are discussed and the implications for reservoir scheduling drawn out.

Introduction

The aim of reservoir management in a power system is to minimise expected costs while maintaining an adequate security of supply. In a purely hydro-electric system, there is no fuel cost and security of supply is the only concern. But in mixed hydro/therman systems, balancing short term costs with long term economic and security considerations is a complex and important problem which has attracted considerable attention over the years. Yeh [1] provides a comprehensive, state-of-the-art review of alternative approaches to this problem, including a variety of linear and non-linear programming models, simulation, and DP, concluding that there is no universally applicable method.

The model developed here, based on Stochastic Dynamic Programming (SDP), is used to optimise an hydro release policy for the New Zealand power system, on a weekly basis, so as to achieve economy and security throughout the year. Short term schedulers then dispatch generation on an hourly basis throughout the week so as to minimise costs, given the overall operating policy determined by the long term model. Before this study the system was scheduled using a heuristic, but the first oil crisis stimulated research into improved methods. Daellenbach and Read [2] reviewed representative examples of the practical implementation of Linear Programming (Pacific Gas and Electric), non-linear decomposition using a "trajectory method" (Electricité de France), and SDP (Swedish State Power Board [3], [4]).

Two deterministic multi-reservoir models were developed, one based on Linear Programming [5] and the other using non-linear decomposition [6], but the random nature of the inflows is a major feature of the New Zealand power system, and it was not clear whether such models were appropriate. Thus a simple, one reservoir, power system model was used as a test-bed for several approaches. The program was designed for flexibility, and testing focussed on the quality of the solutions produced, rather than computational efficiency. It was concluded that, although deterministic models have been successfully applied elsewhere (see [7] and [8] for example), they are not adequate for our system. An "iterative method", based on SDP, was the best method tested, producing significant savings. Boshier et al. [9] describe a more efficient implementation which is now used in practice. Stochastic variations on the trajectory method were also tested, because they can be generalised to handle many reservoirs relatively easily, thus offering a potential way of bypassing the "curse of dimensionality".

These tests confirmed that the biases predicted by [10] and [11] are significant for the New Zealand system. That is models, which are too optimistic about the ability of management to cope with random inflow variations tend to store insufficient water, while those which are too pessimistic store too much. This is in line with the experimental results of Loucks and Dorfman [12] with respect to linear decision rules, and also of Wunderlich and Giles [13] and Halliburton and Sirisena [14]. The "iterative method" used here was based on that of Stage and Larsson [4] and [15]. Lanna [16] has recently provided a more formal statement of this theory, which we refer to as "Marginalistic SDP". Yakowitz [17] surveys a variety of DP models which have been applied to water resources problems, while recent applications of DP to practical reservoir scheduling in power systems include [18] and [19].

Conclusions

The iterative method, based on SDP, is quite suitable for the single reservoir problem, and has been shown to produce significant savings over traditional methods. Although it may be slightly conservative, this is seen as a favourable feature by management, and it has been adopted in practice. But the computational requirements of this method increase dramatically when it is extended to the multi-reservoir case. On the other hand, alternative approaches to handling uncertainty may bias release recommendations.

Our results show that direct application of deterministic methods for scheduling purposes can not be recommended, at least for this system, because they consistently recommend holding too little water in storage. To the extent that this bias is due to assuming mean inflows, it can be overcome by adopting the "averaged trajectory method," which is relatively easy to apply, even in a multi-reservoir context, using repeated runs of a deterministic model. It is less conservative than the ideal, but the impact of this bias was negligible for this system. On the other hand the alternative of assuming that future decisions will be made using a deterministic model was far too conservative to be of any use.

Examples can doubtless be constructed for which one method or another works particularly well, and the biases discussed here may even be reversed with other marginal cost curves. But we have shown that care must be exercised, since the way in which uncertainty is handled can have a major impact on the quality of the results, even if the approximations employed seem reasonable. Although our conclusions were derived for a specific power system, they are reinforced by the fact that similar biases were observed for the, very different, TVA system by Wunderlich and Giles [13]. They studied the degree to which foresight should be assumed in their DP based model, and concluded that, using the "long run guides" (and implied marginal water values), "short sighted" policies lead to more conservative releases than those which assume some foresight by simulating deterministic management for the first few weeks of the planning horizon.

Finally, since New Zealand consists of two islands, with limited capacity to transfer power between them, there is a significant incentive to model at least two aggregate reservoirs, representing North and South Island storage. A generalisation of the iterative approach to this case is described in [9]. In practice, either this model, or a single reservoir model of the North Island on its own, are used, depending on the balance of storage between the islands at the time. Aggregate release requirements are determined by these models and apportioned among the individual reservoirs so as to equalise the probability of spill as far as possible. More recently [20] and [14] have also used twin reservoir SDP models to derive operating rules for long term studies.

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IX.2. DYNAMIC PROGRAMMING FOR OPTIMIZATION OF PUMP SELECTION AND SCHEDULING IN WATER SUPPLY SYSTEMS

B. COULBECK and C. H. ORR

Abstract

This article considers the problem of optimal control of water systems which consist of reservoirs and pump stations coupled by direct pipe lines. Under specified conditions, the overall problem of optimized pumping can be divided into the two main areas of optimized pump selection and optimized pump scheduling. Optimized pump selection is a static optimization problem consumption, to satisfy the instantaneous system operating conditions. Optimized pump scheduling is a dynamic optimization problem to take account of system storage and time varying electricity tariffs in order to minimize the overall operating costs over a particular control period. A forward dynamic programming procedure has been formulated which incorporates both aspects to provide optimal operation of single reservoir sub-systems. Data is provided which completely defines an actual supply system and the procedure is used to optimize the system operation. The computer program developed as part of the study is now in operational use.

Introduction

Typical water supply systems consist of large numbers of interconnecting pipes together with valves and pumps. The networks are often provided with storage capacity in the form of service reservoirs. Determination of both instantaneous pumping conditions and longer term operational policies has long been a major concern in the control of these systems. Results from the water industry show that a significant proportion of the total operational expense is due to electricity costs for pumping. This provides a strong motivation for optimizing the pumping operations. Locally, the optimization objective is to select the pump combination to minimize the resulting power consumption. Globally, the main objective is to determine pumping policies which minimize the overall costs.

Improved control schemes require accurate models of the distribution networks. However, the strong interaction between the non-linear network components and the large number of system variables imposes severe theoretical and computational restrictions in the application of optimization techniques for system control. Various proposals have been made for optimization of particular systems, [1,2,3,4,5]. In most cases, restrictive assumptions have been made which either simplify the optimization considerations while retaining the overall system model, or attempt complete optimization of a simplified system.

In this article, the fundamental optimization problems of both pump selection and pump scheduling are identified and examined. Pump stations usually contain parallel combinations of pumps where each pump can have different control characteristics. This can result in either a discrete type control, or a mixed type control with both discrete and continuous variables. The primary objective in pump optimization is to determine appropirate combinations of these variables. The resulting formulation then forms the basis for development of optimized scheduling procedures; these can be used in conjunction with the forward dynamic programming technique for the optimization of a class of water supply systems.

For demonstration purposes the developed method is applied to an actual supply system. A comprehensive set of data is included which completely defines the system structure and the characteristics of the components. The resulting optimized schedules correspond to a given set of practical operating conditions.

Conclusions

In this article, the essential features of optimized pump selection and optimized pump scheduling are identified. Optimized pump selection can be regarded as a static optimization problem, in which the specific aim is to select least power pump combinations to satisfy pre-specified system operating conditions. The minimum power condition will then ensure minimum electricity cost at that particular time instant.

In contrast, optimized pump scheduling is a dynamic optimization problem to minimize the operating cost over a given control period. In order to achieve this, the dynamic characteristics of both the electricity tariffs and the reservoir storage must be considered. At each time step, an average operating condition is assumed. The resulting system behaviour is then similar to the instantaneous operating conditions during optimal pump selection. Therefore, in optimized pump selection, the static optimization procedure is extended to take advantage of the dynamic nature of the system behaviour to derive cost effective operating policies for the overall system.

A flexible computer program has been written to perform both of these optimization tasks. The program is based on a general one-dimensional supply system and provides an accurate model of all non-linearities and system interactions. Forward dynamic programming is used as the basic pump scheduling optimization procedure with pump combination selection based on pump flow and power considerations. This particular formulation has provided an accurate and efficient computational algorithm for optimized system control. The solution gives both discrete and continuous controls corresponding to on-off pump combinations and pump speeds. Obtained results for the given set of system data have demonstrated the expected operation of the pump sources, notably

(1) an increase in overnight pumping,
(2) the use of the most efficient pumps,
(3) reduction of pump switching,
(4) limitations on variations of reservoir levels,
(5) limitations on maximum power demanded, and
(6) limitations on source supply flows.

The achievable 5-10 percent saving can be significant since typical water supply schemes have annual operating costs exceeding one million pounds (Sterling).

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PART TEN

APPENDICES

APPENDIX I: BIOGRAPHICAL NOTES ABOUT AUTHORS

APPENDIX II: ROSTER OF WORKSHOP PARTICIPANTS

APPENDIX III: CONFERENCE PROGRAM

NOTES ABOUT AUTHORS

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Chun-Hou Orr ("Dynamic Programming for Optimization of Pump Selection and Scheduling in Water Supply Systems") received the B.Sc. degree in electronics from the Chinese University of Hong Kong, Hong Kong, in 1975, and both the M.Sc. and Ph.D. degrees in electrical and electronic engineering from Queen Mary College, University of London, London, in 1977 and 1980 respectively. Since 1979 he has been with the Water Control Unit, Leicester Polytechnic, Leicester, England. His current research interests include the application of computing technologies and control techniques in the optimization of large-scale water distribution systems.

José A. Ramos ("Closed-Loop Control, Balancing, and Model Reduction of Large Scale Water Resource Systems") received the BSCE degree from the University of Puerto Rico, Mayaguez, in 1978, and the MSCE and Ph.D. degrees in hydrosystems and systems engineering from the Georgia Institute of Technology, Atlanta, in 1979 and 1985, respectively. From 1979 to 1980 he was a research engineer for the Water Resources Research Institute at the University of Puerto Rico. From 1984 to 1985 he was a technical consultant for the Georgia Pacific Corporation, Atlanta, Georgia. Dr. Ramos has been an associate research engineer since 1985 at United Technologies Optical Systems, Inc., West Palm Beach, Florida, where he is involved in the application of modern estimation and signal processing techniques to space defense systems. His research interests are in the areas of estimation and control theory, robust modeling and approximation of large systems, and mathematical programming.

E. Grant Read (*"A Dual Approach to Stochastic Dynamic Programming for Reservoir Release Scheduling"* and *"Biases in Stochastic Reservoir Scheduling Models"*), born and educated in New Zealand, received the Ph.D. in operations research from the University of Canterbury in 1979. He worked at the New Zealand Ministry of Energy on a variety of topics including oil stockpiling and gas depletion models, but concentrating on optimization of planning, operations, pricing and organizational structure for the electricity industry. He has been a consultant to New Zealand Electricity and the Tennessee Valley Authority, and taught at universities in the United States. Currently, he is teaching at the University of Canterbury, and pursuing his interests in electricity economics and planning methods, as well as in dual approaches to dynamic programming.

Ramesh Sharda (*"An Adaptive Control Model for Single Reservoir Operation"*) is associate professor of management science in the College of Business Administration at Oklahoma State University, Stillwater, Oklahoma. He received a B. Engg. from the University of Udaipur (India), an M.S. from the Ohio State University, an M.B.A. and the Ph.D. from the University of Wisconsin-Madison. His papers have appeared in *Management Science, Interfaces, Computers and Operations Research, Annals of Operations Research, Management Science and Policy Analysis, Environment and Planning A, Simulation and Games*, and other journals. His research interests are in stochastic programming, financial applications of management science models, DSS, integration of microcomputers in OR/MS, and policy analysis. He is a member of ORSA, TIMS, DSI, and ABSEL.

Moshe Sniedovich (*"Dynamic Programming and Non-Separable Water Resources Problems"*) is a chief specialist researcher at the Center for Advanced Computing and Decision Support of the CSIR, Pretoria 0001, South Africa. He received a B.Sc. from the Technion, Haifa, Israel, and the Ph.D. from the University of Arizona, Tucson, Arizona. His publications have appeared in journals such as *Water Resources Research, Advances in Water Resources, Operations Research, Management Science, Operations Research Letters, Journal of the Operational Research Society, Engineering Optimization, Journal of Optimization Theory and Applications, Journal of Mathematical Analysis and Applications*, and *APL Quote Quad*. Dr. Sniedovich's current research focuses on sequential decision processes, computers in mathematical education, and interactive computing modelling and analysis.

Matthew J. Sobel (*"A Multi-Reservoir Model With A Myopic Optimum"* is leading professor at the State University of New York at Stony Brook where he is in the Institute for Decision Sciences, the Department of Applied Mathematics and Statistics, and the W. Averell Harriman School for Management and Policy. His research concerns stochastic models in operations research and their applications. The primary application areas are water resources (since 1962), logistics and manufacturing, and economics. Dr. Sobel's degrees are from Columbia University and Stanford University and his previous permanent faculty positions have been at Yale University and the Georgia Institute of Technology.

Soroosh Sorooshian ("Identification of Demand Models from Noisy Observations: An Application to Water Resources") received the B.S. in mechanical engineering from California State Polytechnic University, San Luis Obispo, in 1971, the M.S. in operations research in 1973 and the Ph.D. in systems engineering in 1978, both from the University of California at Los Angeles. He was on the faculty of Case Western Reserve University in Cleveland, Ohio until 1982 as assistant professor of systems engineering and civil engineering. He is currently professor of engineering at the University of Arizona in Tucson, Arizona. Dr. Sorooshian is an associate editor of the *Water Resources Research* journal (American Geophysical Union), program chairman of the Hydrology Section of AGU's Fall Meeting, and a member of the Working Group on Water Resources of the IFAC Technical Committee on Systems Engineering (SECOM). His research interests include hydrologic modeling, linear and nonlinear systems with noisy observations, nonlinear compartment models, flash-flood and acid rain modeling, and application of statistical models to ground-water problems related to the nuclear waste disposal sites.

Hiroshi Sugiyama ("Improving Water Quality by Optimal Aeration Control via Dynamic Programming") received the D.Sc. in mathematics from Kyushu University in 1960 and the Doctor of Medical Science from Osaka City Medical School in 1961. From 1962-1985 he was chair professor of industrial mathematics at National Osaka University and chairman of the Department of Applied Physics (1982-1984). He has held many visiting research appointments in the United States including the Rand Corporation in Santa Monica, the University of Southern California and recently Kansas State University, Manhattan, Kansas. Dr. Sugiyama's publications dealing mostly with statistics, dynamic programming, medical and water resources systems have appeared in Japanese and U.S. journals.

George Tauxe ("Multi-Objective Dynamic Programming in Water Resources") is associate professor of civil engineering at Oklahoma University, Norman, Oklahoma. He received his Ph.D. in 1973 in water resources systems engineering from the University of California, Los Angeles, California. He has served on various committees of the American Geophysical Union and the American Society of Civil Engineers. He is president of Tauxe and Associates and has consulted nationally and internationally. Dr. Tauxe's research publications which have primarily been in the areas of water resources and hydrologic systems have appeared in numerous journals.

David M. Word ("State Water Research Management Plan") is Chief of the Water Resources Management Branch of the Georgia Department of Natural Resources. He has over fourteen years experience in water resources problems at the State level. He holds an M.S. in Environmental Engineering from the University of Maryland and a B.S. in Civil Engineering from Duke University.

APPENDIX II

ROSTER OF PARTICIPANTS

AT

THE BELLMAN CONTINUUM
SPECIAL NSF WORKSHOP ON DYNAMIC PROGRAMMING AND WATER RESOURCES
JUNE 25-27, 1986

Dr. Gary W. Poehlein
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Georgia Institute of Technology
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Associate Dean of Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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Industrial and Systems Engineering
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APPENDIX III

THE GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA

THE BELLMAN CONTINUUM - SPECIAL NSF WORKSHOP ON DYNAMIC PROGRAMMING AND WATER RESOURCES

June 25 - 27, 1986

The Paul Weber Building, Room 5
(Formerly Space Sciences & Technology)

PROGRAM SUMMARY

WEDNESDAY, JUNE 25, 1986

9:00 - 1:30	Conference Registration
1:30 - 2:00	WELCOMING AND OPENING REMARKS
2:00 - 3:00	KEY NOTE ADDRESS
3:00 - 3:30	Coffee Break
3:30 - 5:30	WATER SUPPLY PLANNING AND MANAGEMENT
7:00 - 9:00	CONFERENCE RECEPTION: AN AFRICAN CELEBRATION

THURSDAY, JUNE 26, 1986

9:00 - 10:00	MULTIOBJECTIVE-MULTIPURPOSE WATER RESOURCE SYSTEMS
10:00 - 10:30	Coffee Break
10:30 - 12:30	LARGE SCALE WATER SYSTEMS: MODELING AND SOLUTION APPROACHES
12:30 - 2:00	CONFERENCE LUNCHEON - FERST ROOM, GEORGIA TECH STUDENT CENTER
2:00 - 3:00	WATER QUALITY AND WASTE TREATMENT SYSTEMS
3:00 - 5:00	WATER SUPPLY AND DISTRIBUTION SYSTEMS
5:00 - 6:00	CONFERENCE ROUNDTABLE DISCUSSION

FRIDAY, JUNE 27, 1986

9:00 - 10:45	STOCHASTIC RESERVOIR OPERATION MODELS
10:45 - 12:00	FLOOD CONTROL AND MANAGEMENT
12:00 - 1:30	LUNCH BREAK
1:30 - 2:30	SUCCESSFUL APPLICATIONS: RESERVOIR & HYDROPOWER MANAGEMENT
2:30 - 3:00	ROUND TABLE DISCUSSION II - WORKSHOP WRAP UP

THE GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA

THE BELLMAN CONTINUUM - SPECIAL NSF WORKSHOP ON DYNAMIC PROGRAMMING AND WATER RESOURCES

June 25 - 27, 1986

The Paul Weber Building, Room 5
(Formerly Space Sciences & Technology)

TECHNICAL PROGRAM

WEDNESDAY, JUNE 25, 1986

9:00 am - 1:30 pm *Conference Registration*

1:30 pm - 2:00 pm ***WELCOMING AND OPENING REMARKS***

1. *Gary W. Poehlein, Associate Vice President, (Research)*
   Georgia Institute of Technology, Atlanta, Georgia
2. *W. Denny Freeston, Associate Dean of Engineering,*
   Georgia Institute of Technology, Atlanta, Georgia
3. *Nina Bellman*
   Santa Monica, California

2:00 pm - 3:00 pm ***KEY NOTE ADDRESS***

Dynamic Programming and Practical Water Resources Systems Engineering
Warren A. Hall, Elwood Mead Professor of Engineering, Colorado State University, Fort Collins, Colorado and formerly Director, Office of Water Research and Technology, U.S. Department of the Interior

3:30 pm - 5:30 pm ***WATER SUPPLY PLANNING AND MANAGEMENT***

1. *Water Problems of the State of Georgia*
   Clay Burdette, Department of Natural Resources, State of Georgia
2. *Identification of Water Demand Models from Noisy Data*
   Lov Kumar Kher, AT&T Bell Laboratories, Middletown, New Jersey
   Soroosh Sorooshian, University of Arizona, Tucson, Arizona
3. *Dynamics Programming and Optimal Management of Stream-Aquifer Systems*
   Nathan Buras, University of Arizona, Tucson, Arizona
4. *On Optimal Pumping Policies for Groundwater*
   Toshio Odanaka, The Metropolitan College of Technology, Tokyo, Japan

7:00 pm - 9:00 pm ***CONFERENCE RECEPTION: AN AFRICAN CELEBRATION***
RESIDENCE OF PROFESSOR ESOGBUE, SOUTHWEST ATLANTA

THURSDAY, JUNE 26, 1986

9:00 am - 10:00 am MULTIOBJECTIVE-MULTIPURPOSE WATER RESOURCE SYSTEMS

1. Multi-Objective Dynamic Programming
   George W. Tauxe, University of Oklahoma,
   Norman, Oklahoma

2. Objective-Space Dynamic Programming Approach to Multidimensional Problems in Water Resources
   John W. Labadie and Darrell G. Fontane,
   Colorado State University, Fort Collins, Colorado

10:30 am - 12:30 pm LARGE SCALE WATER SYSTEMS: MODELING AND SOLUTION APPROACHES

1. Knowledge Based Dynamic Programming for Water Resources Management
   Osman Coskunoglu, University of Illinois, Urbana,
   Illinois

2. Dimensionality Curse and Hydrology Memory in Dynamic Programming Models of Water Resources Systems
   Luis Valaderes Tavares, Instituto Superior Tecnico,
   Lisbon, Portugal

3. Using Dynamic Programming in Solving Non-Separable Water Resources Problems
   Moshe Sniedovich, National Research Institute for
   Mathematical Sciences, Pretoria, South Africa

4. Closed-Loop Control, Balancing, and Model Reduction of Large Scale Water Resource Systems
   Jose A. Ramos, Georgia Pacific Co., Atlanta, Georgia

12:30 pm - 2:00 pm CONFERENCE LUNCHEON - FERST ROOM, GEORGIA TECH STUDENT CENTER
Entertainment - Cynthia Watts, Story Teller

2:00 pm - 3:00 pm WATER QUALITY AND WASTE TREATMENT SYSTEMS

1. Optimal Aeration Control for Improving Water Quality via Dynamic Programming
   Hiroshi Sugiyama, Osaka University, Osaka, Japan

2. A Variable State-Space Dynamic Programming Model for Optimizing Industrial Waste Treatment Sequences
   J. Hugh Ellis, The Johns Hopkins University,
   Baltimore, Maryland

3:00 pm - 5:00 pm WATER SUPPLY AND DISTRIBUTION SYSTEMS

1. Dynamic Programming for Optimized Control of Water Supply and Distribution Systems
   Bryan Coulbeck, Leicester Polytechnic, Leiceste
   England

2. *Optimal Design of Large Complex Water Resources Conveyance Systems Via Nonserial Dynamic Programming*
   Augustine O. Esogbue, Georgia Institute of Technology, Atlanta, Georgia
   Chae Y. Lee, Korea Institute of Technology, Taejun, Korea

5:00 pm - 6:00 pm *CONFERENCE ROUNDTABLE DISCUSSION*

FRIDAY, JUNE 27, 1986

9:00 am - 10:45 am *STOCHASTIC RESERVOIR OPERATION MODELS*

1. *Application of A Small-Perturbation Solution to Stochastic Optimal Control of Reservoirs*
   Peter K. Kitanidis, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota

2. *A Dual Approach to Stochastic Dynamic Programming for Reservoir Release Scheduling*
   E.G. Read, University of Canterbury, Christchurch, New Zealand

3. *Multi Reservoir Optimization Problems With Myopic Optima*
   Matthew J. Sobel, Georgia Institute of Technology, Atlanta, Georgia

4. *Optimal Real-Time Operation of Water Supply Systems*
   J. Pinter, Research Center for Water Resources Development, Budapest, Hungary

10:45 am - 12:00 pm *FLOOD CONTROL AND MANAGEMENT*

1. *Optimal Operation of a Multireservoir During Flood Periods*
   F. Wakamori, S. Masui, M. Funabashi and M. Ohnari, Systems Development Laboratory, Hitachi, Kawasaki, Japan

2. *Optimal Mix of Adjustments to Floods*
   T.L. Morin, Purdue University, Lafayette, Indiana
   W.L. Meier, Pennsylvania State University
   K.S. Nagaraj, University of Iowa, Ames, Iowa

1:30 pm - 2:30 pm *SUCCESSFUL APPLICATIONS: RESERVOIR & HYDROPOWER MANAGEMENT*

1. *Biases in Stochastic Reservoir Scheduling Models*
   E.G. Read, University of Canterbury, Christchurch, New Zealand
   J.F. Boshier, Ministry Of Energy, Wellington, New Zealand

2. ***United Kingdom Experiences With Applications***
   Bryan H. Coulbeck and C.H. Orr, Leicester Polytechnic Water Control Unit, Leicester, England

2:30 pm - 3:00 pm ROUND TABLE DISCUSSION II - WORKSHOP WRAP UP

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

1. Institution and Address: Georgia Tech Research Corporation

2. NSF Program: General 107/000 DRECES

3. NSF Award Number: ECE-8609130

4. Award Period: From 860401 To 880331

5. Cumulative Award Amount: $9,999

6. Project Title: Proceedings of the NSF Workshop on Dynamic Programming and Water Resources

PART II—SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

The field of water resources planning, design, and management contains an assortment of important but complex problems whose efficient treatment can be approached via various tools of operations research and systems engineering. Among the most potent and popular of such methodologies is dynamic programming. The use of this problem solving philosophy and technique has grown very rapidly in recent times.

As part of the Bellman Continuum, a gathering of professional associates of Professor Bellman dedicated to the furtherance of his works, a Special Workshop on Dynamic Programming and Water Resources sponsored by the National Science Foundation was held at the Georgia Institute of Technology, Atlanta, Georgia from June 25 - 27, 1986. This report contains the Conference program and Summaries of papers presented at, as well as those submitted to, that Workshop. It is also a completion of a long project, under the inspiration of Professor Bellman, to write a book on the subject entitled Dynamic Programming for Optimal Water Resources Analysis under production by Prentice Hall.

Since dynamic programming has become identified as one of the most applicable techniques in water resources systems management, the Workshop sought to facilitate its appropriate and increased usage by practitioners, model builders and technique developers. The conference proceedings was divided into nine sections. The first part motivates the subject of the Workshop and includes surveys of origins and uses of dynamic programming in water resources and how both fields have complemented each other. Part Two deals with Water Supply Planning and Management.

Most water resources problems or projects are multifaceted, multidimensional and even multistaged. Part Three introduces multiobjective dynamic programming as it relates to the optimal analysis of multi-objective-multipurpose and large scale water resources systems. In Part Four, the methods of dynamic programming and associated algorithms which are useful in the modeling of large scale water resources systems are presented. The emphasis is on the development of techniques which can aid in models of greater fidelity as well as intelligent methods for obtaining results from such otherwise complex models.

(See attachment for continuation of Summary)

PART III—TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (✓)	Approx. Date
a. Abstracts of Theses					
b. Publication Citations					
c. Data on Scientific Collaborators					
d. Information on Inventions					
e. Technical Description of Project and Results					
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*:

3. Principal Investigator/Project Director Signature:

4. Date:

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PART II-SUMMARY OF COMPLETED PROJECT (continued)

Part Five contains papers on water quality and industrial waste treatment systems. Included are contributions by Hiroshi Sugiyama, who discusses an intelligent readily computable dynamic program for improving the water quality via optimal aeration, and J. Hugh Ellis, who presents a model for sequencing industrial waste treatment. In Part Six, problems of water supply and distribution particularly efficient management aspects are considered. New methodologies as well as successful real life applications, as for example in England, are reported. Section Seven deals with real time operation of reservoirs with emphasis on stochastic models. In the Taxonomy paper, it was shown that considerable attention has been paid to the subject recently in the literature. Therefore, it was not surprising that it attracted special interest of both model builders and users at the Workshop particularly during the round table discussion that followed.

In Section Eight, problems of flood control management are addressed. Morin et al. discuss the use of a hybrid algorithm to select and sequence some combination of structural and nonstructural flood management alternatives. The final section deals with successful application studies with emphasis on reservoir and hydropower management. The section contains papers for on line control and successful real life applications notably in New Zealand and Egypt. The Appendix contains the list of conference participants and authors as well as the program.

PART IV - SUMMARY DATA ON PROJECT PERSONNEL

NSF Division ____________________

The data requested below will be used to develop a statistical profile on the personnel supported through NSF grants. The information on this part is solicited under the authority of the National Science Foundation Act of 1950, as amended. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. NSF requires that a single copy of this part be submitted with each Final Project Report (NSF Form 98A); however, submission of the requested information is not mandatory and is not a precondition of future awards. If you do not wish to submit this information, please check this box ☐

Please enter the numbers of individuals supported under this NSF grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

*U.S. Citizens/ Permanent Visa	PI's/PD's		Post-doctorals		Graduate Students		Under-graduates		Precollege Teachers		Others	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
American Indian or Alaskan Native	0											
Asian or Pacific Islander	0											
Black, Not of Hispanic Origin	1											
Hispanic	0											
White, Not of Hispanic Origin	0											
Total U.S. Citizens	1											
Non U.S. Citizens	0											
Total U.S. & Non-U.S. ..	1											
Number of individuals who have a handicap that limits a major life activity.	0											

*Use the category that best describes person's ethnic/racial status. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN OR PACIFIC ISLANDER: A person having origins in any of the original peoples of the Far East, Southeast Asia, the Indian subcontinent, or the Pacific Islands. This area includes, for example, China, India, [illegible]n, Korea, the Philippine Islands and Samoa.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa or the Middle East.

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