Operating Rule Optimization for Missouri River Reservoir System

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Abstract: This paper describes the application of deterministic optimization to the main stem Missouri River reservoir system and the development and testing of inferred optimal operating rules from these model results. An implicit stochastic optimization approach is taken and tested using a simplified simulation model. This work illustrates the applicability and limitations of applying deterministic optimization to development of strategic operating rules for large-scale water resource systems. For this multipurpose multireservoir system, simple data display and simulation modeling are found to be superior to classical regression techniques for inferring and refining promising operating rules from deterministic optimization results.

INTRODUCTION

As demands on reservoir systems increase and diversify, reservoir system operation becomes a more pressing and controversial issue. Engineering methods are required to aid in resolving the conflicting demands that arise when water and water storage resources are limited. This paper describes application of an optimization-simulation approach for developing preliminary economically-based operating rules for the Missouri River main stem reservoir system.

The development of economically based reservoir operating rules is a classical problem in water resources engineering (Yeh 1985). Two approaches have generally been taken in applying mathematical optimization techniques to this problem. The most theoretically appealing approach is the application of explicitly stochastic optimization methods (Tejada-Guibert et al. 1993; Loucks et al. 1981). These explicit stochastic methods often suffer from great computational inconvenience and limited computational feasibility (Young 1967). In addition, explicit stochastic formulations naturally require explicit representation of probabilistic streamflows or other uncertain aspects of the problem. These representations of probabilistic phenomena are difficult statistically (are uncertain themselves) and typically must conform to one of only a few mathematical forms (such as a Markov chain) (Loucks et al. 1981).

Another approach is to employ deterministic optimization methods to what is admittedly a probabilistic problem. Deterministic representations can typically be more detailed and can almost always be solved more quickly. Deterministic formulations and solution methods also tend to be easier to explain. Most uses of deterministic methods base their formulations on "representative" streamflow or other conditions, selecting "normal," "wet," and "dry" hydrologies, and using deterministic optimization methods to identify promising operating procedures under such conditions (Evenson and Moseley 1970).

A more sophisticated application of deterministic methods, *implicit stochastic optimization*, greatly enlarges the optimization problem by optimizing over a very long representative hydrology. The hydrology often is created from a synthetic streamflow generator, but also has been taken from the historical record (Jettmar and Young 1975). This large deterministic solution, which is hydrologically omniscient, is then scrutinized for consistent operating relationships. Classically, regression techniques have been used to infer reservoir release rules that are functions of presently knowable conditions, such as current season, storage, and inflows, and sometimes inflow forecasts (Young 1967; Bhaskar and Whitlatch 1980; Karamouz and Houck 1982).

More recent applications of implicit stochastic optimization have mixed optimization, regression, and simulation techniques to refine promising operating rules iteratively and test proposed operating rules (Bhaskar and Whitlatch 1980; Karamouz et al. 1992). Some comparisons of advanced explicit and implicit stochastic optimization techniques have found implicit techniques to yield better results, because they can be formulated to more closely represent the problem, often by representing inflows and storage levels less coarsely (Karamouz and Houck 1987). Su et al. (1991) apply stochastic dominance to evaluate alternative operating rules.

However, none of these approaches for establishing optimal operating rules is perfect. Perhaps this is why the problem remains classical. The work presented here extends the application of implicit stochastic optimization through application of a network flow programming model to the six-reservoir main stem Missouri River system, using 90 yr of monthly historical streamflows. The objective function is the sum of economically based penalty functions representing a wide range of operating flow and storage objectives. For this more complex than usual application of implicit stochastic optimization, reservoir operating rules are inferred from the deterministic results using elementary data visualization techniques and are refined and tested using a simplified system simulation model. The work presented here summarizes several reports on this project (Ferreira and Lund 1994; Lund 1992; USACE 1991a,b,c; 1992).

MISSOURI RIVER SYSTEM

The main stem Missouri River system and its operation are described elsewhere in considerable detail (Lund 1992; USACE 1979; USACE 1994). For the purposes of this paper, the main stem of the Missouri River is regulated by six major reservoirs in series, Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point, as depicted in Fig. 1 and described in Table 1. These six reservoirs, with a total storage capacity of roughly 91 km^3 [74 million acre-ft (MAF)], represent about 3.5 times the mean annual flow of the river at Gavins Point. Major purposes for the operation of these reservoirs include hydropower, flood control, recreation (both reservoir and instream), water supply, and navigation. Reservoir operation decisions entail trade-offs between these different purposes, especially during long droughts. These trade-offs have prompted a major review of the operation of the Missouri River main stem system, including the development of reservoir simula-

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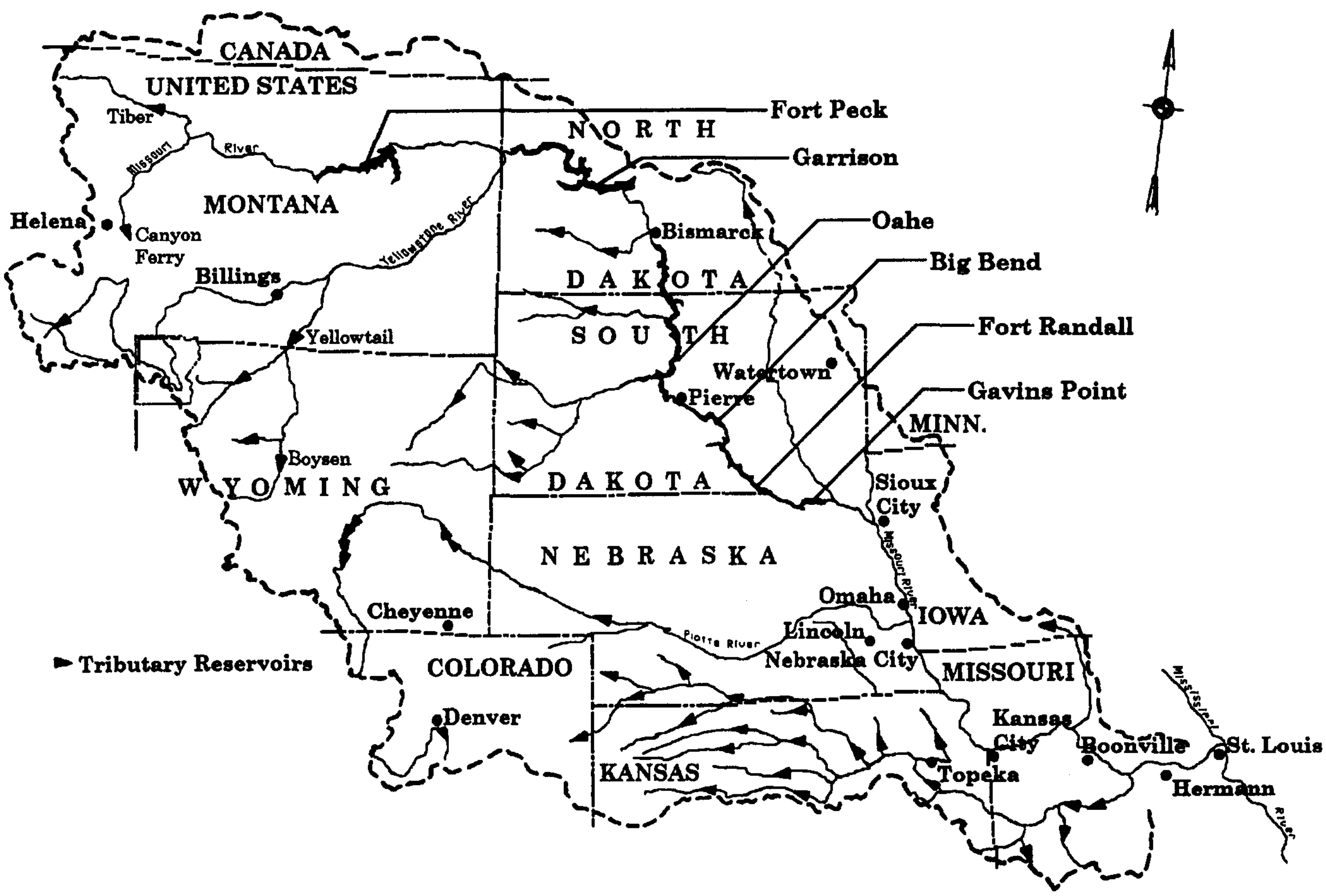

FIG. 1. Map of Missouri River Main Stem System

TABLE 1. Operating Pool Sizes Estimated from HEC-PRM and MRD Model Results (MAF)[a]

Reservoir pool (1)	Maximum storage capacity (2)	Exclusive flood control pool for both models (3)	Annual Operating Pool		Drought Storage		Minimum 90-yr Pool	
			HEC-PRM (4)	Current operations (5)	HEC-PRM (6)	Current operations (7)	HEC-PRM (8)	Current operations (9)
Fort Peck	18.7	1.0	3.5	2.8	3.5	11.1	10.7	3.8
Garrison	23.9	1.5	3.8	4.3	2.3	12.9	16.3	5.2
Oahe	23.3	1.1	1.0	4.0	5.1	12.4	16.1	5.8
Big Bend	1.9	0.1	0.1	—[b]	0.0	—[b]	1.7	—[b]
Fort Randall	5.6	1.3	1.0	1.9	0.0	0.0	3.3	2.4
Gavins Point	0.5	0.1	0.0	—[b]	0.0	—[b]	0.3	—[b]

[a]1MAF = 1.233 km^3.
[b]Reservoirs not included in Missouri River Division long-term simulation model.

tion models for the system that incorporate value functions for individual project purposes (USACE 1994).

HEC-PRM SYSTEM MODEL

The U.S. Army Corps of Engineers' Prescriptive Reservoir Model (HEC-PRM) is a network-flow–based optimization model intended for application to reservoir system analysis problems (USACE 1991c). Convex penalty functions for this model may be incorporated as piecewise linear functions. Typically, penalty functions for the model are created by estimating penalty functions for each reservoir purpose and at each designated flow or storage location in the model, summing these penalty functions at each location, and editing this total penalty function into a convex, piecewise-linear form.

For the Missouri River application (USACE 1991a,b; 1992), the system was represented by six storage links (one for each main stem reservoir), six reservoir release links, and six downstream flow links (since significant flows enter the system downstream of the reservoirs, especially during floods). The furthest downstream link was Herrmann, Mo. Ninety-two years of historical streamflow records were available, with monthly flows being used for the model. Given the potential for floods to occur within a month's time, existing "exclusive flood control" storage volumes in each reservoir were excluded from the model. For the Missouri River application, hydropower penalties for each reservoir were decomposed into two simpler independent penalties based on reservoir release and storage. [Later applications of HEC-PRM to other basins improve hydropower representation with a sequential optimal solution method for the full nonlinear hydropower equation (USACE 1993).]

Economic penalties for hydropower, flood control, recreation, water supply, and navigation purposes were developed for the Missouri River HEC-PRM model by economists with the U.S. Army Corps of Engineers Missouri River Division and Institute for Water Resources (USACE 1991b). These monthly penalty functions were edited to a convex piecewise linear form at the U.S. Army Corps of Engineers Hydrologic Engineering Center. Model results consisted of 92 years of monthly "optimal" releases, storages, and flows for each of the six reservoirs and six downstream reaches. These results represent ideal operation under present reservoir purposes given a repetition of the historical hydrology. Since no end-of-analysis storage level was specified, the last 2 yr of the "optimized" operations drained the system, and so were dropped as anomalous, leaving a 90-yr period of results.

DEVELOPMENT OF SYSTEM OPERATING RULES

The operating rule implications of the HEC-PRM model results were developed in two ways. First, as a preliminary approach, the results were digested into a set of traditional "reservoir pools." Second, a more complete and precise specification of operating rules was inferred from the deterministic optimization results.

Pool-Based Rule System

Most Corps of Engineers reservoirs are operated based on a set of defined reservoir storage "pools." For the Missouri River main stem system, total storage for each reservoir is currently divided into exclusive flood control, flood control and multiple use, carryover multiple use, and permanent pools (Fig. 2). Exclusive flood control storage is operated exclusively for downstream flood regulation. The flood control and multiple use pool is an annual operating pool emptied in the fall for flood control purposes and refilled in the spring for supplying water to reservoir and downstream uses. The carryover pool is essentially "conservation" storage for overyear droughts. Permanent pool storage is storage unneeded or unavailable ("dead" storage) for implementing the current operating strategy for a repeat of the 12-yr 1930s drought of record.

Results of the 90-yr HEC-PRM Missouri River system model were reduced to a similar set of synthetic operating pools by the following algorithm for each reservoir:

1. Exclusive flood control pool capacities were subtracted from the storages available to the HEC-PRM model, reflecting HEC-PRM's inability to operate for less than a 1-month time step. Exclusive flood control pools were taken to be those from current operating policies.
2. The minimum pool for each reservoir was defined as the minimum storage result for each reservoir for the 90-yr optimization analysis period. This was called the 90-yr minimum pool, reflecting the length of the analysis period and is analogous to the current "permanent pool."
3. A value for drought carryover storage was then found by subtracting the 90-yr minimum pool value from the median minimum monthly storage value from the HEC-PRM results. In 50% of the years, storage below this level was untapped, a surrogate for dry-year or "carryover" storage.
4. The remaining reservoir storage capacity, between the median minimum monthly storage value and the bottom of the exclusive flood control pool, was taken to represent a typical within-year or flood control and multiple use pool.

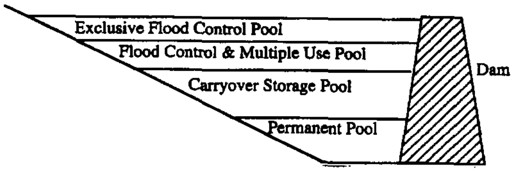

FIG. 2. Pool-Based Operating Rules

For comparability, this algorithm was applied to both HEC-PRM results and the results of the Corps' Missouri River Division's (MRD) long-term simulation model to provide the pool sizes appearing in Table 1.

These results illustrate some significant differences between Missouri River operations suggested by the HEC-PRM model and current operations. As explained earlier, exclusive flood control storage was constrained to the same volumes as those in current operations. Essentially, in HEC-PRM this "pool" was used to represent a safeguard against flood peaks within a one-month time step (USACE 1991a,b).

The total within-year operating pool (flood control and multiple use pool) under HEC-PRM operations was reduced considerably, from about 16 km^3 (13 MAF) to about 11.6 km^3 (9.4 MAF), with a significant shift of this storage pool from the lowest large reservoirs (Oahe and Fort Randall) to the highest reservoir (Fort Peck). As discussed later, one reason for this reduction and upstream shift in the annual operating pool is the absence of seasonal changes in downstream flooding penalties, as a result of changes in ice conditions during the winter.

The overall drought storage pool is reduced from 44.9 km^3 (36.4 MAF) under current operations to 13.4 km^3 (10.9 MAF) under operations suggested by HEC-PRM. HEC-PRM draws down system storage relatively little during significant droughts compared to current operations, valuing in-reservoir uses of water, such as maintaining hydropower head and reservoir recreation, more than release uses, such as downstream navigation. Even during drought, downstream flows are maintained at some minimal level.

The minimum pool level experienced during the 90-yr simulation and optimization model runs totaled 57.2 km^3 (46.4 MAF) for the HEC-PRM model (neglecting Big Bend and Gavins Point storage, which are not included in the MRD simulation model) and 21.2 km^3 (17.2 MAF) for current operations. This vastly increased minimum pool level under HEC-PRM operations also reflects the value placed on avoiding storage-based penalties during droughts.

While these pool-based operating rules are an interesting point of comparison with current system operations (represented by MRD model results) and illustrate some qualitative differences in HEC-PRM's operation of the system, this pool-based approach does not directly offer detailed operating rules, such as detailed seasonal operating advice. A more detailed, but still preliminary, mathematical representation of operating rules was developed, refined, and tested.

Operating Rule System

Simple statistics, tables, and figures of HEC-PRM results were used to infer a structure of operating rules for the Missouri River system and to develop preliminary calibrations for these rules. These rules were structured into three parts and are described in great detail elsewhere (Lund 1992; Ferreira and Lund 1994).

Storage Rules for Three Downstream Reservoirs

The three lowest reservoirs (Big Bend, Fort Randall, and Gavins Point) were found to adhere to rather regular storage levels, varying seasonally throughout the year. This pattern was readily apparent from plots of storage quartiles for each reservoir for each month. These fixed storage target rules are illustrated by the quartile plot in Fig. 3 for Fort Randall. Storage targets were established for each of these three lower reservoirs for each month. Of these three reservoirs, Fort Randall conformed least well to this rule.

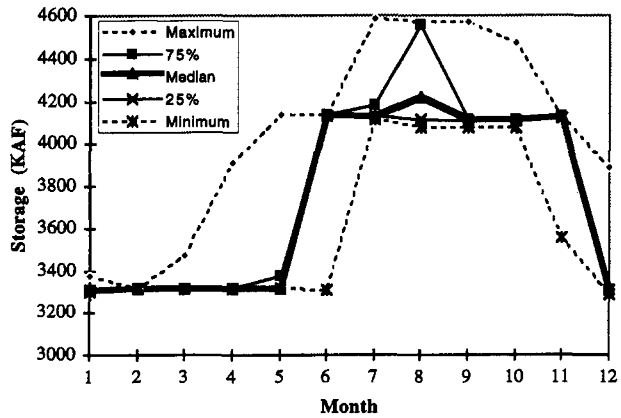

FIG. 3. Quartiles of Seasonal Storage in Fort Randall under HEC-PRM Operations

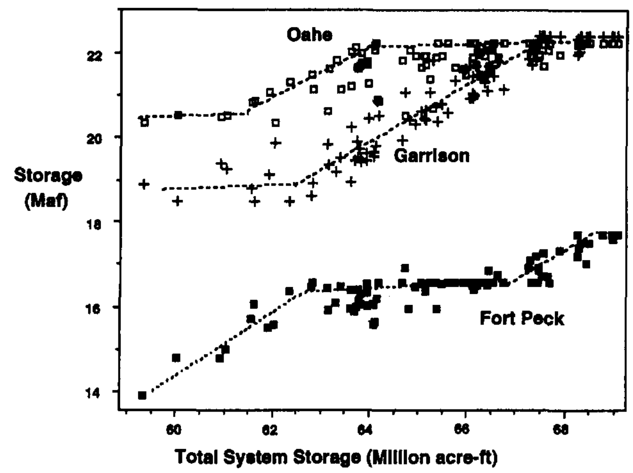

FIG. 4. Storage Allocation in Upper Three Reservoirs for July

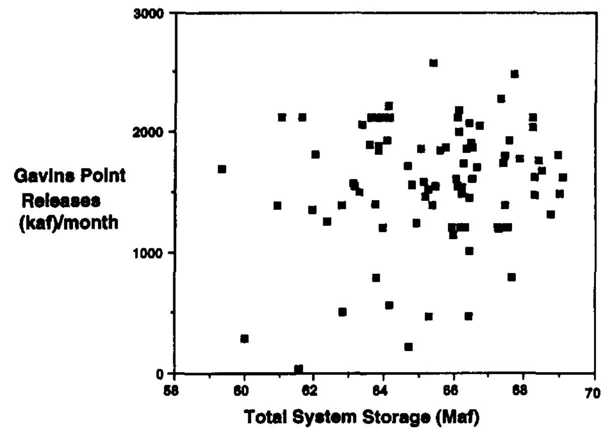

FIG. 5. Plot of Optimal Release Versus Total System Storage for July

Storage Allocation Rules for Upper Reservoirs

Operation of the three large upper reservoirs (Fort Peck, Garrison, and Oahe) is more complex. The dominant pattern was found to be a seasonally varying storage allocation rule that allocates total storage among the three upper reservoirs. A nonlinear pattern became apparent from plots like those in Fig. 4. In this figure, each point represents a storage result from HEC-PRM from July of a particular year. Thus there are 90 points for each reservoir, each of which occurs at a different level of total system storage. Given the small size and constant storage operation of the lower three reservoirs, total system storage is essentially equivalent to total storage in the upper three reservoirs.

The results suggest a consistent nonlinear or piecewise linear allocation of total system storage among the upper three reservoirs. Referring to Fig. 4, as the system is drawn down from a full condition, Fort Peck is drawn down first, until total system storage (including the three downstream reservoirs) reaches roughly 83 km^3 (67 MAF). Further drawdown is then taken primarily from Garrison, then Oahe, and then Fort Peck again. Refill storage allocation follows these rules in reverse. For July, this pattern reduced to the following mathematical rules, where TS is total system storage and units are in MAF (1 MAF = 1.233 km^3):

Fort Peck: If TS < 56.5 then Fort Peck Storage = 0.714∗TS − 23.9
else if TS < 60.5 then Fort Peck Storage = 16.5
else Fort Peck Storage = 0.60∗TS − 19.8
Garrison: If TS < 56.2 then Garrison Storage = 18.5
else if TS < 61.3 Then Garrison Storage = 0.765∗TS − 24.5
else Garrison Storage = 22.4
Oahe: TS − (Fort Peck Storage + Garrison Storage).

Such storage allocation rules were found for each month.

Release Rules from Total System Storage

With monthly storage target rules for the lower three reservoirs and storage allocation rules in place for the upper three reservoirs, complete specification of system operation awaits only a rule for finding total system storage. This requires a rule for establishing releases from the system, either at Oahe, or any of the three downstream reservoirs governed by storage target rules. In this case, release rules for Oahe were developed for each month from HEC-PRM results and greatly refined and improved using a simplified system simulation model (Ferreira and Lund 1994).

The development of release rules from Oahe was the most difficult part of this study. First, plots and regressions were attempted to relate total system storage to release. Such a plot appears in Fig. 5. Attempts at regression, including multiple linear regression including upstream and downstream inflows and various stepwise multiple linear regressions, yielded poor results, with r^2 achieving high values of about 45%. Classical regression methods for developing rules from optimization results were inadequate. For this system, more complex rules were required. These rules were developed and refined manually and iteratively, using a simulation model and tabular and graphical displays and comparisons of simulation and HEC-PRM results.

Typically, these rules had three general parts, releases for flood conditions, drought conditions, and intermediate conditions. The Oahe release rule (with units in thousands of acre-ft, KAF) (1 KAF = 1,233,000 m^3) developed for August follows:

if (inflows upstream of Oahe < 360) Then 1,300
else if (890 < inflows upstream of Oahe < 950) and (1,000 < Inflow downstream of Fort Randall < 1,700) then 2,400
else if (700 < inflows upstream of Oahe < 1,200) and (Inflow downstream of Fort Randall < 900) Then 1,850
else if (inflows upstream of Oahe > 1,200) and (Inflow downstream of Fort Randall < 900) Then 2,100
else if (Inflow downstream of Fort Randall > 10,000) Then 13
else 1,500.

The first line is a drought release rule. If inflows upstream of Oahe are less than 444,000,000 m^3 (360 KAF), then the August Oahe release should be 1.06 km³ (1,300 KAF). This particular rule was triggered in 8 of 90 yr, seven of these during the drought of the 1930s. Given flow, storage, and release data, low inflows above Oahe were found to be the best indicator of a drought.

The next to last line is a flood release rule. Most flooding in this basin occurs largely due to inflows entering below the reservoirs. If inflows in this region are high, flood damage is reduced by greatly curtailing reservoir releases. Thus, if inflows between Fort Randall and Herrmann exceed 12.33 km³ (10,000 KAF), releases from Oahe are reduced to 16,000,000 m³ (13 KAF). This particular rule for August was triggered in only 1 yr. August is typically not a high-flow month.

The remaining parts of this August rule attempt to fine tune releases during intermediate conditions. The development of these rules was largely an empirical exercise. Many rules were tried, with these being selected as being able to reproduce fairly closely the HEC-PRM time series of total system storage, using a simplified simulation model.

An interesting result of this rule development was that in no case, except for spill, was optimal release found to be related to reservoir storage, contradicting traditional reservoir operating rule assumptions developed for predominantly water supply problems (Young 1967). For this problem, optimal releases were found to be better determined by inflows at various locations. This conclusion was supported by the success of these nonstorage-based release rules in simulation results.

TESTING AND REFINEMENT OF RULES THROUGH SIMULATION

The development of storage targets for the lower three reservoirs and storage allocation rules for the upper three reservoirs was accomplished almost solely based on HEC-PRM results. The development of Oahe release rules and the testing of all rules required development of a simulation model for the system. This simulation model needed to be flexible enough to readily include a wide variety of reservoir operating rules, including simple rules not typically part of many reservoir simulation modeling packages, such as the nonlinear storage allocation rules. For purposes of preliminary testing and rule refinement, the model also did not need to contain many system details found in the MRD long-range study simulation model. A simplified monthly system model was developed, called SiMM (Simplified Missouri Model), using the STELLA II modeling package. Inflows to the system and reservoir evaporation volumes were those used in the HEC-PRM model. Reservoir releases were determined using the rules established for the system. Testing and refinement of preliminary operating rules were conducted in three stages and are presented in detail elsewhere (Ferreira and Lund 1994).

1. Testing storage target rules was the first stage. Operation using the reservoir storage targets established for the lower three reservoirs was first compared with HEC-PRM results. The results were quite close, except for some flood control operations at Big Bend and Fort Randall, where HEC-PRM increased reservoir storage to reduce downstream flood damages. This suggests some room for improving these storage target rules and the reasonableness of some operator judgment for flood control. It was felt that these flood control operations would probably be better examined using more detailed models with a smaller time step.
2. Testing storage allocation rules was the next step. The storage allocation rules for Fort Peck, Garrison, and Oahe were tested by applying the storage allocation rules (calibrated from plots such as Fig. 4 for each month) and the time series of HEC-PRM releases from Oahe in the simulation model. This kept total upstream storage the same in SiMM and HEC-PRM and allowed comparison of storage allocation between the two models.

   The results of this test were very positive, as detailed by Ferreira and Lund (1994). A sample comparison of storage time-series appears in Fig. 6. No further calibration of the storage allocation rules was made.
3. The final stage of preliminary testing of operating rules was to compare simulated results of "optimal" rule-based operation (using SiMM) with HEC-PRM results

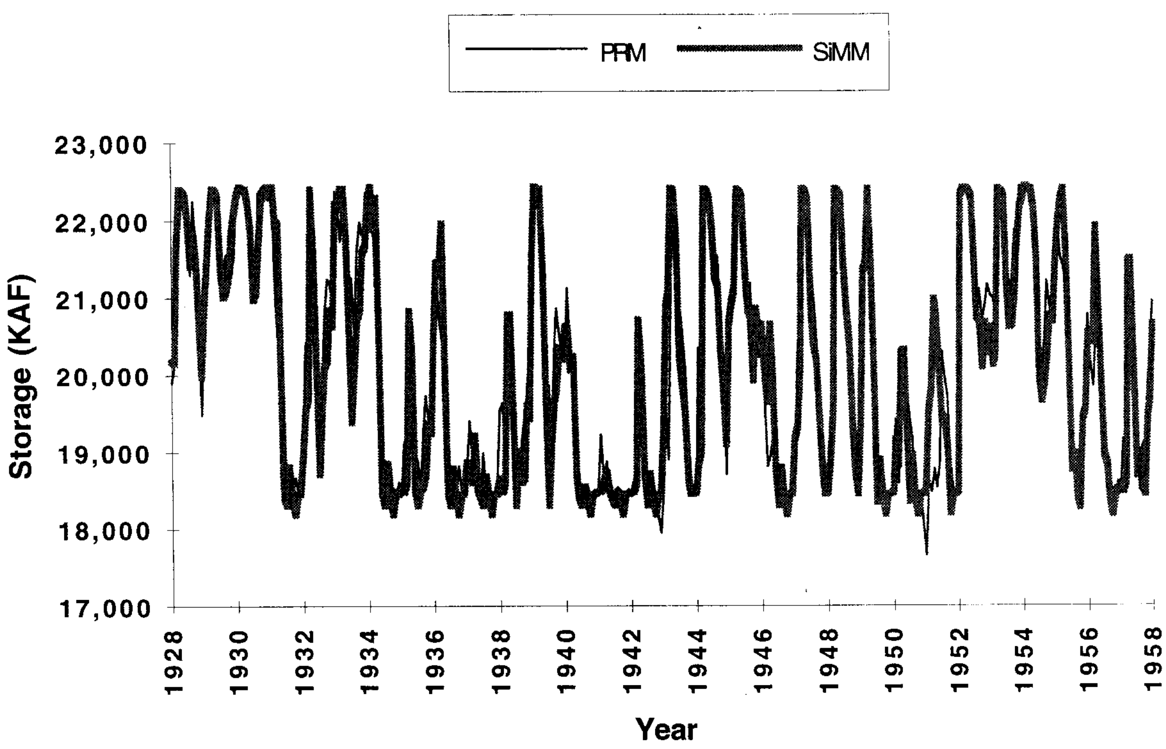

FIG. 6. Sample of Test Results for Storage Allocation Rule for Garrison

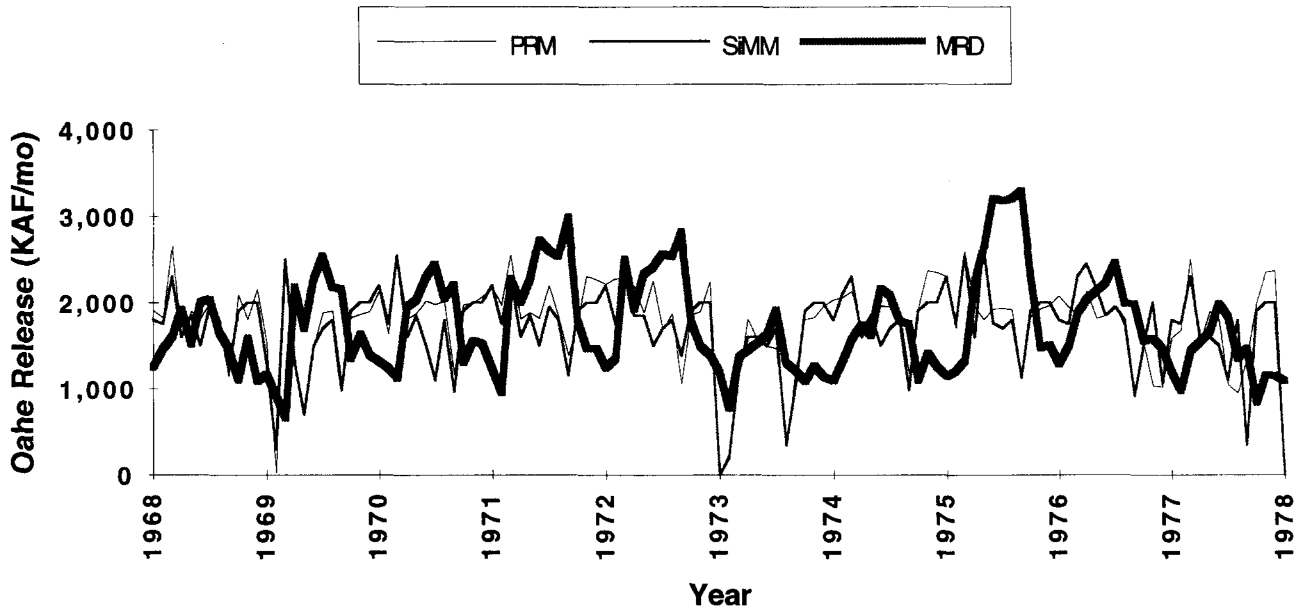

FIG. 7. Comparison of "Optimal" Rule, HEC-PRM, and MRD Simulation Results for Oahe Releases, 1968–1978

and simulated current operating policies, represented by the MRD long-range simulation model. These differences were compared with time-series plots of individual decisions and statistically by the square root of mean squared differences. The square root of the mean squared difference is defined as

$$\sqrt{\frac{1}{n}\sum_{j=1}^{n}(X_{PRMj} - X_{SIMMj})^2} \quad (1)$$

where n = the number of data compared; and X_{PRMj} and X_{SIMMj} = the HEC-PRM and simulated data values for which the difference measure is calculated. These comparative statistics and plots were prepared for all reservoir decision time series, as well as resulting reservoir storage and downstream flow results time series (Ferreira and Lund 1994).

Fig. 7 compares SiMM Oahe releases between 1968 and 1978 with those from HEC-PRM and the MRD simulation model. This particular plot shows the effect of SiMM's inflow-based drought release rules compared with current operating rules, which are based to a greater degree on total system storage. Similar plots were developed for all other modeled periods and reservoirs (Ferreira and Lund 1994). The statistical comparison of release results is more compactly displayed in Table 2. Only for Fort Peck are current release policies (MRD simulation results) closer to HEC-PRM results than SiMM results. For most reservoir releases, SiMM-simulated "optimal" operating rules produced results much closer to HEC-PRM than would current operating procedures.

Other results of the simulation of "optimal" operating rules were also fairly close to HEC-PRM results. Table 3 compares the square root of mean squared differences between SiMM results and the HEC-PRM and MRD simulation of downstream flow results.

Fig. 8 compares simulated and HEC-PRM Garrison storage results for 1928–1958, including performance during the 1930s drought. Table 4 shows statistical comparison of model results for storage at all reservoirs. Both comparisons seem to indicate close, but imperfect, correspondence between simulated "optimal" rules and HEC-PRM results.

TABLE 2. Square Root of Mean Squared Differences from HEC-PRM Results for Reservoir Releases

Reservoir (1)	Full Time Series SiMM (2)	Full Time Series MRD (3)	1930s and 1950s Droughts Excluded SiMM (4)	1930s and 1950s Droughts Excluded MRD (5)
Fort Peck	326	295	301	280
Garrison	546	646	536	573
Oahe	440	625	452	658
Fort Randall	480	699	494	759

TABLE 3. Square Root of Mean Squared Differences from HEC-PRM Results for Streamflows at all Downstream Links

Model (1)	Full time series (2)	1930s and 1950s droughts excluded (3)
SiMM	481	495
MRD	711	777

COMMENTARY ON METHOD

Limitations

The practical implications of these results for the Missouri River system are limited by several approximations made for the Missouri River HEC-PRM application. Under current operations, concerns for ice-related flooding in winter induce drawdown of Fort Randall and Oahe in the fall, to be refilled with hydropower releases from the upper reservoirs before spring. The absence of seasonal variations in downstream flooding penalties used in the HEC-PRM application implies that this important consideration is neglected in operations suggested by HEC-PRM.

Hydropower penalties in the HEC-PRM model used for this study took the form of independent piecewise penalty functions; hydropower generation penalties were represented with independent functions of release and storage. Newer versions of HEC-PRM incorporate a sequential mathematical programming approach to allow more accurate representation of hydropower production, as well as a new network flow program solver (Martin 1987; USACE 1993).

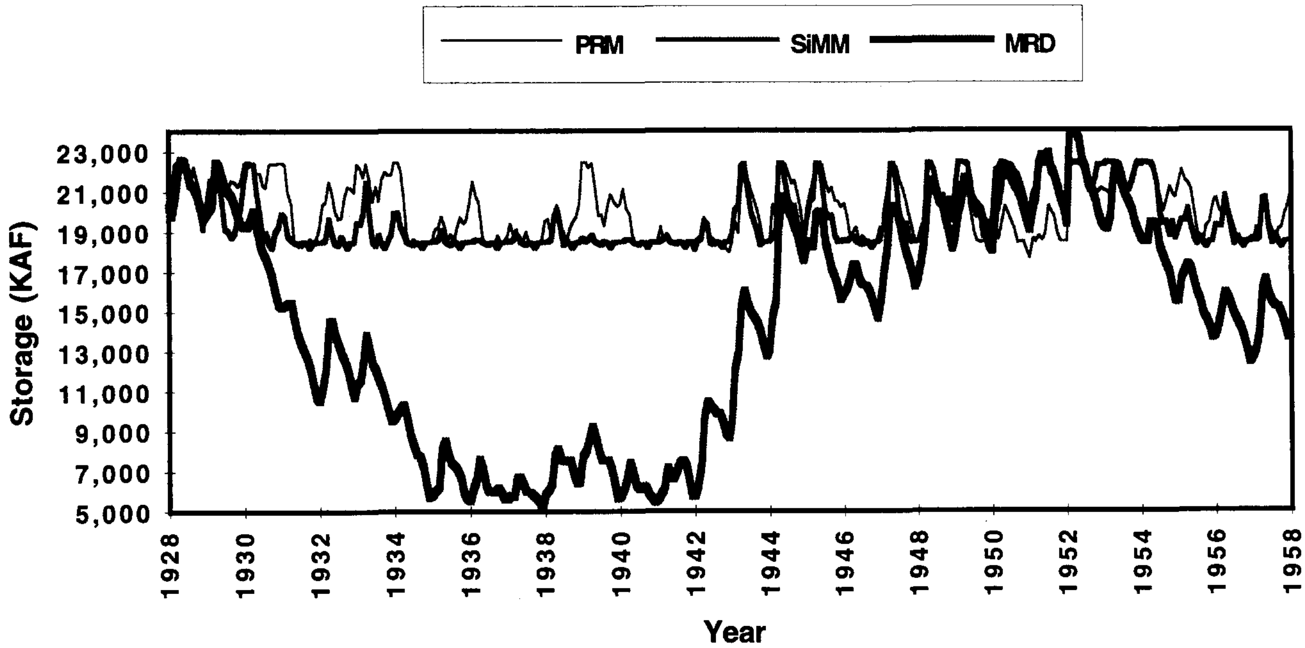

FIG. 8. Comparison of Simulated and HEC-PRM Garrison Storage for 1928–1958

TABLE 4. Square Root of Mean Squared Differences from HEC-PRM Results for Reservoir Storages

Reservoir (1)	Full Time Series SIMM (2)	Full Time Series MRD (3)	1930s and 1950s Droughts Excluded SIMM (4)	1930s and 1950s Droughts Excluded MRD (5)
Fort Peck	1,524	3,385	1,136	1,374
Garrison	1,393	4,776	1,323	1,584
Oahe	1,969	5,193	1,615	2,650
Fort Randall	131	638	135	609
Upper three reservoirs	4,026	12,686	3,211	3,511

The addition of forecast flows to the data set used for inferring and testing operating rules could have aided in making Oahe reservoir release decisions and general flood control operations. A significant portion of annual runoff derives from snowmelt, so some estimate of this quantity should be available for real operations. Unfortunately, these data were unavailable for this study.

The results of deterministic optimization models, such as HEC-PRM, also presume perfect and long forecasts of streamflows. Thus, HEC-PRM results draw down reservoirs in anticipation of floods, often several months ahead of time, and never hedge releases in false anticipation of drought. Such operations, while optimal with perfect prescience, are unlikely to be optimal in a world with limited hydrologic information. These inherent limitations of deterministic optimization must be corrected for during subsequent simulation studies.

For the reasons described above, the operation rules developed in this study cannot be considered final. However, it is clear that HEC-PRM and similar deterministic optimization models can be useful analytical tools in reservoir operation planning studies. HEC-PRM offers a rigorous and yet simple approach for the development and updating of preliminary reservoir operation plans. The results of such optimization studies should be considered as a point of departure for more detailed simulation studies, assessing the sensitivity, further refining, and testing these preliminary rules.

Historical Hydrology

The use of a long (92 yr) historical streamflow record for this study also was a departure from most applications of implicit stochastic optimization, which are classically based on statistical hydrology (Young 1967; Jettmar and Young 1975; Bhaskar and Whitlatch 1980). For optimizing normal operations, the use of a long historical record seems as representative as the use of stochastic hydrology under the best circumstances and assumptions, and has the added benefits of clarity of method, avoidance of methodological intricacies, and lack of expense. For suggesting optimal drought operations, the use of the historical flow record for this case, where economic values for storage are relatively high, storage volumes are rather large, and droughts are typically of long duration, seemed to give consistent operating rule advice: make minimal releases during drought. It seems unlikely that this advice would have changed significantly if stochastic hydrology had been used for this case. Drought operations here were motivated more to preserve storage uses of water (recreation and hydropower) than as a form of hedging to meet downstream water uses, where the frequency of shortages can motivate holding water in storage.

Further Applications of this Approach

Although only monthly operations were investigated in the Missouri River study, there appears to be enough similarities among some months to develop seasonal operation rules, combining rules for some months.

Since completion of this Missouri River study, the approach of applying HEC-PRM to infer optimal operating rules has been applied to the Columbia River system (USACE 1995) and Alamo Reservoir in Arizona (Kirby 1994) using long streamflow records (50 yr for the Columbia River system and 103 yr of Alamo Reservoir inflows). In both cases, preliminary results indicate that relatively clear operating rules can be inferred from long periods of deterministic optimization results.

Methodological Sophistication

The advent of computers in water resources engineering has facilitated great advances in methodology. A host of simulation and optimization techniques are now possible. Some of these techniques have even become relatively easy to use. While inexpensive computational capacity and sophisticated techniques are now widely available, relatively "low-tech" approaches can still provide valuable engineering functions and have also been facilitated by improvements in computer technology.

As illustrated by this study, the value of computers for enhancing traditional, simpler approaches to data analysis and data display (summary statistics, tables, and figures) have been relatively neglected and may be of ultimately greater importance for engineering practice in reservoir operations. The yield from combining computerized traditional data analysis with simulation and optimization is likely to be great.

Additional statistical and relationship-fitting techniques have recently been suggested (Quentin Martin, unpublished memo, 1992) and applied to developing reservoir operation rules from deterministic optimization results, including the use of principal components analysis (Saad and Turgeon 1988; Saad et al. 1992) and artificial neural networks (Saad et al. 1994). These are promising and more flexible extensions to classical regression approaches for inferring operating rules from deterministic optimization results. These newer methods for inferring operating rules from deterministic optimization results were not explored for this Missouri River study.

While the limitations of implicit stochastic optimization are evident, the method is amenable to application by local reservoir operation engineers and relatively understandable for users potentially in conflict over operation of particular reservoir systems.

CONCLUSIONS

Operation plans were successfully inferred from deterministic network flow optimization results for the main stem Missouri River system, one of the nation's largest multipurpose, multireservoir water resource systems. Common tabular and graphical display techniques and careful observation of data listings were used to infer operation plans from deterministic optimization results. A simple reservoir simulation model was used to refine and test proposed operation rules. Several conclusions are drawn from this work.

HEC-PRM can be used to identify promising operation plans for a large complex system, such as the Missouri River system. The methodology used in the development of rules was simple: observation of patterns and trends in HEC-PRM output data followed by refinement and testing of rules by a simple mass balance simulation model. A simple but flexible simulation model of the Missouri River system greatly aided the task of testing and refining the operation rules. Reservoir operating rules suggested in this report are simple. They include (1) monthly storage target rules for Big Bend, Fort Randall and Gavins Point reservoirs; (2) monthly storage allocation rules for Fort Peck, Garrison, and Oahe; and (3) monthly release rules for Oahe.

Deterministic optimization using historical streamflows is not outdated. Preliminary system operation rules for a large multipurpose multireservoir system can be inferred from deterministic optimization results based on a long hydrologic record. In this case, a network flow formulation and solution method furnished optimization results for a 90 yr period with a monthly time step. This approach had several significant advantages, as well as disadvantages, relative to explicitly stochastic optimization.

Simulation modeling is an essential companion for refinement and testing of "optimal" operating rules. Several parts of the proposed operating rules, such as Oahe releases, required the use of simulation modeling for operating rule calibration. Further, more detailed simulation modeling, performed by the actual managers of the reservoirs, would be required for further refinement and testing of these rules.

"Low-tech" data analysis is still valuable. A variety of simple tables, plots, and statistics were essential for analyzing the extensive results of simulation and optimization models. These data display techniques were more successful for identifying promising operating rules than linear regression techniques, classically used for this problem. The same computer technology that has facilitated development of very sophisticated data analysis techniques also greatly facilitates use of simple data analysis techniques. Tens or hundreds of plots can now be generated and examined with the same effort needed to implement more sophisticated data analysis techniques.

Release rules based on storage are not always optimal. For this case, no relationship, other than spill, was found between optimal reservoir releases and reservoir storage. The best release rules were found to be functions of upstream and downstream inflows only. This differs from the now classical use of reservoir storage as the most important basis for reservoir release decisions.

Optimization models are only as good as their penalty functions. The most difficult and expensive part of any practical optimization model is usually the development of penalty functions. Error in penalty functions is also likely to be the greatest cause to doubt the utility of model results. In this case, one of the greatest practical limitations of the results is the absence of seasonal variations in flood control penalties to reflect ice-related changes in channel hydraulics.

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