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Multi-Reservoir Flood Control Operation by Optimization Technique: A Review

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***Abstract*— This paper presents a review on the multi-reservoir flood control operation using optimization techniques. It is difficult to manage a multi-reservoir system, owing to number of dams and its conflicting objectives. The objective of a multi-reservoir flood control operation is to minimize the damage caused by the flood at the reservoir downstream. This objective deals with the minimization of flood damage under the physical, hydraulic and operational constraints. The problem of flood control operation of multi-reservoir system deals with an optimization model consists of an objective function and a set of constraints. An optimization technique includes Linear Programming (LP), Dynamic Programming (DP), Non-Linear Programming (NLP) and Simulation. The objective of this paper is to extend previous state-of-the-art review on optimization technique for the operation of a multi-reservoir system for flood control with recent developments.**

Keywords*— Optimization, flood, multi-reservoir systems, modeling, simulation.

I. INTRODUCTION

An optimal operation of a multi-reservoir system can enhance flow management in the flooding conditions by considering the simultaneous operation of reservoirs in multi-reservoir system. Multi-reservoir system operation analysis includes optimization techniques and simulation modeling techniques that provide the quantitative information depending on the different hydraulic and hydrologic parameters.

Development of optimal operation policy for flood control in multi-reservoir system is a very complex problem. Analysis through conventional methods requires a long series of calculations for each subsystem. Instead of analysing number of subsystems in the multi reservoir system it would appear more desirable to analyse a whole system in an integrated manner by applying any sophisticated optimization technique. The advantage of this approach is that the whole system is being operated under a single management unit.

Windor (1973) stated that although programming models for generation of hydropower [Hall et al. (1967)] and irrigation [Windsor et al. (1971)] have been developed but the analysis of flood control is so far received limited attention. For the analysis of flood control in multi reservoir system Windor (1973) applied a linear programming of recursive nature as the tool for optimization.

Multi reservoir system may include number of reservoirs which are in series and/or in parallel. The complexity of the problem is directly dependent on the number of reservoirs. In multi-reservoir system, optimal release decision of one reservoir depends on the optimal release decisions of other reservoirs. For this reservoir and channel routing equations are required to describe the flood water movement within the system with respect to space and time. Reservoir inflows and outflows relation is generally expressed by Mass balance equation for reservoirs with gated spillways.

Windor (1973) demonstrated two-step procedure for flood control operation in the system. The first step is to generate a series of flood hydrographs for each significant point in the system by applying appropriate simulation methods. Second, using the hydrographs which are updated in first step by considering current hydrometeorological data and the flood storage levels as input data to optimize the system's short-term release schedule. Recursive linear programming for suitable time intervals during the flood period was introduced for varying storage and hydrometeorological conditions.

II. OPTIMIZATION TECHNIQUES

Extensive literature review on the topic optimal operation of reservoirs shows that there is no general algorithm for all the types of problem. There are numerous techniques to develop optimum operating policy for reservoirs. The selection of techniques depends upon the reservoir system features, data availability, research objective and related constraints. Optimization techniques can be generally categorized as given below:

A. *Linear Programming (LP)*

In Linear Programming, an objective function and its constraints must be linear in nature. It is one of the most favored optimization techniques due to ability to solve large scale problems efficiently; sensitivity analysis by well-developed duality theory; convergence to global optimal solutions and easy setup and solution of problem with readily available low-cost LP solver.

Dorfman (1962) demonstrated one of the earliest attempts of applications of LP to a water resource system by developing a design model for a system of reservoirs. Vedula et al. (1986) considered the monthly operation of Bhadra reservoir project in India.

To develop daily operation policy for flood control in multiple reservoir system combined optimization and a flow routing model was applied by Wasimi and Kitanidis (1983). A comparison in between Linear programming and goal programming models for flood conditions in multi-reservoir system was carried out by Can and Houck (1984). Karbowski (1993) developed an optimal operation method for flood control in cascade reservoirs.

Extension of LP into binary, integer and mixed integer programming are able to represent objective function and constraints in the terms of highly nonlinear, non convex terms. All these methods are computationally less efficient.

Needham et al. (2000) developed operational management system for network of reservoirs by Mixed-Integer Linear Programming (MILP) model for optimization of flood control operation to protect downstream control points at the Des Moines and Lowa Rivers.

Wei and Hsu(2008) used Balanced Water Level Index (BWLI) and MILP optimization models for reservoir operation. They suggested real time release policy based on a simulation-optimization method for two reservoir system during flooding condition.

Moridi and Yazdi (2017) developed an optimization model for the multi-objective multireservoir system operation to minimize flood damage at downstream area of Karkheh multireservoir system in Iran. Decision variables used in the model were the discharge and reservoir flood control capacity. The MILP optimization method was applied with the technique of ε-constraint method.

The objective function and its every constraint must be linear, is the main limitation of the linear programming model. Furthermore, linear programming cannot be implemented to issues where the probabilistic coefficients of decision variables exist.

B. Dynamic Programming (DP)

Dynamic programming (DP) was initially developed by Bellman in 1957. In Dynamic Programming the complex problem is decomposed into a set of simple sub problems that are solved successively over the time period. The earlier application of DP is reported by Hall and Burae (1961), Hall and Howell (1963) and Hall (1964) for the problem of resources allocation for single reservoir.

Various modifications were made to modify the curse of dimensionality of Dynamic programming on the original DP formulation. This includes Dynamic Programming with Successive Approximations (DPSA), Incremental Dynamic Programming (IDP), Discrete Differential Dynamic Programming (DDDP), Differential Dynamic Programming (DDP), Constrained Differential Dynamic Programming (CDDP) and the Progressive Optimality Algorithm (POA).

Bellman and Dreyfus (1962) initially proposed the metho d of DP with successive approximations (DPSA), subsequentl y described by Larson in 1968.In DPSA the multidimensional complex problem is decomposed into a set of simple one-dimensional problem by optimizing one decision variable at a time and maintaining all other decision variables at current values. DPSA for convex issues, it has been expected to adhere to a global optimum, but for non convex issues it is not expected to adhere to local optima.

DPSA with its derivatives (e.g. IDPSA, incorporates IDP and DPSA) have been introduced to numerous multi-reservoir systems, i.e. in the Central Valley Project by Yeh and Trott in 1972 and the Tennessee Valley Authority by Giles and Wunderlich in 1981.Shim et al. (2002) implemented DPSA in the Han River Basin, Korea, for instantaneous control of flood. An iterative method integrating successive DPSA algorithm solutions with revised river range routing coefficient allowed complete integration routing over hourly time measure in optimization.

Larson (1968) introduced Incremental Dynamic Program (IDP) first and later implemented by Hall et al. (1969).IDP had been further used by Fults et al. (1976) in an extension of the study of Fults and Hancock (1972), to formulate a monthly water and power schedule model for the four-reservoir system.
Discrete Differential Dynamic Programming (DDDP) had been subsequently implemented by Heidari et al. in 1971, to the same problem of Larson (1968), but strongly resembles the IDP method. Turgeon (1982) referred to the DDDP strategy as Incremental Dynamic Programming (IDP). Nopmongcol and Askew (1976) examined the distinction bet ween IDP and DDDP and found that DDDP is IDP generaliza tion. These algorithms tackle the issue of dimensionality by li miting the statespace to a corridor around a specified present alternative.

Differential Dynamic programming (DDP) technique presented by Jacobson and Mayne (1970) eliminates and discretization of state-space. It utilizes the special structure of DP formulation in which, at each stage a Linear Dynamic and Quadratic Performance (LQP) problem is formulated and solved to obtain a linear control law. A LQP problem is characterized by ordinal objective function approximated to quadratic objective function and the system dynamics approximated to linear system dynamics by truncated Taylor's series expansion. The methodology and computational aspect of DDP has been given by Dreyfus and Law (1977), Murray (1978) and Yakowitz and Rutherford (1984). The direct application of the method to the reservoir operation problem is restricted due to the inability in handling constraints on the state or decision space explicitly. However, this limitation leads to the development of Constrained Differential Dynamic programming (CDDP).

Unlike DDDP and DPSA, the global convergence of CDDP technique has been established (Yakowitz, 1985). Application of CDDP to a real large- scale reservoir systems have been reported by Shrivastava (1989) who applied this technique to Mahanadi Reservoir Project MRP in India for deriving optimal operating policy.

Howson and Sancho (1975) presented the Progressive Optimality Algorithm (POA) method to solve the nth single reservoir operating problems. The multi-stage problem converts into multiple two-stage sub-problems in POA. Turgeon (1981) suggested that POA minimize the overall production cost. To solve the combined operation of the Three Gorges multi-reservoir structures and the Qingjiang cascade reservoirs the POA method was applied by Guo et al. (2011). In POA technique, the final optimal results depend on the original alternatives.

Zhou et.al. (2018) developed operating policy for cascade reservoirs to protect downstream area from flooding. They suggested DP-POA, DP model coupled with the POA. That was an optimal reservoir operation model in two-stage for optimal operation of cascade reservoirs for flood control. The average reduction of flood peak has been observed after the optimal operation of cascade reservoirs, for all floods. The flood control reservoir operation depends on the available storage capacity of the reservoir and incoming flood magnitude. For multi-reservoir system a real time optimal operation policy Decision Support System (DSS) was developed by Shim, K. C. and Shim, S. B. (1999) using DP model.

Some research has been carried out on multireservoir system operation for flood control used for design of reservoir for which the minimization objective functions were applied for the cost estimation of potential flood damage, Yazdi (2012). Lee et al. (2009), Qi et al. (2017) and Chen et al. (2010) carried out their research on minimizing the maximum water level (MWL) in reservoir for multi-reservoir optimal operation for flood control which minimize the releases of the flood at the control points in downstream. A lot of study works on limiting water level for dynamic flood control have been carried to manage the two conflicts arise due to conservation and flood control by Li et al. (2010), Chen et al. (2013) and Zhou et al. (2014). He et al. (2017) not considered the optimal operation technique, but they developed policy for flood control by equal water storage method in cascade reservoirs at Jinsha River.

C. Nonlinear programming(NLP)

Nonlinear programming (NLP) such as Successive Linear Programming (SLP), Successive Quadratic Programming (SQP), Method of Multipliers (MOM) and the Generalized Reduced Gradient (GRG) method are prevailing methods.

Grygier and Stendinger (1985) found that SLP was the mo st effective of the assessed mathematical programming algorit hms.Hiew (1987) concluded that the SLP technique was the most efficient technique in non-linear programming method.

Arnold et al. applied SQP coupled method along with Method of Multipliers (MOM) in 1994. MOM utilizes a SQP-like Lagrangian function but is enhanced with precise penalty term. Peng and Buras introduced GRG method for the five rivers in the watershed of Penobscot River West Branch, Maine in 2000.Non-LinearProgramming has not been enjoyed popularity like LP and DP in the water resource system analysis due to its slow process, requirement of large storage in computer and more time to solve any problem.

D. Simulation

Simulation models in computer have been used to operate and manage the reservoir system in many river basins for several decades. It is a modelling technique used to predict the behaviour of a system, depicting the features of the system by a mathematical description (Mas et al.,1962).

Optimization modelsset out the strategy to be taken to me et the defined choice requirements to satisfy specified decision criteria; while simulation models show what will occur if a specifed plan is adopted. Optimization model can be applied for monitoring the set of feasible plans and pick a plan which are useful for simulation. (Jacoby and Locks, 1972).

Yeh (1985) suggested the use of simulation models to evaluate consequences of variations in certain model inputs. Simulation model provides system response for the inputs, which contains decision rules, so that it is possible to examine the implications of different situations on the system. Wurbs et al. (1985); Yeh (1985); Wurbs (1995) and Wurbs (1996) reviewed a number of such models.

Simulation model combined with LP model for multi-reservoir operation in flooding condition was applied by Zagona et al. (1998) and Biddle (1999). Fuzzylogy based optimization model for flood control in multi-reservoir system was established by Cheng in1999.

An application software FC-MWS; flood control multi-reservoir water system was developed by Niewiadomska Szynkiewicz (2002). They also used evolutionary strategy and controlled random search optimization technique to minimize downstream flood damages (2004). For real-time multi-reservoir operationthey used computing grids as a decision-making tool for flood control (2005).

A real time optimization-simulation model with MILP developed to determine reservoir releases under floods by Wei and Hsu (2008) in 2008. Simulation-optimization model to manage the flood was used by Malekmohammadi et al. (2010).

III. RECENT DEVELOPMENTS

Genetic Algorithm (GA) method was applied to solve one-dimensional unsteady flow optimization problem for cascade reservoirs by Dessalegne et al. (2004). Napiorkowski and Dysarz (2004) created a decision support system for multi-reservoir system flood control. Weighted pre-emptive goal programming model for uncontrolled streams was established by Choudhury (2010). The shuffled complicated evolution optimization algorithm was developed to minimize downstream pick floods by operating a two-reservoir system by Saavedra et al. (2010).Babak Bayat(2017) applied simulation-based optimization model combined with Particle Swarm Optimization (PSO) to minimize flood damage in a three-reservoir system at south west Iran.

Genetic Algorithm for the real time operation of a river-reservoir systems was applied by Che and Mays (2015) A methodology based on Genetic Algorithm for computing reservoir release schedules in pre and post extreme flood condition in real time was developed by them. Genetic Algorithm was used to generate stage hydrograph for open channel routing by Mehdipour et al. (2015).

Malekmohammadi et al. (2011) used the ELECTRETRI method for ideal alternatives obtained by GA, which was crea ted for multi-objective operation for optimization of operation policy in cascade reservoir in the condition of floods.

Myo Lin et al. (2018) introduced Model Predictive Contro l (MPC); a sophisticated real-time monitoring method to run a multireservoir scheme with f lood mitigation and water conservation as two control objectives at the Sittaung River Basin, Myanmar.

They also used performance indicators to present a comparison between Model Predictive Control based operation and the current reservoir operating rule. MPC is model based optimization technique, in which optimization was accomplished for control problem using the receding horizon principle. MPC internal model predicted state of the system over given domain and optimization problem was solved by control actions.

Lin and et al. (2016) discussed technique for model predictive control application for optimization of operation of network of multipurpose reservoirs. They also presented the state of art review on optimal operation of a network of multipurpose reservoir.

To regulate a water system, MPC can have elevated efficiency. The primary benefit of MPC is that by using the receding horizon concept, potential occurrences are carried into consideration in every monitoring time-step.

Network Interdiction Problem (NIP) applications for flood control on a real case in Tabriz- Iranis developed by Soleimani Alyar M. et al. in 2016.

IV. CONCLUSION

Comprehensive review of optimization methods was published several years earlier by Yeh (1985), Wurbs (1993) and Labadie (2004). However, due to the physical and functional features of the methods, a unique algorithm cannot be selected as the best conventional method. Various researches have been carried out study on the optimal operations for flood control in single and multi-reservoir systems. The study concluded that for reservoir flood-control operation, dynamic programming (DP) technique is widely used optimization technique because it can accommodate the nonlinear and stochastic features of the system. However, DP suffers from the problem of “curse of dimensionality” although some researchers such as Wasimi and Kitanidis (1983) and Kumarand Baliarsingh (2003) proposed employed some techniques to overcome this difficulty. Linear and Nonlinear programming are two conventional approaches for the development of optimal operational policy rules in reservoirs.

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REFERENCES

[1] Windsor, J. S. (1973). Optimization model for the operation of flood control systems. Water Resources Research, 9(5), 1219–1226. doi:10.1029/wr009i005p01219

[2] Yeh, W. W.-G. (1985). Reservoir Management and Operations Models: A State-of-the-Art Review. Water Resources Research, 21(12), 1797–1818.

[3] J. T. Needham, D. W. W. Jr., J. R. Lund and S. K. Nanda, “Linear programming for flood control in the Iowa and Des Moines Rivers,” *Water Resources Planning and Management*, vol. 126, no. June, pp. 118-127, 2000.

[4] C. C. Wei and N. S. Hsu, “Multi-reservoir real time operations for flood control using balanced water level index method,” *Journal of Environmental Management*, vol. 88, no. 4, pp. 1624-1639, 2008.

[5] Zhou, Chao & Sun, Na & Chen, Lu & Ding, Yi & Zhou, Jianzhong&Zha, Gang & Luo, Guanglei& Dai, Ling & Yang, Xin. (2018). Optimal Operation of Cascade Reservoirs for Flood Control of Multiple Areas Downstream: A Case Study in the Upper Yangtze River Basin. Water. 10. 1250. 10.3390/w10091250.

[6] Yazdi, J.; Neyshabouri, S.A.A.S. Optimal design of flood-control multi-reservoir system on a watershed scale. *Nat. Hazards* 2012, *63*, 629–646.

[7] Lee, S.Y.; Hamlet, A.F.; Fitzgerald, C.J.; Burges, S.J. Optimized flood control in the columbia river basin for a global warming scenario. *J. Water Resour. Plan. Manag. ASCE* 2009, *135*, 440–450.

[8] Qi, Y.; Yu, J.; Li, X.; Wei, Y.; Miao, Q. Reservoir flood control operation using multi-objective evolutionary algorithm with decomposition and preferences. *Appl. Soft Comput.* 2017, *50*, 21–33.

[9] Li, X.; Guo, S.; Liu, P.; Chen, G. Dynamic control of flood limited water level for reservoir operation by considering inflow uncertainty. *J. Hydrol.* 2010, *391*, 126–134.

[10] He, X.; Zhang, L.; Liu, L. Study on flood control operation of jinsha river cascade reservoirs combined with the three gorges along the yangtze river. Mater. Sci. Eng. 2017, 199, 012032.

[11] Howson, H.R.; Sancho, N.G.F. A new algorithm for the solution of multi-state dynamic programming problems. Math. Program. 1975, 8, 114–116. [CrossRef]

[12] Turgeon, A. Optimal short-term hydro scheduling from the principle of progressive optimality. Water Resour. Res. 1981, 17, 481–486. [CrossRef]

[13] Guo, S.L.; Chen, J.H.; Li, Y.; Liu, P.; Li, T.Y. Joint operation of the multi-reservoir system of the three gorges and the qingjiang cascade reservoirs. Energies 2011, 4, 1036–1050. [CrossRef]

[14] Bayat, Babak. (2017). Nonstructural Flood Control using Multi-reservoir Operation. Asian Journal of Fuzzy and Applied Mathematics. 5. 10.24203/ajfam. v5i2.4668.

[15] Wasimi, S. A. and Kitanidis, P. K. Real-time forecasting and daily operation of a multi-reservoir system during floods by linear quadratic Gaussian control, Water Resources Research, 19: 1511-1522, 1983.

[16] Can, E. K. and Houck, M. H. Real-time reservoir operations by goal programming, Journal of Water Resources Planning and Management, ASCE, 110: 297-309, 1984.

[17] Karbowski, A., Optimal flood control in multi-reservoir cascade systems with deterministic inflow forecasts, Water Resources Management, 7: 207-223, 1993.

[18] Zagona, E. A., Fulp, T. J., Goranflo, H. M. and Shane, R. M. RiverWare: A general river and reservoir modeling environment., Proc. 1st Federal Interagency Hydrologic Modeling Conf., 113–120, 1998.

[19] Biddle, S. H. RiverWare applications at TVA., Proc. ASCE Water Power Conference, ASCE, Reston, Va. , 1999.

[20] Cheng, C. Fuzzy optimal model for the flood control system of the upper and middle reaches of the Yangtze River, Hydrological Sciences, 44(4): 573-582, 1999.

[21] Shim, K. C. and Shim, S. B. Optimal predictive flood control for river-reservoir operation system, Proceedings (Abstract Volume) of the XXVIIIth IAHR Congress, p. 435, Paper on CD ROM, Graz, 1999.

[22] Needham, J., Watkins, D., Lund, J. and Nanda, S. Linear programming for flood control on the Iowa and Des Moines Rivers., Journal of Water Resources Planning and Management, ASCE, 126(3): 118–127, 2000.

[23] Shim, K. C. Spatial decision support system for integrated river basin flood control, Ph.D. Dissertation, Dept. of Civil Engineering, Colorado State Univ., Ft. Collins, Colo. , 1999.

[24] Shim, K. C., Fontane, D. G. and Labadie, J. W. Spatial decision support system for integrated river basin flood control, Journal of Water Resources Planning and Management, ASCE, 128(3): 190–201, 2002.

[25] Niewiadomska-Szynkiewicz, E. Software environment for simulation of flood control in multiple-reservoir systems, 5th International Conference on Hydro-Science and Engineering (ICHE), Faculty of Environmental Engineering, Warsaw University of Technology, 2002.

[26] Niewiadomska-Szynkiewicz, E. FC-MWS: A software environment for flood operation in multi-reservoir systems, Acta Geophysica Polonica, 52(1): 91-103, 2004b.

[27] Myo Lin, Nay & Rutten, Martine & Tian, Xin. (2018). Flood Mitigation through Optimal Operation of a Multi-Reservoir System by Using Model Predictive Control: A Case Study in Myanmar. Water. 10. 1371. 10.3390/w10101371

[28] Moridi, A., &Yazdi, J. (2017). Optimal Allocation of Flood Control Capacity for Multi-Reservoir Systems Using Multi-Objective Optimization Approach. Water Resources Management, 31(14), 4521–4538. doi:10.1007/s11269-017-1763-x

[29] Heydari, M., Othman, F., &Taghieh, M. (2016). *Optimization of Multiple and Multipurpose Reservoir System Operations by Using Matrix Structure (Case Study: Karun and Dez Reservoir Dams). PLOS ONE, 11(6), e0156276*.doi:10.1371/journal.pone.0156276

[30] Yeh WWG. Reservoir management and operations models: A state of the art review. Water resources research. 1985; 21(12):1797–818.

[31] Wurbs RA. Reservoir-system simulation and optimization models. Journal of water resources planning and management. 1993; 119(4):455–72.

[32] Labadie JW. Optimal operation of multireservoir systems: State-of-the-art review. Journal of water resources planning and management. 2004; 130(2):93–111.

[33] Lin, N. M., & Rutten, M. (2016). *Optimal Operation of a Network of Multi-purpose Reservoir: A Review. Procedia Engineering, 154, 1376–1384*.doi:10.1016/j.proeng. 2016.07.504

[34] Soleimani-Alyar, M., Ghaffari-Hadigheh, A., & Sadeghi, F. (2016). Controlling Floods by Optimization Methods. Water Resources Management, 30(12), 4053–4062. doi:10.1007/s11269-016-1272-3

[35] Needham et al. (2000) applied mixed integer linear programming to deterministic J. T. Needham, D. W. W. Jr., J. R. Lund and S. K. Nanda, “Linear programming for flood control in the Iowa and Des Moines Rivers,” *Water Resources Planning and Management,* vol. 126, no. June, pp. 118-127, 2000.

[36] C. C. Wei and N. S. Hsu, “Multi-reservoir real time operations for flood control using balanced water level index method,” *Journal of Environmental Management,* vol. 88, no. 4, pp. 1624-1639, 2008.