AN ON-LINE RESERVOIR OPERATION MODEL FOR MULTI-RESERVOIR SYSTEMS

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CERTIFICATE

This is to certify that the thesis entitled **'AN ON-LINE RESERVOIR OPERATION MODEL FOR MULTI RESERVOIR SYSTEMS'** being submitted by Mr. **Rakesh Kumar Shrivastava** to the Indian Institute of Technology, Delhi, India, for the award of the degree of **DOCTOR OF PHILOSOPHY**, is a record of bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for the said degree. The research report and the results presented in this thesis have not been submitted, in part or in full, to any other University or Institute, for the award of any degree or diploma.

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SYNOPSIS

AN ON-LINE RESERVOIR OPERATION MODEL FOR MULTI RESERVOIR SYSTEMS

Introduction

The operation of a multiple reservoir system for optimal allocation of water considering real time streamflows, varying and conflicting demands, and constraints, is a problem quite often faced by the water resources system manager. Development of optimal operating policies for a reservoir system is a multistage decision making process in which a decision at each discrete point in time depends on the state of the system and optimization of the stated objective function. Often limited hydrological data are available at the time of planning of the system. As data accumulate, better estimates of input variables are possible and operational decisions need to be updated on the basis of the most recent data. System analysis techniques and operations research methodologies introduced in the recent past in the area of water resources planning and management offer a good basis to develop optimal operating policies for reservoir systems.

Linear Programming (LP), Dynamic Programming (DP), and Simulation are the most commonly used system analysis techniques for decision making in water resources planning and management. Dynamic Programming developed by Bellman (1957) and which works on Bellman's principle of optimality, is very suitable for sequential decision making. It can also handle non-linear, non-convex, discontinuous functions and stochasticity, and thus is a better candidate for identifying optimal operating procedures forreservoir systems as compared to any other system analysis

ellman,R.E.,1957,Dynamic Programming, Princeton University Press rinceton, N.J.

technique. Conventional DP technique does suffer with the curse of dimensionality thus limiting its use to problems with only few state variables (i.e. number of reservoirs in a reservoir system). But due to its utility in the optimization of large scale systems, researchers had been working continuously to develop techniques to solve or reduce this dimensionality problem, as a result of which various techniques are now available to tackle this problem. The present study presents a methodology for formulating monthly operating policies of MRP complex using "Constrained Differential Dynamic Programming" technique (Murray and Yakowitz,1979). MRP complex refers to Mahanadi Reservoir Project complex, a multiple reservoir system on the river Mahanadi in the state of Madhya Pradesh (India). The results have been compared with the similar reported studies (Pendse and Garg, 1987; Khaliquzzaman, 1987; Singh et.al., 1987; Sharma, 1988) on performance evaluation of MRP complex system.

Murray,D.M., and S.J.Yakowitz, 1979, Constrained differential dynamic programming and its application to multi reservoir control, Water Resources Research, Vol.15, No.5, pp.1017-1027.

Pendse,Y.D.,and I.D.Garg,1987, Simulation studies for itegrated operation of a multi reservoir system,Proceedings of Seminar on Application of Systems Analysis for Water Resources Development, Systems Engg. Organisation,Central Water Commission, New Delhi, 27-28 Feb., pp.323-339.

Khaliquzzaman, 1987, Derivation of operational guidelines for a system of reservoirs in MRP complex, Proceedings of Seminar on Application of Systems Analysis for Water Resources Development, Systems Engg. Organisation, Central Water Commission, New Delhi, 27-28 Feb., pp.341-358.

ingh,R.N.P., M.Ilangovan, and P.K.Sharma,1987, Application of llocation and simulation models for reservoir operation - A case tudy, Proceedings of Seminar on Application of Systems Analysis or Water Resources Development, Systems Engg. Organisation, entral Water Commission, New Delhi, 27-28 Feb., pp.359-375.

arma, P.K., 1988, Development of mathematical model using goal ogramming and its application to Mahanadi Reservoir Project mplex, M.Tech. thesis submitted to Department of Civil Engg dian Institute of Technology, New Delhi

The study has been further extended to make the proposed mc suitable for real time use in an adaptive manner.

Review of DP Techniques

The major problems associated with DP when it is applied multiple reservoir systems is its severe demand on compute memory and time. The avenues available for overcoming thi limitation of DP are collectively known as 'Successive Approximation Methods'.In all successive approximation algorithms an initial estimate of the optimal policy called 'nominal policy' is supplied by the user and the technique describes the construction of a new policy in the neighbourhood of nominal state (derived from nominal policy and system dynamics). The new policy, in turn, serves as the input policy from which another modified policy in the next iteration is obtained and the process is continued till a convergence criterion is satisfied.

Heidari et.al.(1971) suggested one such technique in the name of Discrete Differential Dynamic Programming (DDDP) which was initially introduced by Hall et.al. (1969a,b) as incremental dynamic programming which at present denotes a different technique. The DDDP technique had been further developed and

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Heidari,M.,V.T.Chow,P.V.Kokotovic, and D.D.Meredith,1971,Discrete differential dynamic programming approach to water resources system optimization, Water Resources Research, Vol.7, No.2, pp.273-283.

all,W.A.,R.Harboe,W.W.G.Yeh,and A.Askew,1969a,Optimum firm power utput from a two reservoir system by incremental dynamic rogramming, Contribution 130, Water Resources Center, University

california at Los Angeles, Los Angeles.

ll,W.A.,G.Tauxe, and W.W.G.Yeh, 1969b, An alternate procedure r the optimization of operations for planning with multiple- ver multiple-purpose systems, Water Resources Research, ..5, No.6, pp.1367-1372.

applied to multiple reservoir system studies by Chow and Cortes-Rivera (1974),Chow et.al.(1975) and,Nopmongcol and Askew (1976).

Larson (1968) and, Korsak and Larson (1970) introduced State Increment Dynamic Programming (SIDP or IDP). It decomposes an original multiple state variable DP into a series of sub-problems of one state variable in such a manner that sequence of optimizations over the sub-problems converges to the solution of the original problem. The technique was refined and exploited by Trott and Yeh (1973) and also used in TVA (1974,1976) studies and was designated as Dynamic Programming with Successive Approximations (DPSA) by the hydrologists.

Both the above mentioned techniques require discretization of state space, also an inverse mapping of the law of motion is

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Chow,V.T., and G.Cortes-Rivera, 1974, Application of DDDP in water resources planning, Research Report 78, University of Illinois, Water Resources Center, Urbana.

Chow,V.T., D.R.Maidment, and G.W.Tauxe, 1975, Computer time and memory requirements for DP and DDDP in water resources systems analysis, Water Resources Research, Vol.11, No.5, pp.621-628.

Nopmongcol,P.,and A.Askew, 1976, Multi-level incremental dynamic programming, Water Resources Research, Vol.12,No.6, pp.1291-1297.

Larson,R.E.,1968, State Increment Dynamic Programming, Elsevier, New York.

Korsak,A.J.,and R.E.Larson,1970, A dynamic programming successive approximation technique with convergenge proofs II, Convergence proofs, Automatica, Vol.6, pp.253-260.

rott,W., and W.W.G.Yeh, 1973, Optimization of multiple reservoir ystem, Journal of Hydraulics Division, ASCE, Vol.99, No.HY10, p.1865-1884.

ennessee Valley Authority, 1974, Development of comprehensive ater resource management program, Report for a conference of e TVA experience, International Institute for Applied stem Analysis, Schloss Laxenburg, Austria.

nnessee Valley Authority, 1976, Development of water resource nagement methods of the TVA reservoir system, project status, ne 1976, A report for a short course, Division of Water nagement, Water System Development Branch Knoxville, Tennessee.

needed which makes them unsuitable for reservoir systems w branching. The discretization of the state space may further l to either the dimensionality problem or decoupling of the sta variables. Moreover, the convergence to a global optimum has n been proved (Yeh,1985).

Murray and Yakowitz (1979) proposed a Constraine Differential Dynamic Programming (CDDP) technique, applicable t a multiple reservoir system by modifying the Differential DP (Jacobson and Mayne, 1970). This is based on control problems with Linear dynamics and Quadratic Performance that enables handling of problems with a large number of state variables. The advantages of CDDP are:(i) it does not require discretization of state and control spaces, (ii) no state variable decoupling is done, thus coupling information is available to increase convergence rate, (iii) state transition function need not be invertible, (iv) it achieves a quadratic convergence which is the fastest achieved by any of the well known successive approximation methods. The superiority of CDDP had also been established by Murray and Yakowitz (1979) by comparing its computational results for a hypothetical four reservoir problem with DDDP and SIDP, a hypothetical ten reservoir problem was also solved. The technique had been successfully applied to a 40 state control variables problem in unconstrained case by Yakowitz and Rutherford (1984). The global convergence of the CDDP technique

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'eh W.W.G.,1985,Reservoir management & operations models: A state of the art review, Water Resources Research, Vol.21, No.12, p.1797-1818.

acobson,D., and D.Mayne, 1970, Differential Dynamic Programming, lsevier, New York.

ıkowitz,S., and B.Rutherford, 1984, Computational aspects of screte time optimal control, Automatica, Vol.15, pp.29-45.

had also been established (Yakowitz,1986).

Becker and Yeh (1974) developed an optimization model for real time monthly operation of a large scale water resources system making use of LP & DP combination alongwith deterministic forecasts of streamflows.

It emerged from the critical review that CDDP algorithm has definite advantages over other techniques and hence, it was decided to use it in the present study for developing the real time operational policies of MRP complex.

The CDDP Algorithm

The CDDP algorithm undertakes constrained minimization of a quadratic at each stage. The algorithm is initialized by choosing a non-optimal policy defined as `nominal policy' which determines a nominal state trajectory using law of motion. Also the objective function value for the nominal policy is evaluated. CDDP then performs a succession of backward and forward runs. On backward run (i = n,...1; n being the number of stages), at each stage a quadratic programming problem is solved using Fletcher's (1981) algorithm and a control law is determined expressing it as ι linear function of state. The objective function value is also ·valuated at each stage using backward DP recursive equation. On he subsequent forward run (i = 1,...,n), the control law is used

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ιkowitz,S., 1986, The stage-wise Kuhn-Tucker conditions and ιfferential dynamic programming, IEEE Transactions on Automatic ›ntrol, Vol. AC-31, No.1, pp.25-30.

cker,L., and W.W.G.Yeh, 1974, Optimization of real time erations of multiple reservoir sysyems, Water Resources search, Vol.10, No.6, pp.1107-1112.

etcher, R., 1981, Practical Methods of Optimization,Vol.2, John ley, New York.

in conjunction with system dynamics and a suitable step-leng parameter to determine the modified policy and state trajectory The objective function is also evaluated for modified polic using forward DP recursive equation. The improvement in objectiv function towards optimality is achieved by suitably adjusting the step-length parameter. If the constraints are satisfied by modified policy and state trajectory, then they are used as input in the next iteration. The iterative procedure stops when a convergence criterion is satisfied.

The MRP System

The Mahanadi Reservoir Projects (MRP) complex is situated in the state of Madhya Pradesh (India) and harnesses the water resources of the Mahanadi river. The development of this system started in 1915 with the construction of the Mahanadi Canal System. At the ultimate stage, the MRP complex will include six reservoirs with total live storage capacity of 2013 MCM, three feeder canals and the Mahanadi and Pairi irrigation systems. This system is intended to provide irrigation to an area of about 0.374 m.hect. and to meet municipal and industrial (M&I) demands of Bhilai steel plant and its township. The average annual rainfall in the project complex is about 1370 mm. The average evapotranspiration values varies from a low of 104 mm in December to a high of 258 mm in May.

The planned intensity of irrigation in MRP complex is 140% (100% Kharif and 40% Rabi). The average inflow in the system is bout 3700 MCM, whereas the average water demand is of the order f 2988 MCM consisting of Kharif irrigation demand of 1358 MCM, abi irrigation demand of 1331 MCM and, M & I demands of 299 MCM. n addition about 200 MCM water is lost annually through evaporation from reservoirs.

Considering the stochasticity and incompatibility of both inflows and demands and the fact that on an average about 1300 MCM water is lost annually by inevitable spills it is difficult to satisfactorily meet the demands. Because of the above it becomes necessary to develop a methodology for optimally operating the system reservoirs for satisfying the demands by the most efficient utilisation of the available water.

Proposed Methodology

The proposed methodology produces the monthly release decisions to be made from each reservoir of MRP complex for meeting the irrigation and, M & I demands of the area, optimizing a criterion function subject to system constraints. The CDDP model has been used for generating optimal policies utilising the available hydrologic data for 30 years period, considering various feasible intensities of irrigation in Rabi and Kharif seasons, keeping high priority demands of M & I as fixed.

For real time operation a forecast model giving one month ahead forecast of streamflows has been used for updating the optimal operating policies generated by CDDP model at the beginning of each time period. The CDDP model is to be rerun a number of times with varied constraint sets to obtain operating criteria which will help the water resources manager to take the best possible decision regarding releases in the current time period. The methodology for real time operation proceeds in the following steps, considering the process starts at the beginning of the monsoon, in the month of June:

1. The problem is formulated by specifying the initial state of the system reservoirs, constraints on storage and release values for all the twelve months, inflows to each reservoir (mean flows of all months at the beginning of June), and the continuity

constraints.

2. The optimal monthly operating policies are generated for the next twelve months, by rerunning CDDP model number of times.

3. At the end of the month, using the observed inflows of June, the inflows for July are forecasted.

4. Using forecasted July flows and mean flows for the rest of the months the problem is reformulated specifying present state as the initial state of the system and modified constraints. Again the optimal monthly operating policies for the next twelve months are generated using CDDP model.

5. The process is to be repeated at the beginning of each time period.

The results obtained were compared with the results of reported simulation studies for the same time period for MRP complex using various simulation models by Pendse and Garg(1987), Khaliquzzaman (1987), Singh et.al. (1987), Sharma (1987). It is further demonstrated that the adaptive approach of the proposed methodology can help the water resources manager in updating the operating policies in the changing state of the system in real time situations. The methodology can be made applicable to any multi reservoir system by defining the system matrix which depends on the reservoir configuration and constraints, necessitating minor changes in the developed software.

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