LINEAR PROGRAMMING FOR FLOOD CONTROL IN THE IOWA AND DES MOINES RIVERS

By Jason T. Needham,[1] David W. Watkins Jr.,[2] Jay R. Lund,[3] Associate Members, ASCE, and S. K. Nanda,[4] Fellow, ASCE

ABSTRACT: This study addresses questions related to flood-control operating procedures followed by the U.S. Army Corps of Engineers, Rock Island District. Application is presented of a mixed integer linear programming model for a reservoir system analysis of three U.S. Army Corps of Engineers' projects on the Iowa and Des Moines rivers. A strategy for evaluating the value of coordinated reservoir operations is developed. Results of this study suggest that operating Coralville Reservoir, on the Iowa River, for flood control on the Mississippi River does not provide appreciable benefits and, therefore, an operation plan coordinating releases from Coralville Reservoir with the two reservoirs on the Des Moines River may be unnecessary. Damage-minimizing results were obtained by operating the three reservoirs independently for 8 of the 10 largest flood events on record. Also, a review of the operating procedures for the flood of 1993 illustrates how much damage could have been reduced if inflows could be predicted months in advance or if the existing operating rules were more averse to extreme flood events.

INTRODUCTION

Record floods in the past decade have caused enormous economic damage and human suffering. In particular, the Great Midwest Flood of 1993 along the Upper Mississippi River and its tributaries caused an estimated 48 fatalities and \$15–\$20 billion in economic damages, surpassing all floods in the United States in modern times (U.S. Department of Commerce 1994). With increasing environmental concern and decreasing public support for large-scale flood-control structures, a growing number of engineers and hydrologists are concentrating on developing computer models for optimizing the operation of existing systems rather than proposing/designing new flood-control projects. Better forecasting methods are being developed to provide the most accurate data possible for these models. Along these lines, this paper describes an application of deterministic optimization to assess flood-control operations for the Iowa/Des Moines River Reservoir System and to provide insight for possible modifications to the current operating plan [U.S. Army Corps of Engineers (USACE) 1999].

Developing optimization models for analyzing operating policies of multiple reservoir systems has been a popular area of research for >30 years. Yeh (1985) and Wurbs (1993) presented in-depth reviews of reservoir management and operations models that contain extensive references in this area. Labadie (1997) presented a thorough discussion and formulation of reservoir optimization models and comments on reasons for the gap between theoretical developments and real-world implementation. The USACE has applied optimization methods in studies of reservoir system operations on both the Missouri and Columbia rivers (USACE 1994, 1996). These studies focused on seasonal and long-term operations using the Hydrologic Engineering Center (HEC) Prescriptive Reservoir Model, which uses a 1-month time step, limiting its capabilities for assessing flood-control operations because decisions need to be made on a daily or even hourly basis during flood events.

Optimization models for reservoir flood-control operations have not been applied as vigorously. One approach that has been applied is dynamic programming (Glanville 1976; Beard and Chang 1979). Dynamic programming is popular because it can directly accommodate the nonlinear and stochastic features that characterize many water resources systems. However, discretization of state, input, and decision variables, especially for multiple reservoirs, causes dimensionality problems. Wasimi and Kitanidis (1983) avoided dimensionality problems through the application of linear quadratic Gaussian control for the optimization of real-time daily operation of a multireservoir system under flood conditions. Their approach, however, is valid only under moderate flood conditions when capacity constraints are not likely to become binding. Windsor (1973) formulated a linear programming (LP) model that includes storage and release capacity constraints, along with some theoretical discussion of how it could be used with the latest forecast information to adjust reservoir operations during a flood event. The model presented in this work is similar to that of Windsor.

IOWA/DES MOINES RIVER RESERVOIR SYSTEM

The Iowa/Des Moines River Reservoir System consists of three reservoirs, one on the Iowa River main stem and two on the Des Moines River main stem, as shown in Fig. 1. The reservoirs are operated and maintained by the USACE, with the Rock Island District responsible for day-to-day decision making. Operators follow guidelines described in the reservoir regulation manuals that have been prepared as part of the design of the system (*Master* 1983, 1988, 1990).

Authorized purposes for these reservoirs include flood control, low-flow augmentation, fish/wildlife, water supply, and recreation. In each case, access and facilities are provided for recreation, but water is not controlled for that purpose (USACE 1992). Total capacities and average inflows for the three reservoirs are shown in Table 1. Other pertinent characteristics of the Iowa and Des Moines rivers are shown in Tables 2 and 3, respectively.

Table 2 illustrates that Coralville Reservoir can regulate no more than 25% of the total average annual flow entering the Mississippi from the Iowa River. Because of this, one could expect that Coralville Reservoir's flood-control effectiveness below the confluence of Cedar River and on the Mississippi

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[1] Assoc. Engr., David Ford Consulting Engineers, Sacramento, CA; formerly, Intern, Hydrologic Engrg. Ctr., Davis, CA 95616. E-mail: needham@ford-consulting.com

[2] Asst. Prof., Dept. of Civ. and Envir. Engrg., Michigan Technol. Univ., Houghton, Mich. 49931; formerly, Hydr. Engr., Hydrologic Engrg. Ctr., Davis, CA. E-mail: dwatkins@mtu.edu

[3] Prof., Dept. of Civ. and Envir. Engrg., Univ. of California at Davis, Davis, CA. E-mail: jrlund@ucdavis.edu

[4] Chf., Hydro. and Hydr., Rock Island Dist., U.S. Army Corps of Engrs. E-mail: s.k.nanda@usace.army.mil

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FIG. 1. Map of Iowa/Des Moines River Reservoir System

TABLE 1. Capacities of, and Average Inflows to, Three Reservoirs

Reservoir (1)	Inflows (acre-ft/year) (2)	Capacity (acre-ft/year) Conservation (3)	Flood control (4)	Total (5)	Percent[a] (6)
Coralville (Iowa River)	1,271,800	25,900[b]	435,300	461,200	18
Saylorville (Des Moines River)	1,540,600	90,000	586,000	676,000	20
Red Rock (Des Moines River)	3,568,000	265,500[b]	1,494,900	1,760,400	62

[a] Percent of total federal project flood storage in Des Moines/Iowa system.
[b] Varies seasonally, value is minimum which corresponds to maximum flood storage.

TABLE 2. Iowa River Characteristics

Location (1)	Drainage area (sq mi) (2)	Mean inflow (cfs) (3)
Coralville Reservoir	3,115	1,760
Iowa River (confluence with Cedar River)	4,770	2,360
Cedar River (confluence with Iowa River)	7,870	4,230
Iowa River (confluence with Mississippi River)	12,980	7,120
Mississippi River (confluence with Iowa River)	89,000	49,000

TABLE 3. Des Moines River Characteristics

Location (1)	Drainage area (sq mi) (2)	Mean inflow (cfs) (3)
Saylorville Reservoir	5,823	2,200
Red Rock Reservoir	12,323	4,928
Des Moines River (confluence with Mississippi River)	14,540	8,210
Mississippi River (confluence with Des Moines River)	119,000	64,520

River is limited. Conversely, as illustrated in Table 3, Saylorville and Red Rock reservoirs regulate more than half of the average flow entering the Mississippi River from the Des Moines River. The main tributaries of the Des Moines River join the main stem upstream of, or at, Lake Red Rock. An important tributary is the Raccoon River, which converges in the southern part of the city of Des Moines and has a large effect on the stage there. The hydrographs at Ottumwa and Keosauqua are similar because no major tributaries join the Des Moines downstream of Ottumwa.

Coralville Reservoir was completed and placed in operation during 1958 as a unit in the general flood-control plan for the Upper Mississippi River Basin. Under current operations, Coralville Reservoir is to be operated for flood control at Lone Tree and Wapello on the Iowa River and Burlington, Iowa, on the Mississippi River (*Master* 1990). Presumably, when operated in conjunction with the reservoirs on the Des Moines River, the flood peaks can be offset enough to cause a significant difference in the water levels on the Mississippi River during flooding.

Saylorville Reservoir and Lake Red Rock projects also are associated with the comprehensive flood-control plan for the Upper Mississippi River Basin. Lake Red Rock was completed in 1969, and Saylorville Dam was completed in 1975. According to the reservoir regulation manuals, Saylorville Reservoir is operated not only to reduce flood damage in the city of Des Moines, but it is also operated in tandem with Red Rock Reservoir to reduce flood damage at Ottumwa and Keosauqua on the Des Moines River and at Quincy, Ill., on the Mississippi River (*Master* 1983, 1988).

MIXED-INTEGER LP MODEL

A mixed-integer LP model, termed HEC-FCLP, has been developed at HEC to assist with USACE's flood management studies. This model is based on work done by Ford (1978), with mixed-integer variables added to the formulation to incorporate nonconvex hydraulic relationships (Watkins et al. 1999). The model treats the flood-operation problem as one of finding a system-wide set of releases that minimize total system penalties for too much or too little release, storage, and flow. A simulation model embedded in the LP model uses given releases to compute storage and downstream flows, accommodates reservoir continuity and linear channel routing (e.g., Muskingum routing), and accounts for hydraulic limitations such as reservoir outlet capacities.

HEC-FCLP reads a description of the flood control system from an ASCII text file and generates a set of linear equations that constitute the LP model. Using IBM/OSL, a general-purpose, large-scale LP/MIP solver (*Optimization* 1995), HEC-FCLP calculates the optimal values of decision variables and then translates the LP results into terms familiar to hydrologic engineers (e.g., release, flows, storage values). HEC-FCLP is linked to the HEC Data Storage System (USACE 1995), from which it reads incremental flow data and to which it writes the model results.

The model constraint set includes continuity constraints for each reservoir and control point, along with constraints on reservoir release capacity, in each time period. The objective function includes penalties for too much or too little storage, release, or flow in each time period.

The general form of the reservoir continuity constraints, for reservoir j, time period i, is

$$\frac{1}{\Delta t}[S_{i,j} - S_{i-1,j}] + f_{i,j} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j} \tag{1}$$

where $S_{i-1,j}$ and $S_{i,j}$ = storage at the beginning and end of period i, respectively; $f_{i,j}$ = total release in period i; Ω = set of all control points upstream of j from which flow is routed to j; $f_{t,k}$ = average flow at control point k in period t; $c_{t,k}$ = linear coefficient to route period t flow from control point k to control point j for period i; and $I_{i,j}$ = inflow to the reservoir. The routing coefficients are found directly from the Muskingum model coefficients.

To model desired storage-balancing schemes among reservoirs, the total storage capacity of each reservoir in the system is divided into zones. The total storage at any time i is the sum of storage in these zones

$$S_{i,j} = \sum_{l=1}^{NLF} S_{i,j,l} \tag{2}$$

where l = index of storage zone; and NLF = number of storage zones. Substituting this in the continuity equation yields

$$\frac{1}{\Delta t}\left[\sum_{l=1}^{NLF} S_{i,j,l} - \sum_{l=1}^{NLF} S_{i-1,j,l}\right] + f_{i,j} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j} \tag{3}$$

The storage in each zone l is constrained as

$$S_{i,j,l} \leq S\max_{j,l} \tag{4}$$

The maximum reservoir release physically possible is limited by the hydraulic properties of the reservoir outlet works. This limitation is expressed as a piecewise linear function of the storage in the reservoir. That is, the maximum release from reservoir j for period i is specified as

$$f_{i,j} \leq \sum_{l=1}^{NLF} \frac{\beta_{j,l}}{2} \cdot (S_{i-1,j,l} + S_{i,j,l}) \tag{5}$$

where $\beta_{j,l}$ = slope of the storage-discharge capacity relationship in storage zone l. To correctly represent nonconvex storage-discharge functions, critical under forced spill conditions, the following binary variable and logical constraints must be added for each reservoir j:

$$\sum_{l=1}^{2} S_{i,j,l} \geq Y_{i,j} \sum_{l=1}^{2} S\max_{j,l} \tag{6}$$

$$S_{i,j,3} \leq Y_{i,j} S\max_{j,3} \tag{7}$$

$$Y_{i,j} \in \{0,1\} \tag{8}$$

These constraints ensure that, for example, storage zones 1 and 2 are filled before water is stored in zone 3.

The continuity constraint for each control point other than a reservoir takes the following general form:

$$f_{i,j} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j} \tag{9}$$

where $f_{i,j}$ = average control-point flow during period j; and $I_{i,j}$ = local inflow during period j. For proper representation of the damage function, control-point flow may also be divided into zones. The control-point continuity equation then takes the form

$$\sum_{l=1}^{NF} f_{i,j,l} - \sum_{k,k\in\Omega} \sum_{t=1}^{i} c_{t,k} f_{t,k} = I_{i,j} \tag{10}$$

where l = index of discharge zone; and NF = number of discharge zones.

Penalties for too much or too little storage represent operators' aversion to storage levels outside of a target range. The penalties are specified for each reservoir as a piecewise linear convex function of volume of water stored in the reservoir during the period. The total penalty for storage SP is defined as

$$SP_j = \sum_{t=1}^{i} \sum_{l=1}^{NLF} A_{j,l} S_{i,j,l} \tag{11}$$

where $A_{j,l}$ = slope of the storage penalty function in zone l of reservoir j.

Penalties for changing release rates too rapidly quantify negative impacts such as bank sloughing or inadequate response time to changing conditions downstream. Changes in release rates may also be limited by the equipment available to change gate or outlet settings. To impose this penalty, the LP model includes a set of auxiliary constraints that segregate the release for each period into the previous period's release, plus or minus a change in release. If the absolute value of this change in release exceeds a specified maximum, a penalty is imposed.

The auxiliary constraints relate the release for each period to release in the previous period by the equation

$$R_{i,j} = R_{i-1,j} + [Ra^{+}_{i,j} + Re^{+}_{i,j}] - [Ra^{-}_{i,j} + Re^{-}_{i,j}] \tag{12}$$

where $Ra^{+}_{i,j}$, $Re^{+}_{i,j}$ = acceptable and excessive release increase, respectively; and Ra^{-}_{ij}, $Re^{-}_{i,j}$ = acceptable and excessive release decrease, respectively. $Ra^{+}_{i,j}$ and $Ra^{-}_{i,j}$ are constrained not to exceed the user-specified desirable limits, and a penalty, RP, is imposed on $Re^{+}_{i,j}$ and $Re^{-}_{i,j}$ at reservoir j as follows:

$$RP_j = \sum_{t=1}^{i} B_{i,j} Re^{+}_{i,j} + \sum_{t=1}^{i} D_{i,j} Re^{-}_{i,j} \tag{13}$$

where $B_{i,j}$ = penalty per unit flow for a positive change in release greater than the user-specified limits; and $D_{i,j}$ = penalty per unit flow for a negative change in release greater than the user-specified limits.

Flow penalties are specified as a piecewise linear convex function of downstream flow, which is the sum of local runoff and routed reservoir releases. The penalty for flow QP is given by

$$QP_k = \sum_{t=1}^{i} \sum_{l=1}^{NF} E_{k,l} f_{i,k,l} \tag{14}$$

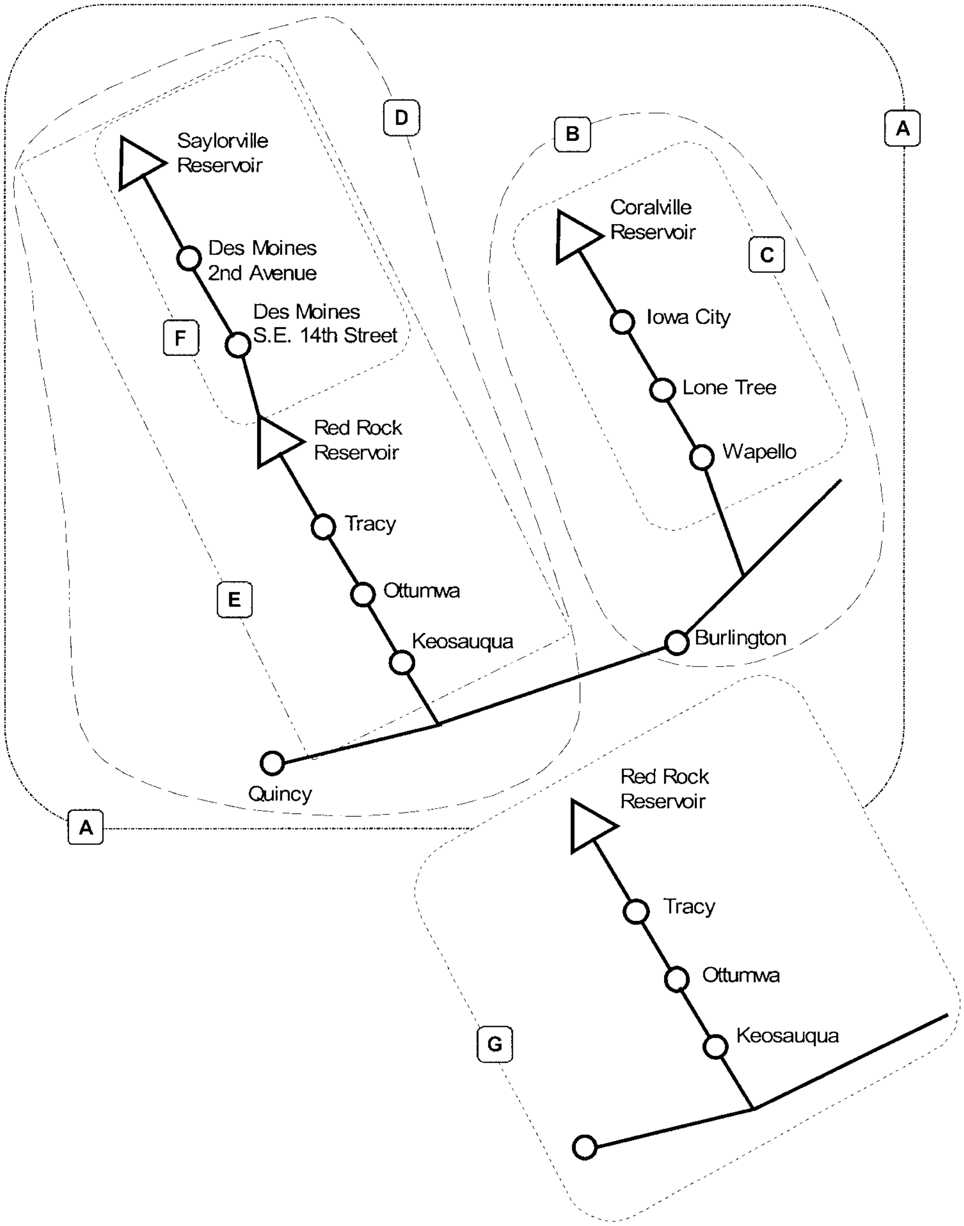

FIG. 2. System Decomposition

where $E_{k,l}$ = slope of the penalty function in flow zone l at control point k.

Incorporating penalty terms given by (11), (13), and (14), the objective function is as follows:

$$\min \mathrm{TP} = \left[\sum_{k,k\in\Psi} QP_k + \sum_{j,j\in\Phi} RP_j + \sum_{j,j\in\Phi} SP_j \right] \qquad (15)$$

where TP = total penalty; Ψ = set of all control points; and ϕ = set of all reservoirs. The release schedule that yields the minimum total penalty is the optimal schedule.

It should be noted that HEC-FCLP makes release decisions for all periods simultaneously, with perfect knowledge of the complete flow hydrographs. Despite their inherent optimism, results from this type of deterministic model have proven useful for inferring general reservoir system operational policies (Lund and Ferreira 1996). Historical operation of a reservoir can be compared with the optimal operation determined by the model to identify possible shortcomings in current procedures, and questions regarding the operation of multiple reservoirs or the effects of changing physical aspects of the system can be addressed quickly.

ANALYSIS STRATEGY

The first step in the analysis is to select a number of flood events out of the approximately 70 years of record. Since the water year and the calendar year are similar in this region, the 10 years with the largest flood events were identified based on a combination of peak flow and total volume at each gauge. For each of the selected years, beginning and ending dates of the flood events were estimated visually from hydrographs.

To estimate the benefits from operating the reservoirs as a coordinated system, the larger Iowa/Des Moines/Mississippi River System was divided into various smaller subsystems as illustrated in Fig. 2. By optimizing the operations of each subsystem independently, the benefits from operating the three reservoirs as a system can be evaluated, and the question of whether or not these benefits are significant and obtainable can be addressed.

System A, the most complex, consists of the three reservoirs located on the Iowa and Des Moines rivers and all 10 control points, two of which are on the Mississippi River. System B isolates the Iowa River, which causes Coralville Reservoir to operate only for damage locations on the Iowa River, plus

Burlington on the Mississippi River. System C is similar to System B except that Burlington is removed from consideration. This illustrates the potential effect of Burlington on the operation of Coralville Reservoir. System D represents the two reservoirs on the Des Moines River operating in tandem for control at all damage locations on the Des Moines River and Quincy on the Mississippi River. System E is identical to System D except that Quincy is not considered. Dividing System D just upstream of Red Rock Reservoir to form Systems F and G helps illustrate the effect of operating Saylorville Reservoir and Red Rock Reservoir independently. Possible combinations of these systems include A, BD, CD, BE, CE, BFG, and CFG.

MODEL APPLICATION

Application of HEC-FCLP to the Iowa/Des Moines River System required the collection of flow data and the estimation of a number of model parameters. Daily incremental (local) flows and Muskingum routing parameters (e.g., Ponce 1989) for each river reach are estimated from USGS stream gauge data. Initial storage levels in each reservoir are set as the top of the conservation pool, and reservoir storage pools were divided into five zones: drought pool, conservation pool, flood-control pool, emergency flood-control pool, and flood surcharge pool. Storage-discharge capacity relationships are derived from outlet and spillway rating curves. All values are obtained from the master reservoir regulation manuals (*Master* 1983, 1988, 1990).

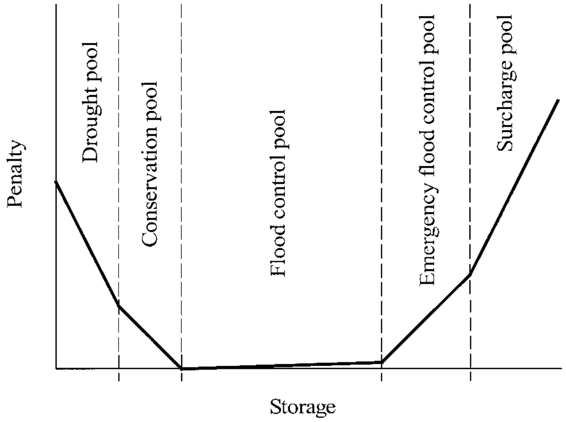

FIG. 3. Example Storage-Penalty Function

Penalties for high flow are based on economic data found in the reservoir regulation manuals and subsequent surveys conducted by the Rock Island District. The penalty functions used in this study represent the total penalty at each location, which is a combination of urban, rural, and agricultural damage. Penalty functions are developed by approximating the nonlinear flow-damage relationships with convex piecewise linear functions. Flows are divided into zones based on vertices of the penalty functions, and the same penalties are used for all flood events studied.

Rate of change of release penalties are difficult to determine. The reservoir regulation manual for Saylorville (*Master* 1983) states that a maximum change of 3,000 cfs/day is allowable during normal flood operations. This limits bank sloughing in the reservoir and along the downstream channel. A relatively large penalty of 0.1 dollars/cfs for rates of change >3,000 cfs/day is set to discourage larger rates of change but still allow them when necessary. Maximum desirable rate of change values of 3,000 cfs/day for Coralville and 6,000 cfs/day for Lake Red Rock were determined through discussions with the Rock Island District and comparisons with historical observed reservoir storage data.

Storage penalties are set to force the model to operate within the flood-control pool when feasible. The penalty prescribed when storage enters the emergency flood-control pool or the surcharge pool represents the risk associated with uncontrolled spills. A small ‘‘persuasion’’ penalty is placed on storage within the flood pool so that reservoir levels return to the top of the conservation pool when downstream flows recede below flood stage. Fig. 3 illustrates an example storage-penalty function.

A more detailed discussion of parameter and penalty function estimation is provided in USACE (1999).

MODEL RESULTS

The flood of 1993 is important not only because of the record-breaking flows, but also because of the time it covered.

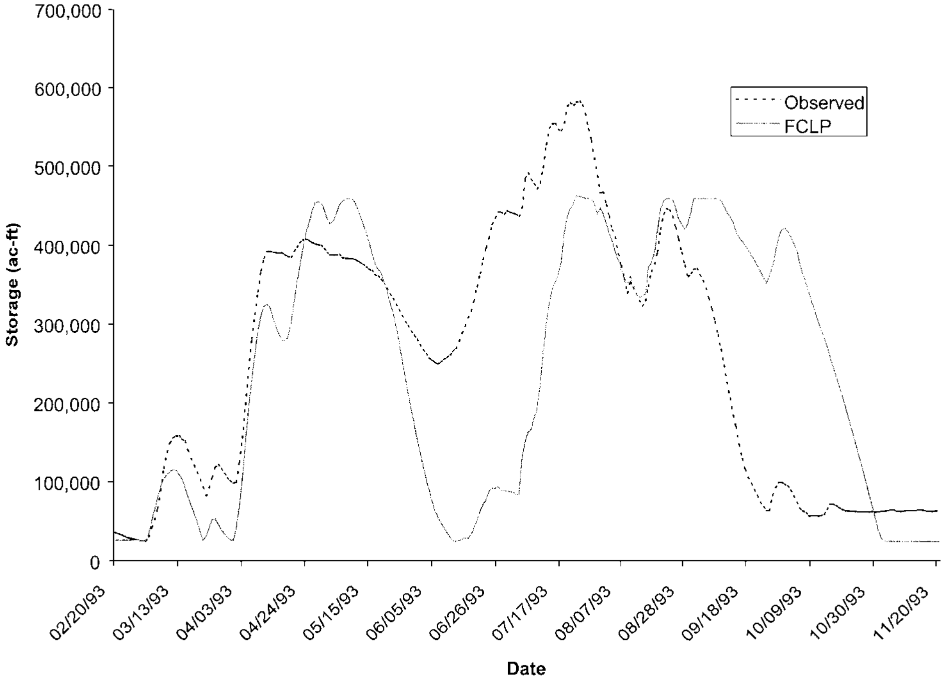

FIG. 4. Coralville Reservoir Storage—Flood of 1993

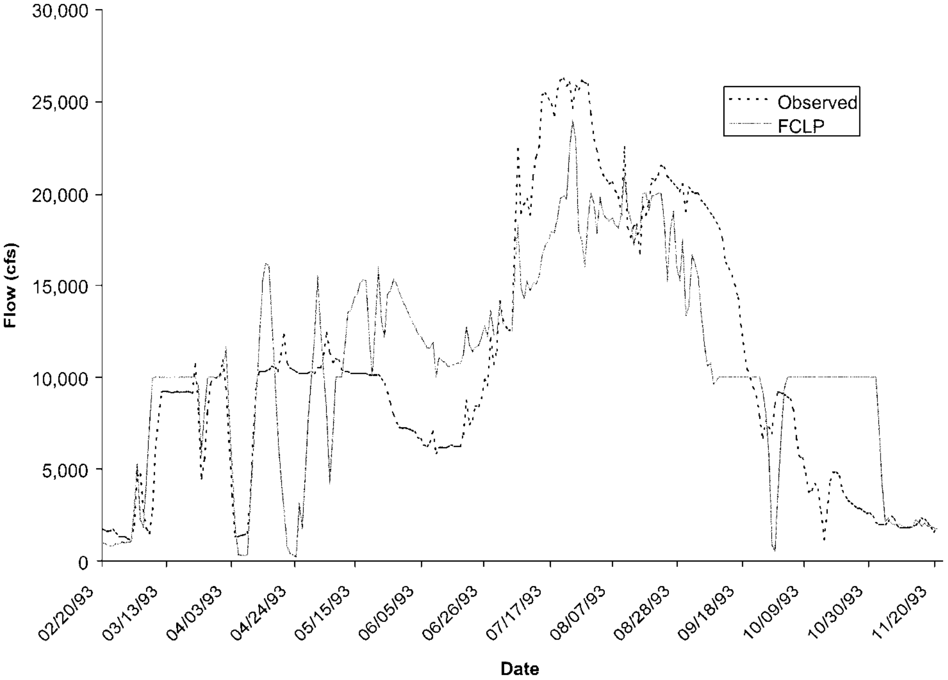

FIG. 5. Iowa City Hydrograph—Flood of 1993

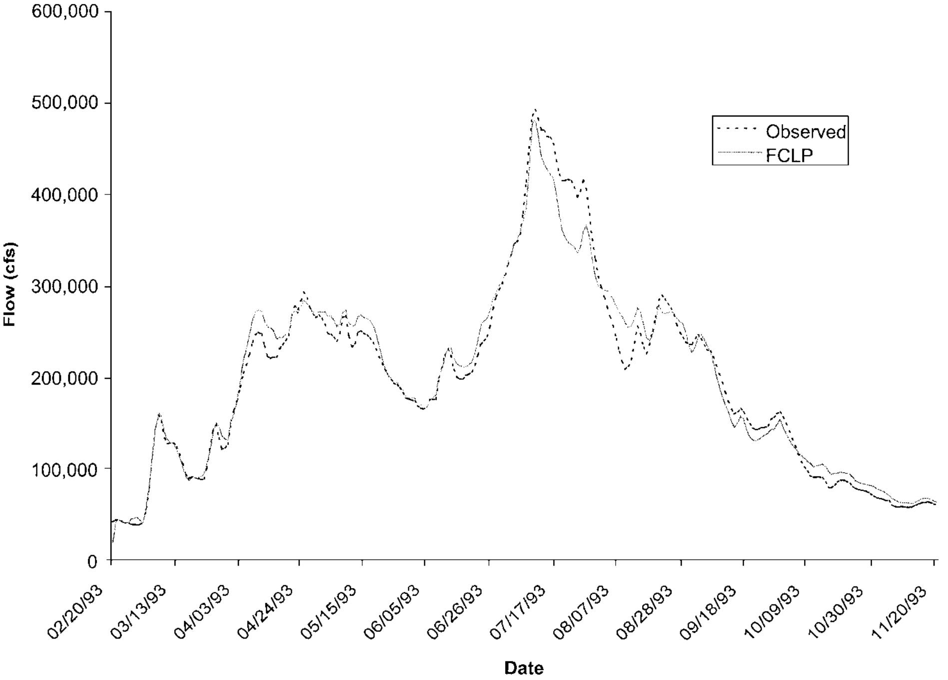

FIG. 6. Quincy Hydrograph—Flood of 1993

To consider the full impact of these flows, the model was configured to run from February 20 through November 25, a total of 282 days, which resulted in a model with >18,000 continuous decision variables, exactly 282 integer (0–1) variables, and >5,600 constraints. Figs. 4–6 illustrate results from the HEC-FCLP model and how they differ from observed data for the flood of 1993.

One would assume that the largest benefit will come from operating the reservoirs as one coordinated system. However, operating as a coordinated system also will lead to the most complex operating procedures, as well as increased hydrologic uncertainty when reservoirs are operated for points far downstream. Therefore, upon comparing the model-computed penalties resulting from the different operating schemes, the simplest operating scheme that leads to penalty values within 2% of those from System A is considered optimal. For example, if Schemes BD and BFG lead to penalty values within 2% of Scheme A, then BFG would be selected as the optimal system.

For the 1993 flood, penalty values resulting from optimal operation of the various Subsystems are listed in Table 4. Since Subsystems BD, CD, BFG, and CFG lead to essentially the same optimal penalty value as System A, there would have been little potential benefit from operating the reservoirs as a system. The only noticeable benefit would have resulted from operating Red Rock Reservoir for flood control at Quincy, indicated by Subsystems BE and CE having significantly higher penalty values than BD and CD, respectively. In 1993, the reservoir system was simply overwhelmed, and the rela-

TABLE 4. Flood of 1993 Calculated Penalties (Subsystems Shown in Fig. 2)

Site (1)	Observed (2)	A (3)	BD (4)	CD (5)	BE (6)	CE (7)	BFG (8)	CFG (9)
Iowa City	69	33	31	31	31	31	31	31
Lone Tree	19	13	13	13	13	13	13	13
Wapello	313	278	278	278	278	278	278	278
2nd Avenue	212	148	148	148	148	148	148	148
14 Street	0	0	0	0	0	0	0	0
Tracy	450	422	422	422	422	422	422	422
Ottumwa	854	853	853	853	853	853	853	853
Keosauqua	102	89	89	89	97	97	89	89
Burlington	154	145	145	145	145	145	145	145
Quincy	2,208	1,427	1,430	1,431	2,006	2,008	1,430	1,431
Coralville	—	10	9	9	9	9	9	9
Saylorville	—	4,414	4,414	4,413	4,414	4,414	4,407	4,407
Red Rock	—	199	200	201	61	61	208	208
Total without storage	4,381	3,408	3,409	3,410	3,993	3,995	3,409	3,410
Total with storage	—	8,031	8,032	8,033	8,477	8,479	8,033	8,034

TABLE 5. Optimal Combinations of Subsystems

Flood year (1)	Optimal system (2)	Within 2% of optimal (3)
1993	CFG	A, BD, CD, BFG
1965	BFG	A, BD
1947	CFG	All
1973	CFG	All
1991	CE	A, BD, CD, BD
1960	CFG	All
1990	CFG	All
1979	CE	A, BD, CD, BE
1974	CFG	All
1944	CFG	All

tively small amount of flood storage provided by the three projects could not be coordinated to make an appreciable difference throughout much of the basin.

Similar reasoning was used to determine the optimal operating scheme for each of the other 10 flood events (USACE 1998). Table 5 summarizes the most basic optimal system (set of subsystems) for each flood event listed, from the most severe flood to the least severe flood.

Table 5 illustrates that during most flood events it is best to operate the three reservoirs independently. Thus, Coralville Reservoir operations are only concerned with flooding on the Iowa River, Saylorville Reservoir flood storage is used only for flood control in the city of Des Moines, and Red Rock Reservoir is operated to control flooding on the lower Des Moines River and at Quincy, Ill. Model results indicate that this policy would be the easiest to implement while still providing near-optimal results.

For the flood of 1991, and to a lesser extent the flood of 1979, potential benefits exist from operating Saylorville Reservoir and Red Rock Reservoir in tandem for flood control on the Des Moines River and at Quincy. Operating Saylorville Reservoir for flood control downstream of Red Rock Reservoir leads to a more complex release policy than the previous one, but in these cases benefits could be realized. Coralville Reservoir operates only for damages on the Iowa River for both of these events.

DISCUSSION

Model runs for the flood of 1965 are the only results in which an appreciable difference (14%) was observed at Burlington with and without flood control from Coralville Reservoir. This is due to the combination of large magnitude flows on the Mississippi River and relatively small flows on the Iowa River. During this event, operators would have been able to use the majority of Coralville Reservoir's storage for flood control at Burlington. For all other events, the penalty at Burlington was reduced by <2%.

Table 6 shows the release priorities for Coralville Reservoir flood-control operations, derived by comparing the penalty function slopes on the Iowa River and at Burlington and arranging them in descending order. Hydrographs of 1965 model results show a release >10,000 cfs from Coralville, which causes damage at Iowa City, to make space in the reservoir to dampen an upcoming peak at Burlington. This operation reduces the flow at Burlington by approximately 2,000 cfs. The 1993 flood event also recorded a peak flow above 265,000 cfs at Burlington; in this case however, Coralville Reservoir's flood control space was needed to reduce the flow at Iowa City below 20,000 cfs. From these results, it appears that operating Coralville Reservoir for flood control at Burlington is beneficial only under very special circumstances—when flows at Iowa City and Wapallo can be maintained below 20,000 and 48,500 cfs, respectively.

Table 7 lists the operating priorities for the reservoirs on the Des Moines River, again based on penalty function slopes. According to this list, Saylorville Reservoir's entire flood-control pool should be used to ensure that flow at 2nd Avenue is <40,000 cfs. Moving down the priority list, if the flow at 2nd

TABLE 6. Coralville Release Priorities

Priority (1)	Keep flow less than (cfs) (2)	Location (3)
1	20,000	Iowa City—Iowa River
2	48,500	Wapello—Iowa River
3	265,000	Burlington—Mississippi River
4	10,000	Iowa City—Iowa River
5	17,500	Lone Tree—Iowa River
6	30,000	Wapello—Iowa River
7	150,000	Burlington—Mississippi River

TABLE 7. Des Moines River Flood Control Priorities

Priority (1)	Keep flow less than (cfs) (2)	Location (3)
1	40,000	2nd Avenue—Des Moines River
2	107,000	Ottumwa—Des Moines River
3	335,000	Quincy—Mississippi River
4	19,400	2nd Avenue—Des Moines River
5	19,000	Ottumwa—Des Moines River
6	270,000	Quincy—Mississippi River
7	90,000	Keosauqua—Des Moines River
8	13,000	Tracy—Des Moines River
9	28,000	Keosauqua—Des Moines River

TABLE 8. Effects of Tandem Operation of Des Moines River Reservoirs

Year (1)	Total Penalty—Des Moines River and Quincy, Ill. Independent (2)	Tandem (3)	Savings (%) (4)
1993	2,943	2,943	0.0
1991	248	194	21.7
1990	33	33	0.0
1979	87	77	11.5
1974	27	27	0.0
1973	183	107	41.5
1965	158	154	2.5
1960	68	67	1.5
1947	211	206	2.4
1944	64	64	0.0
Total	4,022	3,872	3.7

TABLE 9. Effects of Operating Des Moines Reservoir for Flood Control at Quincy

Year (1)	Total Damage—Des Moines River Tandem Operation Without Quincy (2)	With Quincy (3)	Savings (%) (4)
1993	3,526	2,942	16.5
1973	109	108	0.9
1965	205	155	24.4
1960	69	67	2.9

Avenue is not in danger of surpassing 40,000 cfs, the flood-control space of both reservoirs should be utilized to keep the flow at Ottumwa <107,000 cfs. The remaining priorities are more complicated. For example, if the first two priorities are met, then both reservoirs should be used to keep the flow at Quincy <335,000 cfs. However, the question remains as to whether the flood-control burden should be placed evenly on the two reservoirs, or should Lake Red Rock control most of the flows and allow Saylorville Reservoir's flood storage to remain empty for protection of the city of Des Moines?

Analysis of results from Subsystems D and FG can help to answer this question. As illustrated in Table 8, subsystem results indicate that modest benefits can be obtained from operating the two reservoirs on the Des Moines River in tandem. When operating the reservoirs independently, releases from Saylorville Reservoir are regulated only for the city of Des Moines. For most events, only a small portion of Saylorville Reservoir's flood storage capacity is utilized, since inflows into the reservoir are rarely enough to fill the flood-control pool. Model results show that only for the 1965 and 1993 flood events would Saylorville Reservoir reach capacity when operated independently of Red Rock Reservoir. Flooding would be so widespread for these events that Saylorville Reservoir's flood pool would best be used mainly for control in the city of Des Moines whether operated in tandem or independently. When operated in tandem with Red Rock Reservoir, Saylorville Reservoir's flood-control pool would be filled during every event except for 1974. However, reservoir operators do not have perfect foresight, as HEC-FCLP does, and typically it would be imprudent to use the full capacity of Saylorville Reservoir's flood-control space with the city of Des Moines directly downstream.

According to Table 8, a significant benefit would have been obtained through tandem operation in 1973. During this event, large flows entered the Des Moines River System downstream of the city of Des Moines, while flow into Saylorville Reservoir was low. The rare hydrologic conditions of 1973 would have allowed Saylorville Reservoir's flood pool to be used to reduce damages downstream of Lake Red Rock. If operated independently, Lake Red Rock would not have had the flood-control capacity needed to control this flood. During most other events studied, however, the flood pool of Lake Red Rock alone would have been large enough to control the flood flows.

Since the risk assumed is large when filling Saylorville Reservoir's flood pool for control downstream of Lake Red Rock, and Lake Red Rock's flood storage is large enough to contain most floods, the majority of Saylorville Reservoir's flood pool should probably be reserved for flood control in the city of Des Moines. A possible solution would be to divide the Saylorville Reservoir flood pool into two ''virtual'' pools—one for flood control downstream of Lake Red Rock and the other for flood control in the city of Des Moines.

The results endorse operating the Des Moines Reservoirs for flood control on the Mississippi River at Quincy, Ill. Benefits at Quincy are seen in all four of the years studied that had damaging flows on the Mississippi River. Table 9 illustrates the flow-related penalty reduction for these four events when the Des Moines Reservoirs operate for flood control at Quincy.

HEC-FCLP model results and observed 1993 operations have many significant differences. Although Table 4 shows that the total flow-related penalty could have been reduced by nearly 25%, it is incorrect to conclude that current operating procedures are inadequate without first looking at where and why the differences in penalty occur.

The most notable difference between observed and model results during the flood of 1993 is in the operation of Coralville Reservoir. With perfect foresight, HEC-FCLP drew down the reservoir much more in the first few weeks of June than was recorded, as illustrated in Fig. 4. Historical data show releases were cut back to prepare for the planting season downstream although the reservoir was still relatively full. The additional HEC-FCLP drawdown allowed Coralville Reservoir to provide more protection from the large inflows that occurred in late July and August. Were this policy of rapidly drawing down Coralville Reservoir following a flood event adopted every year, it would likely result in greater agricultural losses. The operating procedures for Coralville Reservoir should be reviewed with this in mind.

It is impossible to predict hydrologic conditions 2–3 months in the future with enough certainty to justify making damaging prereleases. Even with much shorter lead times, it is often difficult to convince the general public that they should be flooded today in order to reduce potential system-wide damage in the future. As shown in Fig. 7, such a policy was proposed by the model for the flood of 1993, when the Lake Red Rock flood-control pool was kept empty for 3 months in order to dampen the mid-July flood peak. The optimization results are impracticable in this regard, serving mainly to represent the lower bound of flood damage from a flood event.

LIMITATIONS

As with all reservoir model applications, the implications of the results from this study are limited by the approximations necessary to model an existing physical system. The most widely recognized limitation inherent to LP is that all relationships in the model, such as routing equations and penalty functions, must be approximated with linear or piecewise linear functions. Nonlinear flood routing techniques—those using variable routing coefficients—may provide more accurate results than do linear techniques over a range of discharges [e.g., Ponce (1989)]. Similarly, a nonlinear and/or discontinuous objective function may be more appropriate than the linear (additive) function used in this study.

Additional limitations specific to HEC-FCLP that should be

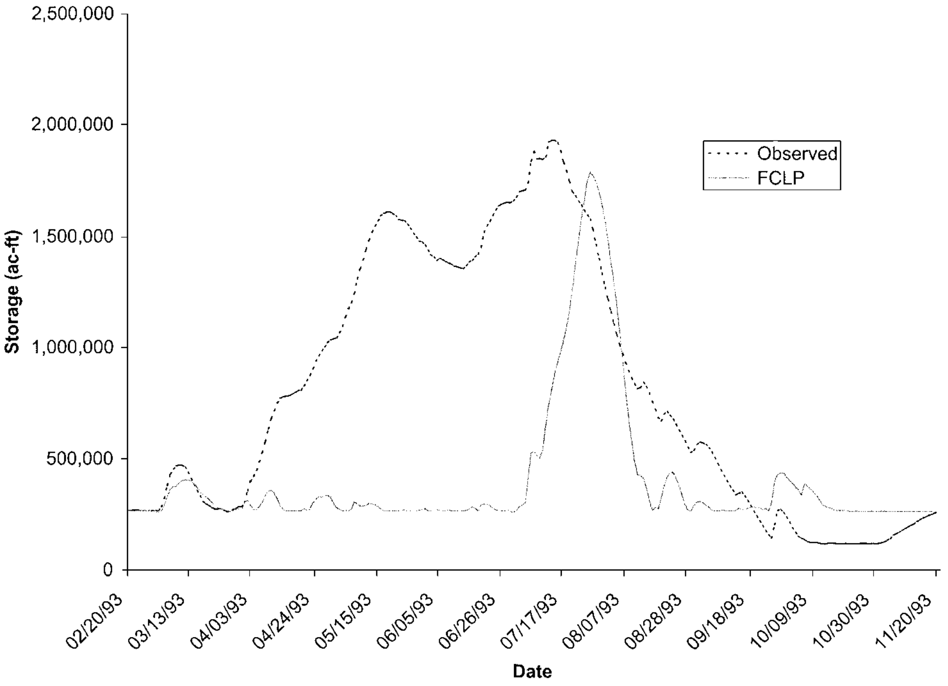

FIG. 7. Lake Red Rock Storage—Flood of 1993

considered during the analysis of practical problems include the following:

- Penalties on change in release, flow, and storage are assessed for each period. This duration-based solution does not directly account for flood damage, especially urban flood damage that is primarily a function of peak discharge, but it does capture the desire of reservoir operators to reduce the flow in flooded areas as soon as possible. The duration-based penalty leads to more realistic results during nonpeak periods than does a penalty function based solely on peak flows. HEC-FCLP is currently being modified to incorporate a combination of peak-based and duration-based penalties.
- HEC-FCLP does not account for the seasonal variation of damage potential that is often associated with agricultural areas. Consequently, for a flood event that spans two or more seasons, it cannot properly optimize the seasonal allocation of flood storage capacity that is common in flood-control systems.
- FCLP is a deterministic model, which means it implicitly assumes that future flows are known with certainty. Thus, as illustrated by this study, HEC-FCLP draws down reservoirs in anticipation of future floods, perhaps even months in advance. While this is not necessarily a limitation, it is an important feature that should be taken into account when using results from deterministic optimization models.

When used for planning studies, computational time is not a limitation of HEC-FCLP. In this study, a global optimum solution to each mixed-integer LP problem was obtained in <15 min using a 200-MHz Pentium II PC. However, this solution time might limit the use of HEC-FCLP for real-time decision support.

CONCLUSIONS

The method of dividing the system into various smaller systems produces results that quantify the potential benefits of making reservoir releases based on selected control points. For the majority of flood events studied, the optimal operational policy would be to operate each reservoir independently. Results indicate that Coralville Reservoir could be operated for flood control on the Iowa River with little consideration for Burlington, Saylorville Reservoir's flood capacity could be used mainly for flood protection in the city of Des Moines, and Lake Red Rock could be operated for flood control on the Lower Des Moines River and at Quincy.

Operating Coralville Reservoir for flood control on the Mississippi River is risky because flood-control space is consumed that could prove more valuable to Iowa City. It is acceptable to operate Coralville Reservoir for flood control on the Mississippi River as long as current and forecasted flows in the Iowa River are low. Optimization results illustrate that this scenario occurred only once during the historical record.

By dividing the Des Moines River just upstream of Lake Red Rock, the effect of operating the two reservoirs, Red Rock and Saylorville, in tandem was illustrated. When operated in tandem, most of Saylorville Reservoir's flood control capacity was used for protection downstream of Lake Red Rock. When operated independently, the majority of Saylorville Reservoir's flood pool capacity was rarely used, and the resulting flows were regulated by Lake Red Rock. Penalty values obtained from tandem and independent operation were within 3% for most of the flood events studied. Since the city of Des Moines is potentially one of the highest damage locations on the river, it would be more risk averse to save a majority of Saylorville Reservoir's flood storage for the city of Des Moines and use Lake Red Rock for flood control downstream.

Review of operations during the Great Flood of 1993, a very rare event, shows that damages could have been reduced if inflows were known months in advance. Obviously, this is not possible with current forecasting technology. However, the damage could also have been reduced during the 1993 flood if current reservoir operation were more averse to extreme events. Release decisions during the flood of 1993 were made based on knowledge of previous events. With new data and a better understanding of the runoff these drainage areas can produce, the release rules should be modified to account for events of this magnitude in the future.

Deterministic optimization models are useful for evaluating the potential benefits of a reservoir system when analyzing operating procedures, but results from these models need to be kept in perspective. Detailed simulation modeling should always accompany these omniscient optimization procedures when developing operating rules for a reservoir or set of reservoirs, since simulation models can give a more accurate estimate of the system performance given a set of operating policies.

Optimization models are only as good as their penalty functions and constraints. Establishing these penalty functions and producing a standard set of historical inflows is an important, though time-consuming task. Not only has this study led to increased understanding of the Iowa/Des Moines Reservoir System—the potential flood control value of each reservoir and the potential damage at various locations—but it has also produced a standardized set of data that will prove invaluable in future studies.

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APPENDIX. REFERENCES

Beard, L. R., and Chang, S. (1979). *Optimizing flood operation rules*. Ctr. for Res. in Water Resour., University of Texas at Austin, Austin, Tex.

Ford, D. T. (1978). ‘‘Optimization model for the evaluation of flood-control benefits of multipurpose multireservoir systems,’’ PhD dissertation, University of Texas at Austin, Austin, Tex.

Glanville, T. D. (1976). ‘‘Optimal operation of a flood control reservoir,’’ Master’s thesis, Iowa State University of Science and Technology, Ames, Iowa.

Labadie, J. W. (1997). ‘‘Reservoir system optimization models.’’ *Water Res. Update*, 108, 83–110.

Lund, J. R., and Ferreira, I. (1996). ‘‘Operating rule optimization for Missouri River Reservoir System.’’ *J. Water Resour. Plng. and Mgmt.*, ASCE, 122(4), 287–295.

Master reservoir regulation manual: Saylorville Lake. (1983). USACE Rock Island Dist., U.S. Army Corps of Engineers.

Master reservoir regulation manual: Lake Red Rock. (1988). USACE Rock Island Dist., U.S. Army Corps of Engineers.

Master reservoir regulation manual: Coralville Lake. (1990). USACE Rock Island Dist., U.S. Army Corps of Engineers.

Optimization subroutine library release 2.1, guide and reference. (1995). IBM Corp., Poughkeepsie, N.Y.

Ponce, V. M. (1989). *Engineering hydrology: Principles and practices*. Prentice-Hall, Englewood Cliffs, N.J.

Scientific Assessment and Strategy Team. (1994). *Science for floodplain management into the 21st century*. Interagency Floodplain Management Review Committee, Washington, D.C.

U.S. Army Corps of Engineers. (1992). Authorized and Operating Purposes of Corps of Engineers Reservoirs. Department of the Army, Washington, D.C.

U.S. Army Corps of Engineers. (1994). ‘‘Operating rules from HEC prescriptive reservoir model results for the Missouri River System: Development and preliminary testing.’’ *Rep. PR-22*, Hydrologic Engrg. Ctr., Davis, Calif.

U.S. Army Corps of Engineers. (1995). ‘‘HEC-DSS user’s guide and utility manuals, user’s manual.’’ *CPD-45*, Hydrologic Engrg. Ctr., Davis, Calif.

U.S. Army Corps of Engineers. (1996). ‘‘Application of HEC-PRM for seasonal reservoir operation of the Columbia River System.’’ *Rep. RD-43*, Hydrologic Engrg. Ctr., Davis, Calif.

U.S. Army Corps of Engineers. (1999). ‘‘Analysis of flood control peration of the Iowa/Des Moines River Reservoir System using linear programming techniques.’’ *Rep. PR-38*, Hydrologic Engrg. Ctr., Davis, Calif.

U.S. Department of Agriculture Soil Conservation Service. (1994). *The Soil Conservation Service responds to the 1993 Midwest floods*. Economics and Social Sciences Division, Washington, D.C.

U.S. Department of Commerce. (1994). ‘‘The Great Flood of 1993.’’ *Natural Disaster Survey Rep.*, Washington, D.C.

Wasimi, S. A., and Kitanidis, P. K. (1983). ‘‘Real-time forecasting and daily operation of a multireservoir system during floods by linear quadratic gaussian control.’’ *Water Resour. Res.*, 19(6), 1511–1522.

Watkins, D. W., Jones, D. J., and Ford, D. T. (1999). ‘‘Flood control optimization using mixed-integer programming.’’ *Proc., 26th Annu. Water Resour. Plng. and Mgmt. Conf.*, ASCE, Reston, Va.

Windsor, J. S. (1973). ‘‘Optimization model for the operation of flood control systems.’’ *Water Resour. Res.*, 9(5), 1219–1226.

Wurbs, R. A. (1993). ‘‘Reservoir-system simulation and optimization models,’’ *J. Water Resour. Plng. and Mgmt.*, ASCE, 119(4), 455–472.

Yeh, W. W-G. (1985). ‘‘Reservoir management and operation models: A state-of-the-art review.’’ *Water Resour. Res.*, 21(12), 1797–1818.