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This report documents preliminary efforts taken to develop reservoir operation plans for the main stem Missouri River System using deterministic optimization results from the Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM). The report discusses the interpretation of the HEC-PRM results for the specific purpose of developing or refining operation plans for the reservoir system. Since the HEC-PRM results for this work were preliminary, the operation plan suggestions uncovered by this work are also necessarily preliminary.

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Preface

This report describes preliminary efforts taken to develop reservoir operation plans for the main stem Missouri River system using deterministic optimization results from the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM).

The interest taken by the profession and the public in improving and "optimizing" the operation of the nation's reservoirs has now led to the application of a computationally tractable optimization model to the management of one of the nation's major reservoir systems, the six-reservoir main stem Missouri River system. As with all modeling (including simulation), the formulation of the model and the interpretation of the results are typically of much more ultimately practical importance than the actual coding and computational performance of the model. The Phase I report (U.S. Army Corps of Engineers, 1991b) amply deals with the formulation of this model application. This report discusses the interpretation of the model's results for the specific purpose of developing or refining operation plans for the reservoir system. Since the HEC-PRM results for this work were preliminary, the operation plan suggestions uncovered by this work are also necessarily preliminary.

This report was written by Jay R. Lund, as a consultant. Many others contributed to and commented on the work presented here. Mike Burnham, George Patenode, Karen Wilson, David Ford, Bob Carl, Marilyn Hurst, Richard Hayes, Darryl Davis, David Moser, and Vern Bonner are all heartily thanked.

Summary

Report Summary

As demands placed on the operation of the nation's reservoirs become greater and more diverse, the problem of finding the most desirable set of operation plans becomes more difficult and controversial. This has certainly been the case with the main stem Missouri River system, whose operation has been affected by recent designations of threatened and endangered species, a major drought, and increasing recreational, water supply, and irrigation uses. This report presents the results of preliminary work which suggests optimal operation plans for this system, through the use of deterministic optimization and long streamflow records.

The problem of determining optimal reservoir operation plans is longstanding, difficult, and unresolved, both in theory and in practice. Numerous approaches have been proposed, but none has proved to be both generally applicable and rigorous. One of the more general and rigorous approaches is to employ deterministic optimization techniques for a given reservoir system using a long record of historical or synthetic system inflows, followed by the development of reservoir operating rules which most closely mimic the time-series of optimal decisions produced by the optimization model. When a long streamflow record is used, this approach can be called *implicit stochastic optimization* (Whitlatch and Bhaskar, 1978; Klemes, 1979; Karamouz, et al., 1992).

In this report, the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) of the main stem Missouri River system is used as the basis for such an implicit stochastic optimization. Phase I of this model application employs 92-years of historic monthly streamflow record, represents the operation of six reservoirs and flows at six downstream locations, and optimizes for five different purposes at these twelve locations. As such, to the author's knowledge this application represents the largest and most multi-purpose reservoir system ever examined for rule development by implicit stochastic optimization.

Preliminary operation plans were successfully developed for this system. Two sets of preliminary operation plans were developed. The first set of plans suggests modifications to the existing operation plan for the system, represented by the system's Master Water Control Manual (U.S. Army Corps of Engineers, 1979). The second set of preliminary operation plans is developed based on qualitatively different operating procedures. The development of these operation plans employed a number of methodologies, including engineering judgement aided by statistical and graphical display, regression, reservoir operation theory, and simple simulation modeling.

While both sets of plans appear to produce operations similar to HEC-PRM results, the plans remain preliminary, unrefined, and largely untested. Testing and refinement of operation plans developed from optimization results is almost always required, owing to the simplifications required in the formulation of even the best optimization models. Such testing and refinement typically employs more traditional simulation modeling and may involve additional optimization model runs. Such testing and refinement was not performed on the preliminary rules developed because it would have been inappropriate to finalize these rules given the preliminary nature of the HEC-PRM penalty function.

Several aspects of the preliminary penalty functions employed here merit further attention:

- The penalty functions for the various purposes require a final review and finalization,
- It may be desirable to re-examine the formulation of arcs and nodes, perhaps extending the network further downstream,
- Penalty functions for ice-related flooding should be added, and
- Some minimum flow/release constraints or penalties might be desirable.

In addition, some adjustment in upstream flow depletions may be required. To provide the basis for insight into the operation of the main stem Missouri River system, additional HEC-PRM runs will be needed which incorporate these changes.

While the operation plans presented in this report are preliminary and untested, they do serve to demonstrate the ability to develop operation plans from HEC-PRM results for a large and complex system. With suitable refinement in the HEC-PRM application, sufficient effort in developing operation plans from refined HEC-PRM results, and sufficient refinement and testing of suggested operation plans through simulation studies, HEC-PRM should be able to provide useful insights for the operation of the main stem Missouri River system.

Results Summary

The primary purpose of this report was to demonstrate the feasibility of developing reservoir operation plans from HEC-PRM results for the Missouri River main stem system. Bearing in mind the preliminary nature of the rules developed in this report, some sample operation plan results are presented briefly below to provide an idea of the types of operating rules that can be produced using HEC-PRM results.

Reservoir operating rules are used by reservoir operators to determine the release from a reservoir, given current knowledge. Current knowledge typically includes the current time period (usually month of the year), current reservoir storage, current inflows, and sometimes short term inflow forecasts. Operating rules may establish release or storage decisions. A release decision rule could have the form, "In June, if reservoir storage is between 300,000 and 400,000 acre-feet, release 50,000 acre-feet." A storage decision rule could have the form, "In June, keep the storage level in the reservoir at 350,000 acre-feet." As discussed in Appendix A, reservoir operating rules can take a wide variety of specific forms.

The report outlines a systematic process by which preliminary operating rules were developed for the Missouri River main stem system using HEC-PRM results. Experience, graphical display, statistical analysis, and regression were all used in the development of these rules (Chapter 5). The preliminary rules developed for the Missouri River main stem system have several forms. For the three smallest reservoirs, simple storage decision rules are suggested by the HEC-PRM results, such as, "In February, keep storage at Fort Randall at 3.3 million acre-feet of storage." These simple rules seemed to fit the HEC-PRM results remarkably well for the three smallest reservoirs, as discussed in Chapters 4 and 5.

For the three largest reservoirs, such simple rules did not match HEC-PRM results at all. A more complex rule form was found to be superior. This rule allocated total storage among the three reservoirs, depending on the month and the amount of total storage. This preliminary rule is depicted in Figure 1 for July. The HEC-PRM results appear as points on this plot, with the preliminary rules graphed as dashed lines. For any amount of total reservoir storage, these rules determine how much of this total storage should reside in each of the three largest reservoirs. Note that the allocation of water varies over the range of total storage levels, with different reservoirs being drawn down or refilled preferentially at different total storage levels. Considering the wide variation in flow conditions over 92-years of input data, rule seems to work remarkably well.

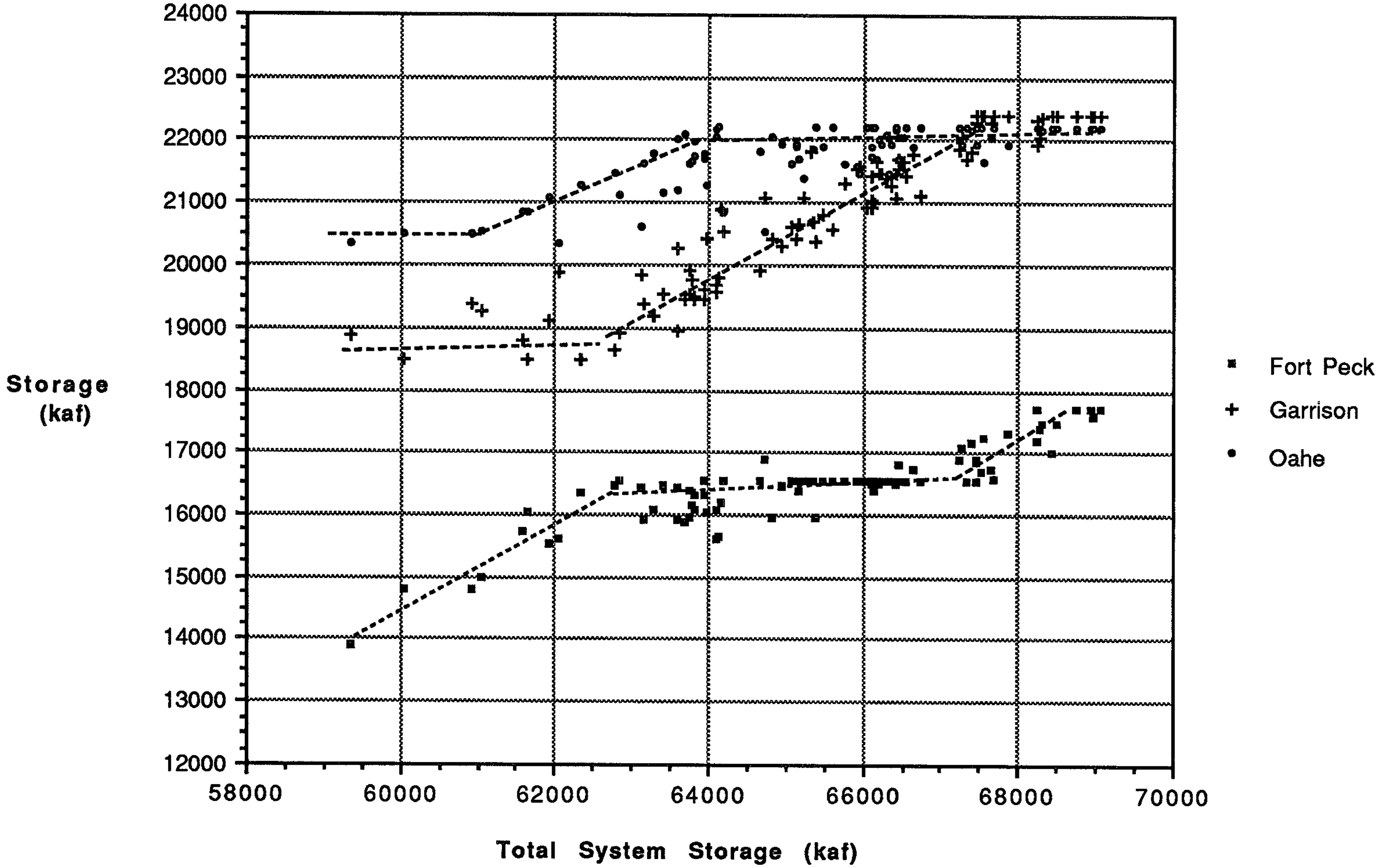

Figure 1

July Optimal Storage Relationships

To completely specify the operation of the reservoir system, a rule is required to determine release to downstream from the reservoir system. These rules were the most difficult to formulate and consisted of maintaining certain minimum flow levels downstream and avoiding contributing to flooding downstream caused primarily by downstream inflows. As shown in Figure 2, optimal releases from Gavins Point (GPToRel) are typically reduced to reduce flooding at downstream locations (Sioux City, SUXoFlow; Omaha, OMAoFlow; Nebraska City, NCNoFlow; and Kansas City, MKCoFlow). This is particularly evident in Figure 2 for the July floods of 1902, 1904, 1909, 1915, 1951, 1958, 1969, 1973, and 1984, which all have a major contribution by flood flows entering downstream of the main stem system. Navigation flows at Sioux City and Omaha are sacrificed to reduced flood damage downstream for these July events. Aside from these flood control events, downstream water supply and navigation flows are maintained in July, even during the long drought of the 1930s. This pattern or releases varies somewhat by month, particularly during the Fall months, when navigation flows are not met during the 1930s drought of record, as discussed in Chapter 5.

Another form of operating rule that can be developed from HEC-PRM results is the derivation of optimal reservoir pool sizes. Quite often, the operation of a reservoir or reservoir system is guided by a set of reservoir pools. For the main stem Missouri River system, the storage in each reservoir is divided into:

- a permanent pool, which should rarely if ever be depleted;
- a carryover or drought storage pool, to maintain downstream flows during drought years;
- an annual operating pool, which balances seasonal flows in "normal" years; and
- exclusive flood control storage, to accommodate especially large or rapid floods.

HEC-PRM results can help estimate the optimal sizes of these pools.

For the Missouri River HEC-PRM application, calculations which estimate the optimal pool sizes from HEC-PRM results are depicted in Table 1. These results are discussed more fully in Chapters 4 and 5. The size of the minimum pool is estimated as the minimum storage found in each reservoir during the entire model optimization of the historical streamflow record (Row 2).

For this application of HEC-PRM the exclusive flood control pool was fixed and excluded from the modeled reservoir capacities. Therefore, the combined size of the carryover and annual operating pools would then be the maximum storage attained over the optimized period minus the permanent pool size (Row 3).

The size of the annual operating pool for each reservoir is estimated by subtracting the minimum monthly median storage (Row 5) from the maximum monthly median storage (Row 4). This yields the median year's annual operating pool (Row 6). For example, as discussed in Chapter 4, for the median year Garrison reservoir has a peak storage in August of 21.314 MAF (Row 4) and a minimum median monthly storage in March or 18.626 MAF (Row 5). The range between these two storages (2.688 MAF) can then be considered as a median annual operating pool (Row 6).

The amount of carryover or drought storage is then estimated by subtracting the annual operating pool size from each reservoir's total capacity (Row 7). In all cases, the actual storage ever encountered for each reservoir during the optimized historical record (Row 1) equaled its modeled storage capacity (Row 8).

Although a great deal of testing, analysis, and probable modification should be done before these results are considered to be more than preliminary, these results, and their more detailed presentation in the body of the report, should provide examples of the practical results that can be achieved through the use of HEC-PRM. The flexible approach taken to develop these rules holds promise for applications of HEC-PRM to other reservoir systems.

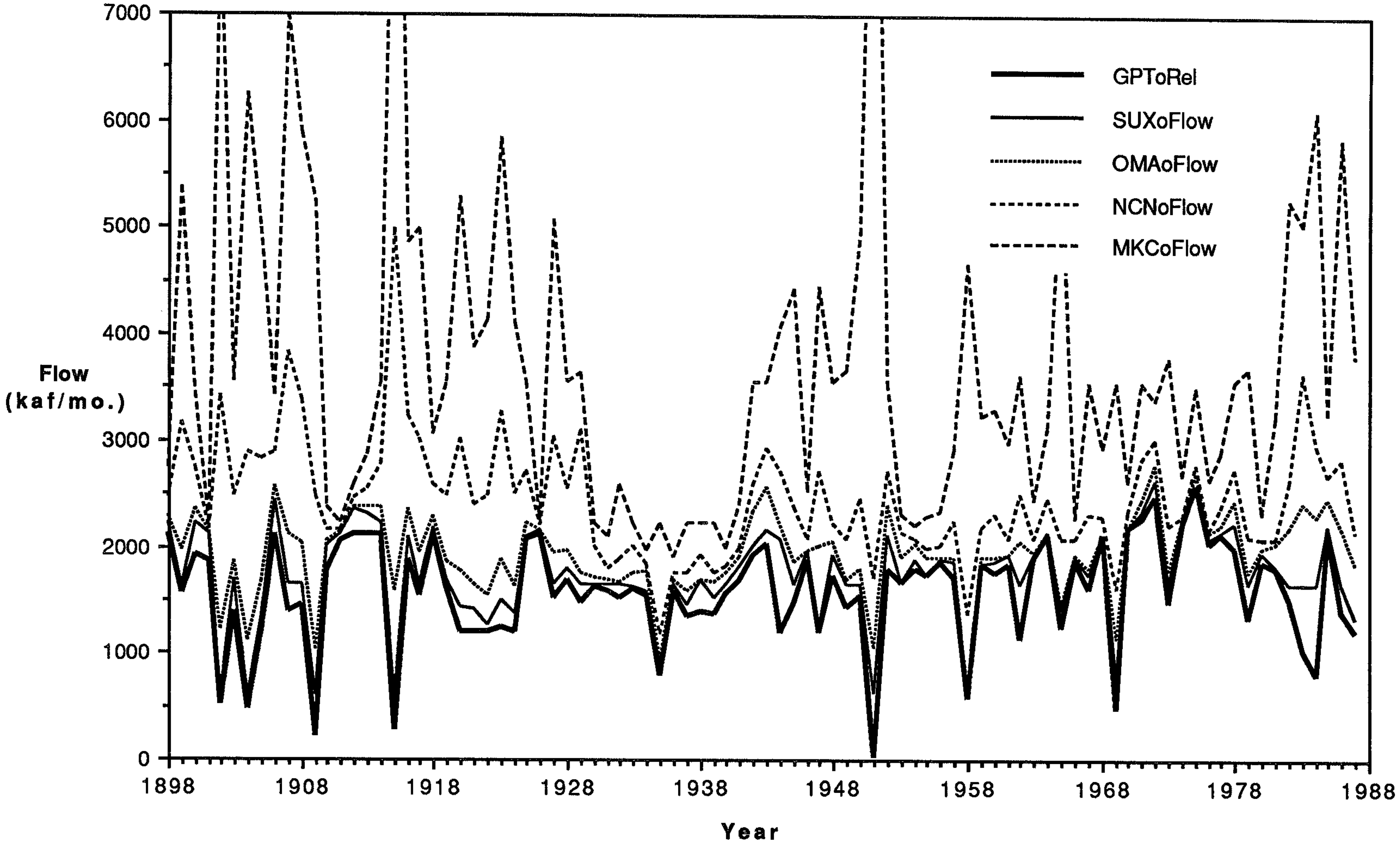

Figure 2

Time Series of Optimal July Flows Downstream

Table 1
Operating Pool Sizes Derived From HEC-PRM Results

		Storage Quantity (MAF):					
	Pool	Ft. Peck	Garrison	Oahe	Big Bend	Ft. Randall	Gavins Point
Row 1:	Maximum Pool of 90-yr. Record	17.699	22.430	22.240	1.813	4.585	0.432
Row 2:	Minimum Pool of 90-yr. Record	10.696	16.308	16.089	1.673	3.287	0.338
Row 3:	Combined Carryover and Within-year Storage (Row 1 - Row 2)	7.003	6.122	6.151	0.140	1.298	0.094
Row 4:	Maximum Median Storage	16.559	21.314	22.240	1.725	4.218	0.432
Row 5:	Minimum Median Storage	14.231	18.626	21.168	1.693	3.305	0.372
Row 6:	Median Year Operating Pool Size (Row 4 - Row 5)	2.328	2.688	1.072	0.032	0.913	0.060
Row 7:	90-Year Carryover Pool Size (Row 3 - Row 6)	4.675	3.434	5.079	0.108	0.385	0.034
Row 8:	Modeled Capacity of Reservoir	17.699	22.430	22.240	1.813	4.585	0.432

Chapter 1

Introduction

This report reviews the role of the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) in the development of operation plans for the Missouri River's main stem reservoir system. The report focuses specifically on how the results of a long-period deterministic optimization model can be used to infer optimal operating rules for a large multi-reservoir system that must operate with significant uncertainty regarding future streamflows.

RESERVOIR OPERATION PROBLEM

The Missouri River's main stem reservoir system is immense. The reservoir system itself spans four states and is the largest source of Missouri River water for three downstream states. As the water regulation facility for the largest river in this region, the operation of the main stem system plays a significant and often predominant role in water-related economic, social, and environmental activities within this large and diverse region.

The operation of such a facility requires compromises and trade-offs to be made. Not everyone will be satisfied with a given operational scenario, given the limited streamflow, limited storage, and water use and storage demands which often exceed water supplies. Yet, as a public facility of unusual and widespread importance, the region's diverse publics have a right to know how these operations were derived and expect some formal and broad-based justification of operational procedures. Furthermore, demands for such justification of reservoir operations and management have necessarily increased as the uses of the reservoir system have multiplied and diversified, water demands have increased relative to water availability, and the publics' perceptions of water uses have evolved. These same changes also raise the prospect that perhaps the operation of the reservoir system should be updated and modified to respond to changed societal expectations and economic conditions.

As part of this need to derive, justify, and update reservoir operation plans, the Missouri River Division (MRD) has undertaken its first comprehensive review and update of the Master Water Control Manual for the Missouri River Main Stem system (Missouri River Division, 1990). Such a review and update is necessarily complex and controversial, given the large and diverse nature of the system, the novelty of such an updating project, and the conduct of the update in the midst of the most severe drought since completion of the main stem system.

Even without changing societal demands, there are some purely engineering justifications for periodic updating of operating plans for water resource projects. In the case of the Missouri River main stem system, there have been some significant reductions in the channel capacities of reaches of the Missouri River between and below the main stem reservoirs. In the case of flows from Fort Randall, floodplain encroachment and the natural evolution of the channel in response to the changed regime of channel flows has reduced the channel capacity from over 150,000 cfs to under 40,000 cfs. Furthermore, since most operational planning is based on the historic record of floods and droughts, there is now over 30-years more hydrologic record than when the reservoir system's operations were initially studied, including several major flood events and a major drought event. This represents a roughly fifty percent increase in the length of record available for operations studies.

OPTIMIZATION APPROACH

One approach to updating and justifying reservoir operation plans is through the use of optimization. Here, a computerized algorithm is used to find the optimal operation of the reservoir system, given a necessarily simplified mathematical formulation of the real reservoir operation problem. As part of the Missouri River system update study, the Hydrologic Engineering Center developed and applied such an optimization method. The optimization model, called the Hydrologic Engineering Center-Prescriptive Reservoir Model (HEC-PRM), found the optimal set of releases for each reservoir for each month given a ninety-two year streamflow record and penalty functions representing each of the purposes served by the reservoir system. More detailed discussion of the method and assumptions appear in U.S. Army Corps of Engineers reports (1991d) and, more briefly, in Chapter 4 of this report.

One problem that arises from the application of the particular optimization approach taken is that the optimization algorithm, in solving for optimal releases from each reservoir, "knows" the values of all future inflows. This particular optimization approach is called deterministic. Indeed, this particular assumption is almost unavoidable, since formulation and solution of a similar problem incorporating the uncertainty in future inflows would be computationally impossible and require a host of assumptions regarding the probabilistic patterns inherent in streamflows. Still, the deterministic results are of potentially great use; they give the best possible pattern of water release decisions. In retrospect, it will never be possible to improve upon these decisions.

There are several potential uses for these deterministic results in the Master Water Control Manual updating process. These include:

1) Use of the optimal value of the objective function (which equals the sum of the penalty function values for the optimal release solution) as an indicator of the upper-bound of possible reservoir performance. Any strategy or plan for operating the reservoir system could not perform better than this value. This provides a standard for comparing the performance of competing alternative operating plans. If an operating plan's performance value is within a few percent of the deterministically optimized value, it is unlikely that the operating plan's performance can be significantly improved.

2) Preliminarily evaluation of the potential value of proposed changes in the system's physical infrastructure. The model can quickly estimate the value of increasing a reservoir's storage capacity, improving the flow capacity of a channel, or increasing the capacity of a reservoir outlet.

3) Inferring a good set of reservoir operating rules from the pattern of deterministically optimized storages and releases. This will be the subject of much of this report.

REPORT ORGANIZATION

This report provides an assessment of the utility of HEC-PRM within the MRD Master Water Control Manual update process. It makes specific technical contributions in the problem of inferring near-optimal reservoir operating rules from deterministic model results and provides a discussion of "lessons learned" from the MRD's experience with the model. The remainder of the report is organized as follows. Chapter 2 provides a brief overview of the Missouri River Main Stem system, its technical, institutional, economic, social, and environmental aspects. Chapter 3 provides a review of the current operation of the main stem reservoir system and how these operation procedures came to be. Chapter 4 summarizes the HEC-PRM application to the main stem system, presents HEC-PRM results, and compares these results to current operating policies. Chapter 5 presents procedures for inferring near-optimal operating rules from HEC-PRM results for the main stem system. Chapter 6 provides a discussion of "lessons learned" from applying HEC-PRM to the Missouri River system update process. Chapter 7 presents some conclusions. Appendices are included that more broadly address the problem of inferring near-optimal reservoir operating rules from optimization model results, discuss some other potential applications for HEC-PRM , and contain references for the report.

Chapter 2

Background on the Missouri River System

This chapter reviews the Missouri River main stem reservoir system. The chapter begins with a review of the technical aspects of the system, followed by descriptions of the institutional environment which oversees its operation and the economic, social, and environmental purposes which the system serves. Finally, some operational issues which are seen as particularly important at this stage in the system's history are reviewed.

SYSTEM DESCRIPTION

There are six reservoirs on the Missouri River main stem system. These six reservoirs have a total combined storage capacity of 73.9 million acre-feet, roughly 3.4 times the river's mean annual flow at the downstream reservoir. The locations of these six reservoirs are shown in Figure 2-1 and their total capacities and average inflows are shown in Table 2-1.

Table 2-1
Capacities and Average Inflows of the Six Main Stem Reservoirs

	Maximum Capacity		Inflows (MAF/yr)	
Reservoir	MAF	per-cent	Main Stem	Tributary (%)
Fort Peck	18.7	25	---	7.0 (32%)
Garrison	23.9	32	7.0	10.3 (47%)
Oahe	23.3	31	17.3	2.2 (10%)
Big Bend	1.9	3	19.5	0 (0%)
Fort Randall	5.6	8	19.5	0.9 (4%)
Gavins Point	0.5	1	20.4	1.5 (7%)
Cumulative:	73.9	100	21.9	21.9(100%)

Roughly 80% of system inflows for the main stem reservoirs enter the two uppermost reservoirs (Fort Peck and Garrison). Therefore, the lower reservoirs largely must operate to regulate the releases from these two uppermost reservoirs. However, the two uppermost reservoirs alone represent about 58% of system storage.

Major inflows to the Missouri River also occur below the main stem reservoir system. As will be seen, these are important because they can contribute or detract from the ability of the main stem system to provide flood protection or water for instream uses or downstream withdrawal. These inflows are summarized in Table 2-2. This table tends to overstate the importance of the tributaries for some purposes, since tributary flows tend to peak during the spring and summer, whereas the important contribution of reservoir flows to downstream users is during the spring and summer flood season and the fall navigation and water supply season.

Table 2-2
Major Inflows to the Missouri River Below the Main Stem System

Lower End of Reach	Tributary Flow (MAF/yr)	Main Stem Flow (MAF/yr)
Sioux City	1.6	21.9
Omaha	1.6	23.5
Nebraska City	4.4	25.1
Kansas City	9.6	29.5
Boonville	6.4	39.1
Hermann	12.3	45.5

Additional storage within the Missouri River basin exists in the form of private, local, U.S. Army Corps of Engineers, and U.S. Bureau of Reclamation reservoirs. The locations of the largest 55 of these tributary reservoirs also are indicated in Figure 2-1. Many of these reservoirs regulate flows which enter the Missouri River below the main stem reservoir system. The tributary reservoirs are much smaller than the major main stem reservoirs and are much more widely distributed, as can be seen in Figure 2-1. The total storage capacity of Corps of Engineers and Bureau of Reclamation tributary reservoirs is roughly 27.6 million acre-feet. About 15.6 MAF of this is flood control storage, leaving about 12 MAF for conservation and other storage.

REGIONAL HYDROLOGY

The operation of any reservoir system is affected by the hydrology of the region. This section briefly reviews the annual streamflow regime and historical floods and droughts for the Missouri River (U.S. Army Corps of Engineers, 1979).

Typical Within-Year Hydrology

There is a pronounced seasonal pattern to the tributary flow and local runoff into the main stem system as well as local inflows into the Missouri River downstream of the main stem system. These are depicted in Figure 2-2 for inflows into the main stem reservoirs and Figure 2-3 for downstream. Over both parts of the system, there is a pronounced low-flow season between August and February, inclusive. The high-flow season, from March until July, consists primarily of snow melt from the plains and mountains.

For the main stem reservoirs, the major inflows are into Garrison, Fort Peck, and Oahe. Lesser flows enter Fort Randall and Gavins Point Reservoirs. Negligible tributary flows enter Big Bend reservoir. Flows into Garrison and Fort Peck reservoirs tend to peak in June, corresponding with snowmelt from the mountains and higher latitudes. Flows into the other reservoirs tend to peak earlier, in March or April.

Downstream of the main stem reservoirs, inflows tend to peak between March and June, responding to snowmelt, rainfall, and releases from tributary reservoirs. The downstream high-flow season (March-July) overlaps half of the traditional navigation season (April-November) on the Missouri River downstream of Sioux City.

The inflows used in this and other studies of the main stem system reflect substantial withdrawals (depletions) for agricultural and water resource developments on tributary streams.

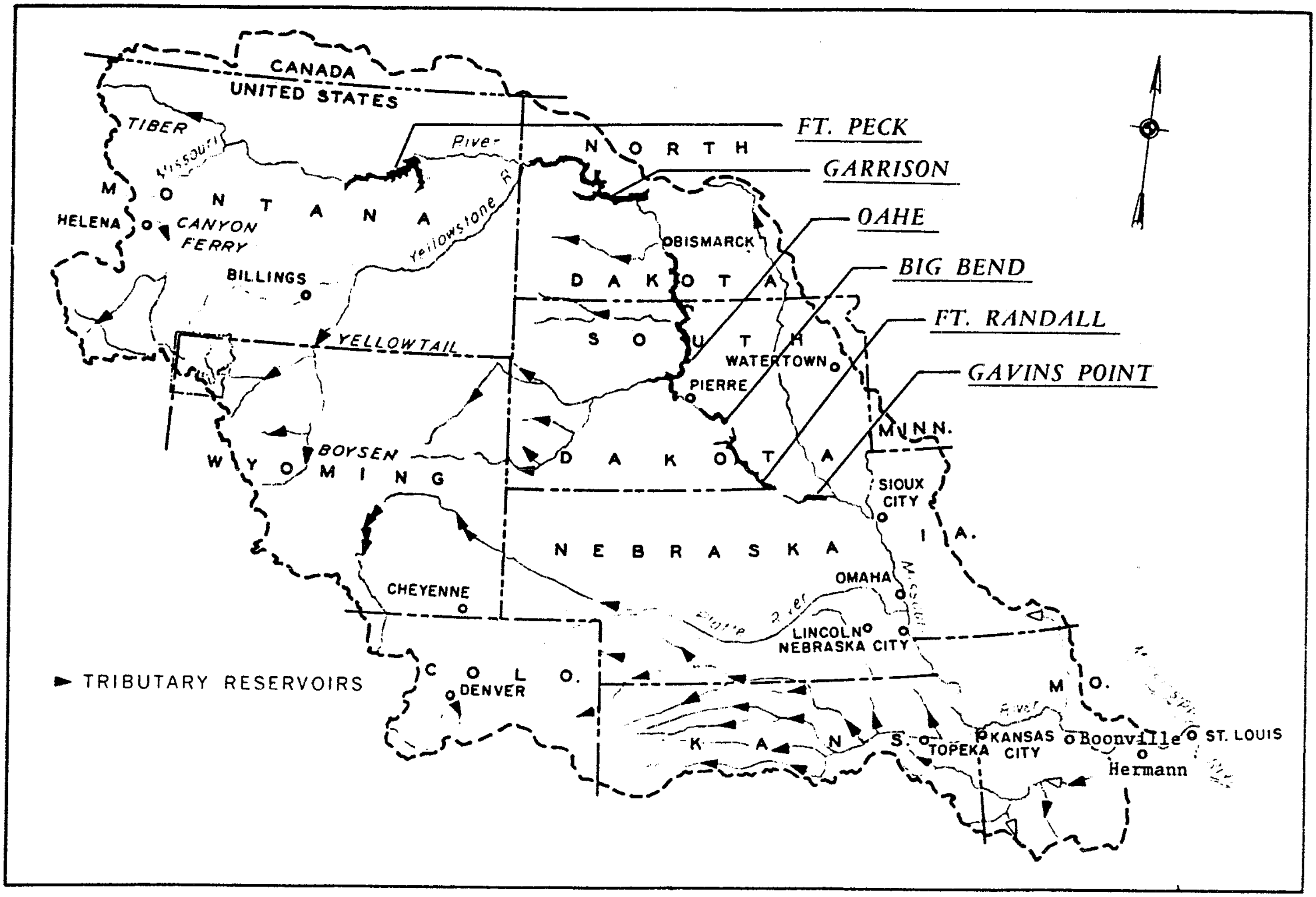

Figure 2-1

Missouri River Reservoir System

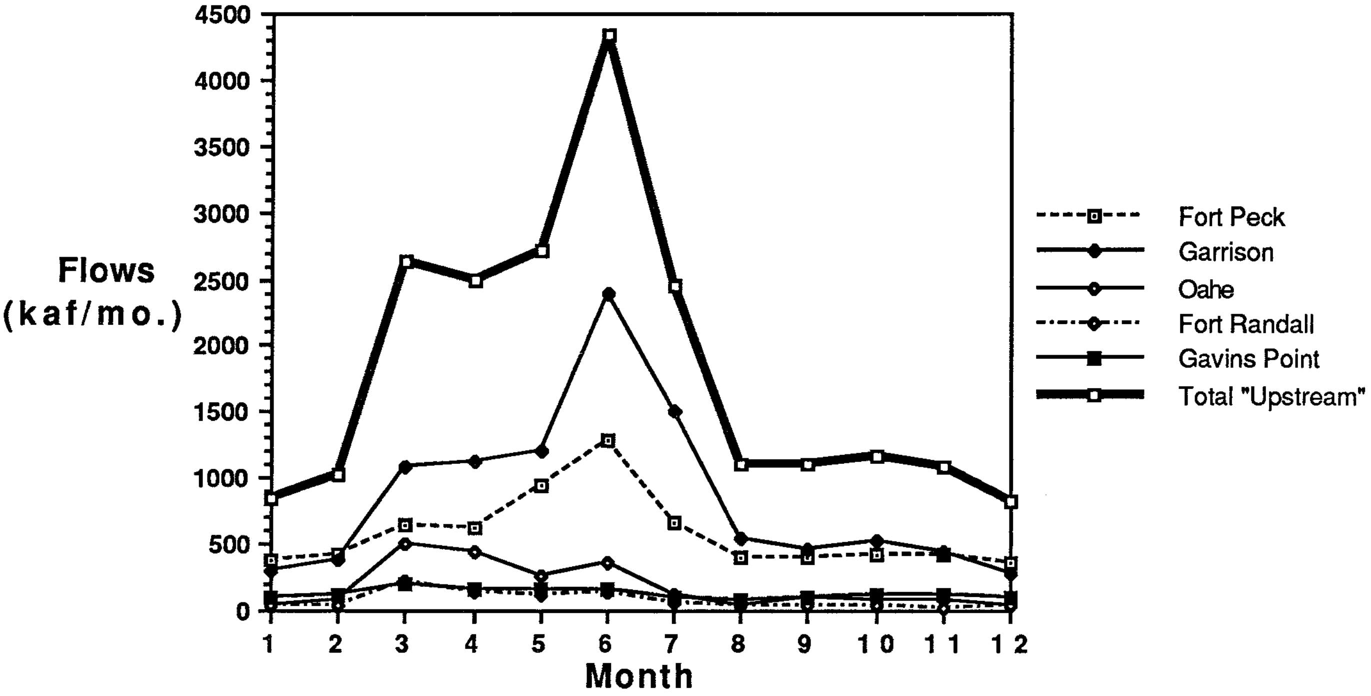

Figure 2-2
Mean Monthly Inflows Into Main Stem Reservoirs

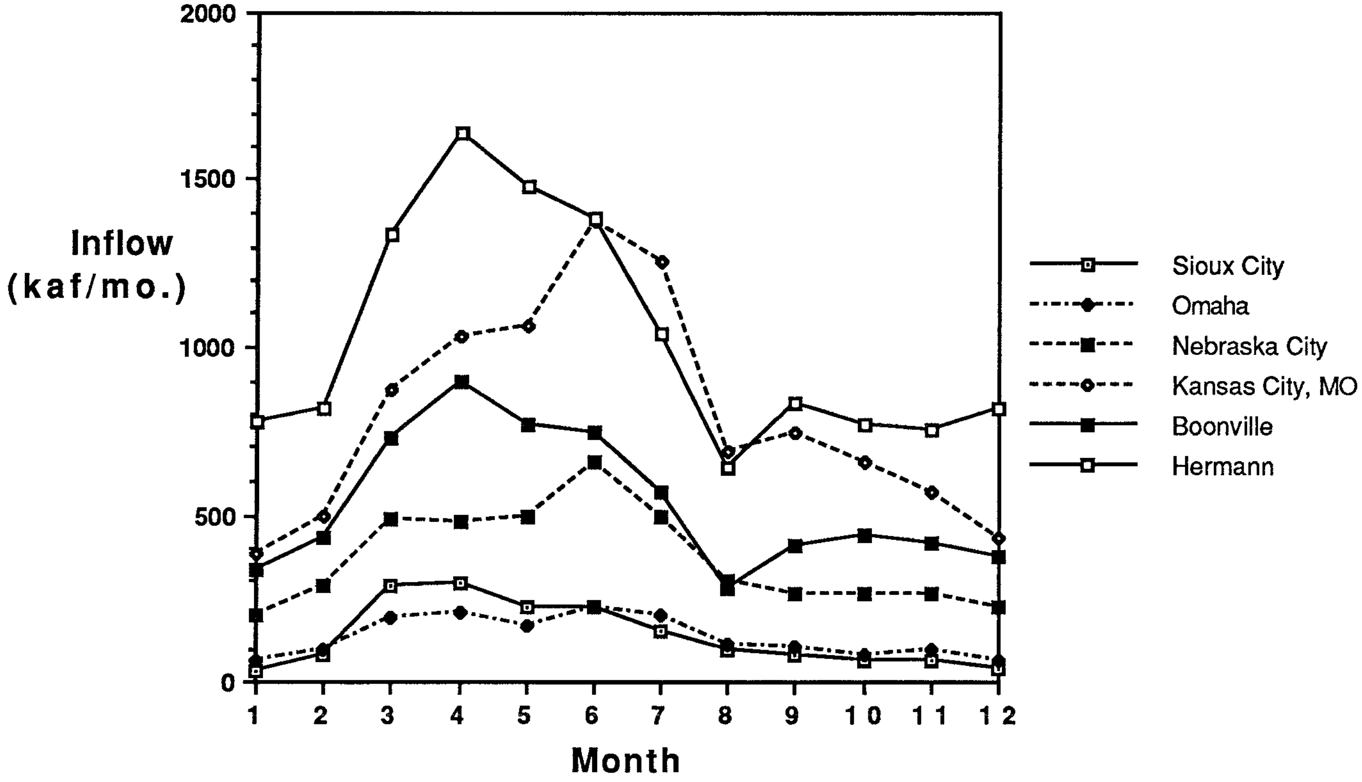

Figure 2-3
Mean Monthly Inflows Downstream of Main Stem Reservoirs

Flooding Patterns

Flood events on the Missouri River tend to occur between March and July. Floods during the March-May season typically result from snowmelt on the plains and the release of ice-jams, with occasional contribution from extensive rainstorms or intense local rainstorms. These floods create the highest discharges for reaches above and within the main stem system. From late May until July, flooding typically results from rainstorms combined with rapid snowmelt from the mountains.

All major floods in the upper basin during modern times have resulted from the above mechanisms, with the exception of a purely rain-fed flood-event in October 1923, which raised discharges above 100,000 cfs at the current locations of Oahe and Garrison reservoirs. In the lower basin, below the main stem reservoirs, the flood season is more extensive and derives much more of its water from rainfall over the lower basin.

The greatest flood in modern times on the lower Missouri River was in June 1844, which resulted from a series of large rainfall events. Little of the water for this flood seems to have come from the upper basin, with the greatest contributions to the flood coming from tributaries entering below Omaha. For this flood, peak flows were estimated to be 625,000 cfs at Kansas City, 710,000 cfs at Boonville, and 892,000 cfs at Hermann. A similar large flood on the lower Missouri River occurred in July 1951 with peak flows of 573,000 cfs and 618,000 cfs at Kansas City and Hermann, respectively. Lesser floods with a similar pattern occurred in June 1908, April 1927, June 1967, and October 1973.

The 1881 flood season created the greatest cumulative flood season flows into the region of the present-day main stem system in modern times. Both March-April and May-July snowmelt events were extraordinarily large. Flood flows resulted from the melting of the heaviest known snow-pack in the upper basin, accumulated over the previous winter. The flood stage was increased by the formation of ice jams along the then-unregulated main stem. These spring floods were followed by one of the wettest summers on record. Total March-July flows at Sioux City were 40 MAF, with March-April flows totalling 18 MAF. The reconstructed 1881 flood season serves as the primary basis for flood control storage in the main stem system.

In addition to the April flood of the lower basin in 1927, this year also produced high May-July flows from the upper basin. These floods resulted mostly from mountain snowmelt and April-May precipitation in the upper basin. The two floods during this year were essentially unrelated, each originating in different parts of the basin at times when flows from the remainder of the basin were unusually low.

The 1951 flood was basinwide, establishing flood records over the majority of the basin above Kansas City. Unusually low winter temperatures had allowed accumulation of a heavy and unusually extensive snowpack over the upper plains. During March and April the quickly melted snows entered the river, this together with large ice jams, contributed the greatest to flooding. At Bismarck, N.D. (above the upper end of present-day Oahe reservoir), flows peaked at 500,000 cfs, seventy-five percent greater than the 1881 flood, and continued with attenuated peaks downstream. The flood was due entirely to snowmelt and the hydrology of snowmelt on frozen ground, which resulted in a more rapid and complete concentration of snowmelt runoff in the river system.

The 1975 flood season created the greatest runoff from the upper basin since the beginning of detailed flow records in 1898. Although flood flows were greatly reduced by the presence of the main stem reservoirs, the channel capacities downstream were reduced and low-lying riverbanks had been encroached upon by agricultural and recreational uses, increasing the potential for flood damage. The formation of a tributary delta downstream of Fort Randall reservoir, in particular, reduced channel capacity from a pre-project state of over 150,000 cfs to under 40,000 cfs under ice-free conditions.

Other notable modern floods occurred in 1943, 1944, 1947, 1960, and 1967. These floods all involved snowmelt in the upper basin.

While flooding tends to follow a seasonal pattern, individual flood events can be rather idiosyncratic in their origins, timing, and magnitude. Flood control operations must be able to respond to these relatively unpredictable variations.

Multi-Year Droughts

The Missouri River has experienced two major droughts in modern times, including lower than average runoff from 1929 until 1941 and, currently, from 1987 until the present. The 12-year 1930s drought has been the "critical period" for drought planning for the main stem system. The late 1950s contained a far less severe eight-year drought. Recent years, from 1987 until the present has been another series of drought years, the worst since the entire reservoir system became operational. The data set used in the HEC-PRM results presented ends in 1988. Drought operation of the Missouri River system must consider very long events.

AUTHORITIES AFFECTING SYSTEM OPERATIONS

Given its large regional nature, a wide variety of institutions representing different levels of government and the private sector have developed roles in the operation and management of the main stem reservoir system. This section briefly reviews these roles, as they have developed, and how they are coordinated. This discussion represents a digest of discussions updated from those presented in the 1979 Master Water Control Manual and more recent Annual Operating Plans.

Federal Institutions

The six main stem reservoirs were constructed and are operated by the U.S. Army Corps of Engineers and are owned by the Federal government. However, other federal agencies also have important roles in their operation.

U.S. Army Corps of Engineers: Several authorities within the Corps have responsibility for the operation of the main stem system.

The Reservoir Control Center is the direct managerial authority for operation and planning for the main stem reservoirs. The Center is a division of the Missouri River Division's Engineering Directorate. The activities of the Center include:

- management of performance of reservoir operations,
- prediction of long and short-term runoff,
- coordination of reservoir management with local, state, and other Federal entities,
- review of proposed water supply contracts,
- technical studies to improve reservoir operation,
- preparation of reservoir regulation manuals for the main stem reservoirs, including the Main Stem Master Water Control Manual,
- review of regulation manuals for the tributary reservoirs, and
- supervision of Federal flood control efforts in the basin.

Within the Corps of Engineers, the Reservoir Control Center coordinates reservoir regulation activities with the Chief of Engineers, other entities within the Missouri River Division, and the Corps District offices and projects.

The major form of coordination with the Chief of Engineers is through the preparation of the Annual Operating Plan (AOP), which is the annual report summarizing the previous year's operations and identifying potential plans for the upcoming year's operations. The potential plans are based on the general guidelines contained in the Master Water Control Manual. Additional coordination with the Chief of Engineers office results under unusual reservoir regulation conditions and through submission of monthly reports, studies, and suggested revisions to operating manuals.

Within the Missouri River Division, the Reservoir Control Center coordinates its activities with other with other offices of the Division. Within the Engineering Directorate, coordination with the Hydraulics and Hydrology Section and the Mechanical and Electrical Section contribute to additional staffing needed during flood control events and the maintenance of power plant equipment. Coordination with the Division's Construction-Operations Directorate is also required to integrate construction activities with reservoir operations and to coordinate reservoir releases with navigation conditions and maintenance activities downstream.

The reservoir management activities of the Reservoir Control Center must also be coordinated with the Omaha and Kansas City Districts of the Corps. The districts provide much of the hydrologic data required for reservoir operation, regulate many of the tributary reservoirs, and prepare reservoir-specific regulation manuals and plans.

Personnel at each reservoir project execute actual releases, balance loads within each power plant, furnish data to District, Division, and Bureau offices, maintain project facilities and equipment, and perform power equipment switching as requested by the Federal power marketing agent.

U.S. Bureau of Reclamation: The Bureau is responsible for most of the tributary reservoir storage capacity within the Missouri River basin. Since the releases and spills from these reservoirs have a substantial effect on the inflows into the main stem system and downstream, these releases are to some degree coordinated with the main stem system. This is particularly true for flood control operations. The Corps is also responsible for flood control operations at Bureau facilities in the basin. In the past, the Corps has arranged for shifts in main stem flood control storage to some of the tributary reservoirs to improve hydropower and other operations in the main stem system.

The Bureau also provides data and forecasts regarding the effects of anticipated operation of Bureau reservoirs on streamflow. These include consideration of the effects of agricultural practices, tributary reservoir evaporation, and changes in storage.

Future coordination with the Bureau might be intensified if the Snake Creek pumping plant begins operations. This is a Bureau of Reclamation project drawing water directly from Garrison Reservoir to irrigate land in the Federally sponsored Garrison Diversion Unit. Completion of this project would require consideration of these irrigation withdrawals and return flows and consequent alteration of current operation plans.

Western Area Power Administration: The Western Area Power Administration (WAPA) is a branch of the Department of Energy responsible for marketing power from Federal water projects. Monthly meetings between representatives of the Reservoir Control Center and WAPA establish short-term plans for hydropower generation, considering market, hydrologic, and power generation and transmission conditions, as well as requirements to coordinate hydropower operations with other reservoir purposes. Daily conferences further integrate hydropower generation with other reservoir purposes. Major power facility maintenance outages are scheduled and coordinated at annual meetings which also provide a forum for discussions of detailed technical aspects of the system's hydropower operations.

National Weather Service: The National Weather Service (NWS) provides weather, snow survey, and river forecast data. Day-by-day exchange of data is accomplished through the River Forecast Center of the NWS Kansas City, Missouri office. The NWS and the Corps also cooperate in hydrologic and meteorologic investigations and the operation of river stage, precipitation, and hydroclimatic monitoring networks.

Other Federal Agencies: Operations planning for the main stem system also involves, to a lesser degree, the U.S. Geological Survey, the Department of Agriculture's Soil Conservation Service, and the Environmental Protection Agency.

State Institutions

The main stem reservoir system has shores in four states, and releases through an additional three states downstream. Each state has its own agencies involved with water and environmental issues related to the Missouri River. In addition, State political authorities are directly accountable for representing the interests of their states. The States are directly represented at the major operations planning meetings that oversee operation of the main stem reservoir system.

The Missouri River Basin States Association: The Missouri River Basin States Association is the successor to the Missouri River Basin Commission. The now-dissolved Commission was an inter-state compact composed of the Governors of each basin state and representatives from Federal departments with water resource development interests in the basin, with a Presidentially-appointed chair. The commission was responsible for overall review and coordination of preliminary planning and water resource development policies for the basin.

The Association performs some of the same functions of the former Commission, providing a forum for representatives of the States to discuss river basin issues. However, the Association has no formal authority and no formal Federal involvement.

Missouri River Natural Resources Committee (MRNRC): The MRNRC consists of members from each of the states adjoining the Missouri river and the U.S. Fish and Wildlife Service. The committee was formed in the mid-1980s to cooperate with the Corps in developing water control plans that provide river flows and reservoir levels conducive to fish and wildlife benefits. The Corps meets formally with the MRNRC in early spring and late summer each year to exchange pertinent data and information.

Local

A number of municipalities downstream of the main stem system rely on the river for water supplies. The quantity of the releases is often not so important as the stage of the river, since the major water supply problem is when the stage drops low enough for a negative suction head to form at the intake pumps. Local jurisdictions coordinate their activities with the reservoir system via communication with Corps Division or District offices or via State authorities.

Private

A number of diverse private interests have important roles in the operation of the main stem reservoir system.

Hydropower Interests: As one of the region's major power producers, the main stem reservoir system must be operationally integrated into the region's power grid and releases must be timed to complement the operation of other thermo-electric power generation facilities and time-varying power demands. This requires a high degree of planning and cooperation between the reservoir operators and the overseers of the regional electric power grid. This is accomplished through contact with the Western Area Power Administration.

Thermo-electric Cooling: A very different electricity generation concern is the need to supply water for cooling thermo-electric power plants downstream of the main stem system. Without sufficient water flowing downstream of the reservoir system, a significant proportion of the region's thermo-electric generation capacity cannot meet thermal standards for their cooling water effluent. Another interest of many of these thermo-electric plants is their need to have downstream reaches of the river at a sufficient stage to avoid negative suction heads on their cooling water intake pumps. These interests need become involved in reservoir operation only when downstream releases are reduced well below their customary levels and communicate these needs primarily through Corps Division offices.

Navigation Firms: The firms engaged in waterborne barge commerce downstream of the main stem reservoir system require certain reservoir releases for navigation. The duration of the barge navigation season must also be long enough to overcome the fixed costs associated with seasonal barge navigation. The concerns of navigation interests in the operation of the main stem system largely involve the length of the navigation season for the year and the flows released during that season.

Recreation Interests: A large number of firms and interests rely on the recreational values of either reservoir levels or seasonal streamflows. During a drought, it is obviously difficult to satisfy both these interests, since releases to create streamflow reduce storage levels, and vice versa. These interests are involved in reservoir operations chiefly through communication with Corps Districts or through State authorities.

Irrigation Interests: A number of private irrigators draw water directly from the main stem system. The Corps grants easements to cross Federal lands and install pumps and pipelines. Irrigators must first obtain state water rights and agree to pump and pipeline specifications with the Corps.

Coordination

Given the large number of diverse interests involved with the operation of the main stem reservoir system, the need for communication and coordination is apparent. This communication and coordination is achieved through a series of formal semi-annual meetings and less formal ongoing and intermittent contacts.

Semi-Annual Public Meetings: Since 1982, the chief formal mechanism for coordinating the operation of the main stem system with its various demands and uses has been semi-annual public meetings. These meetings, held in the Fall and in the Spring of each year, are attended by representatives from each of the ten basin states, representatives of nine Federal agencies, and interested members of the public. The public meetings provide advice and comments related to each year's Annual Operating Plan.

Prior to 1982, overall coordination of main stem reservoir operations with the basin states was primarily through the Coordinating Committee on Missouri River Main Stem Reservoir Operations. From 1953 until 1981 Coordinating Committee meetings were held semi-annually. The advice and recommendations of the Committee guided the actions of the Reservoir Control Center. Committee members consisted of water resources engineers representing the ten basin states and representatives of nine Federal agencies. The committee was dissolved in early 1982 as it came within the purview of the Federal Advisory Committee Act and did not conform to the guidelines of that Act.

Additional coordination is accomplished through the Missouri River Basin States Association and the Missouri River Natural Resources Committee discussed above.

PROJECT PURPOSES

A project of the size and spatial extent of the Missouri River main stem system must serve a multitude of purposes (U.S. Army Corps of Engineers, 1979, 1991a). These purposes must often necessarily interfere with each other, even though all purposes might be well served by the presence of the reservoir system, compared to a situation without reservoirs. This section summarizes the purposes served or significantly affected by the six main stem reservoirs and their authorizing legislation. Operation policies which serve these purposes are discussed in Chapter 3 and in the current Master Manual and recent Annual Operating Plans (U.S. Army Corps of Engineers, 1979, 1991a).

Legal Authorities

The operating purposes of the main stem system are prescribed by the legal laws governing the operation of Federal reservoir systems and more specific legislation pertaining to reservoirs in the main stem system. These items of legislation are summarized by U.S. Army Corps of Engineers (1990b, 1991e). Authorized and operating purposes for the main stem reservoirs include: flood control, navigation, hydroelectric power, irrigation, water supply, water quality, recreation, and fish and wildlife.

For Fort Peck, specific authorizing legislation includes, PL 74-409 and PL 75-529 for flood control, navigation, and hydropower purposes, and PL 99-662 for irrigation and recreation. Federal laws PL 78-534 (Flood Control Act of 1944), PL 93-205 (Endangered Species Act of 1973), and PL 92-500 (Federal Water Pollution Control Act Amendments of 1972) support all authorized and operating purposes at all reservoirs.

Flood Control

Flood control is one of the original authorizing purposes for the main stem system. The high-risk season for flooding coincides with the potential occurrence of snowmelt, ice jams, or long, heavy rainstorms, from roughly the beginning of March until mid-summer. Historically, a large majority of the total flood control benefits of the main stem reservoirs has occurred as a result of flood damage reduction downstream of the reservoir system, as opposed to flood damage reduction between the six main stem reservoirs (U.S. Army Corps of Engineers, 1991a, p. 59). Flood control regulation preempts the use of 4.67 million acre-ft. of storage at all times (exclusive flood control) and 11.65 million acre-ft. of seasonal flood storage.

Hydropower

Hydropower is a major revenue-producing system purpose. In an average year, the system produces roughly 7.3 billion kilowatt-hours, although substantially less is produced in drought years. The installed hydroelectric capacity of the main stem reservoirs appears in Table 2-3. Given the relatively small amounts of storage in the lower three reservoirs, there is some incentive to operate them almost as run-of-river plants, from an exclusively hydropower perspective.

Table 2-3
Installed Power Generation Capacity at Main Stem Reservoirs

Reservoir	Nominal Capacity - Megawatts	Total Storage Capacity (MAF)
Fort Peck	185	18.7
Garrison	518	23.9
Oahe	786	23.3
Big Bend	468	1.9
Fort Randall	320	5.6
Gavins Point	132	0.5

Recreation

The main stem system provides substantial recreation opportunities for a very large region. Recently, visitation on the six reservoirs has totalled roughly fifty-million visitor-hours annually. All reservoirs have significant recreational use. However, recreational visitation is particularly frequent at Garrison, Oahe, Fort Randall, and Gavins Point, relative to Fort Peck and Big Bend (U.S. Army Corps of Engineers, 1991a).

The releases from the reservoirs also contribute to recreation between reservoirs within the system and contribute greatly to summer recreation on the Missouri River downstream of the reservoir system. While stored water enhances recreation on the reservoirs, the reduction in releases required to impound water detracts from water-based recreation between reservoirs and downstream of the reservoir system.

Recreation on the reservoirs, between reservoirs, and downstream of the system is also dependent somewhat on the availability of fish and wildlife at these locations. This is particularly true for sport fishing.

Navigation

Navigation is also one of the initial authorizing purposes of the main stem reservoirs and navigation releases are one of the critical decisions for system operation. The Missouri River barge channel extends 732 miles up the Missouri River to Sioux City, Iowa. There is no commercial navigation within the reservoir system.

The navigation season typically extends from April 1 until the end of November, or in wet years until December 10. During other times of the year, the possibility of ice blockage and floating ice prevents commercial navigation. To maintain commercial viability for a given year, the navigation season is thought to require a minimum duration of six months.

To maintain sufficient river stage for barge traffic, releases from Gavins Point typically range from 25,000 to 35,000 cfs.

Water Supply and Irrigation

The main stem system supplies water for municipalities, industries, and irrigation located both near the reservoirs, between reservoirs, and downstream of the reservoir system. The total quantity of withdrawals for these purposes is small, relative to river flow or reservoir storage. However, the intake levels for pumps withdrawing water for these purposes are generally located below accustomed reservoir levels and river stages. Reduction of reservoir storage or reservoir releases below these accustomed levels, such as required during a severe drought, therefore induces "water shortages" by disabling intake pumps or greatly reducing their pumping capacity.

In winter, water supply intakes are similarly threatened by ice jams or floating ice. This threat is reduced when river flows are greater. Water supply intakes are sometimes also threatened by sediment accumulation. Downstream of the system, the intakes for many municipal water supplies and for a large proportion of the region's thermal-electric power production require that the river be above certain stages. Specific release levels needed to support these activities are presented in Chapter 3.

Water Quality

Releases from and within the reservoir system serve several water quality purposes. Within the six reservoir system, water quality concerns include temperature and dissolved oxygen stratification of the reservoirs, fish-kills below Garrison, Oahe, Fort Randall, and Gavins Point dams, gas supersaturation from spillway releases from Fort Peck and Gavins Point dams, and pollution or spills from agricultural or mining activities in the watershed. However, water quality problems within the reservoir system are considered to be only occasional.

Releases from the system at Gavins Point also serve water quality purposes. These releases are needed to maintain dissolved oxygen concentrations downstream of the reservoir system. These same releases also contribute to dilution of waste heat from the large thermo-electric power plants located well downstream of the main stem system. Most power plants currently do not have cooling towers and rely on the river to dispose of waste heat.

Fish and Wildlife

The operation of the reservoir system can be used to enhance fish, migratory bird, and other wildlife habitat. The existence and operation of the reservoir system has a large impact on the fish populations of the reservoirs and river reaches between reservoirs as well as downstream of the reservoir system. It is common for release schedules between reservoirs to be varied somewhat from year to year so as to provide river stages, flows, and reservoir pool levels conducive to fish spawning in different locations each year. This broadens the beneficial aspects of reservoir operation for the region's fisheries with a limited amount of water.

Different fish and wildlife species require different and sometimes competing flow, stage, and reservoir levels. For example, some fish species require lower flows and the formation of sandbars for spawning, while other fish, perhaps elsewhere, require higher flows or water levels.

Threatened and Endangered Species

Several threatened or endangered species, as determined by the Endangered Species Act of 1973, as amended, have been identified within the area influenced by main stem reservoir operations. The Act requires Federal agencies to ensure that their activities do not jeopardize the existence or habitat of these species.

The interior least tern and the piping plover were listed as endangered and threatened species, respectively, in 1985. These are small shore birds which nest on barren, low-lying sand bars and islands downstream of Fort Peck, Garrison, Fort Randall, and Gavins Point dams. Regular operations for other reservoir purposes, prior to 1985, would periodically inundate many of these nests. Since this time, these species have been the subject of considerable study.

A number of other potentially threatened or endangered species are present in the area affected by the system's operations. The pallid sturgeon was listed as endangered in 1990 and the paddlefish is currently under consideration. The impact of reservoir operations on threatened and endangered species will likely receive increased scrutiny in the future.

Overall Economic Impact

Estimates of the average annual economic benefits accruing from operation of the main stem reservoirs appear in Table 2-4. The economic importance of each reservoir purpose in descending order is hydropower, flood control, water supply, recreation, and navigation.

Table 2-4

Average Annual Benefits of Missouri Main Stem System Operations

(from U.S. Army Corps of Engineers, 1990b, p. 128)

Benefit	Value ($ millions)	Per-Cent of Total
Hydropower	470	59.9
Flood Control (Missouri River)	95	12.1
Flood Control (Mississippi River)	36	4.6
Water Supply (Downstream)	93	11.9
Water Supply (Reservoir)	not evaluated	-----
Recreation (Reservoir)	67	8.5
Recreation (Downstream)	3	0.4
Navigation (Missouri River)	14	1.8
Navigation (Mississippi River)	6	0.8
Total	784	100.0

OPERATIONAL ISSUES

The operation of a reservoir system as large and interwoven into the economy of a vast river basin is bound to be of considerable interest, concern, and occasional controversy. As the economy and society of this vast basin have developed and grown, the multiple demands on the reservoir system have also grown, forcing the always present trade-offs between many purposes to impinge more forcefully and with more significant economic, social, and environmental impact. Some of the more visible operational trade-offs are reviewed below. Several other operational issues are also raised, whose specific operational impacts are currently largely speculative.

Upper-Basin Storage Versus Lower-Basin Release

The most controversial aspects of the main stem system's operations revolve around conflicting reservoir interests between the upper basin states of Montana, North Dakota, and South Dakota and the lower basin states of Nebraska, Iowa, Kansas, and Missouri. As shown in Table 2-5, the upper basin states are the location of most of the storage of the main stem system. This storage, however, is effective at regulating flows in the long unregulated stretch of the Missouri River downstream of the main stem reservoirs. Table 2-5 illustrates that the predominant water resources of the upper basin result from stored water, while the water resources of the lower states stem largely from flow regulation.

Generally, the upper basin states' interests in reservoir regulation are recreation and hydropower, although local flood control and water supply are also important. Both recreation and hydropower interests value retention of Missouri River flows within the reservoir system, resulting in high reservoir pool levels. The interests of the lower basin states are primarily flood control and navigation, with an important interest in maintaining river stages for water supply and water quality as well. These interests would favor increased releases from the reservoir system, timed appropriately, to alternately supply higher river flows for navigation and increased river stages during the summer and fall, and retention of sufficient reservoir storage to control downstream flooding. Both of these interests would tend to result in generally lower reservoir levels, or at least more dramatic fluctuations, than upper basin states would find desirable.

The seriousness of this conflict between upper and lower basin states has extended to the filing of several lawsuits by several of the upper basin states (Farney, 1991). The trade-off between retained storage upstream or continued releases downstream is inevitable during relatively dry years. As water demands for storage upstream and releases downstream increase, even somewhat wet years will demand that these trade-offs be made.

Trade-Offs Within the Six-Reservoir System

For a given amount of water stored within the main stem system, there are trade-offs involved in deciding in which reservoirs the water should be stored. Increasing storage in one reservoir, as opposed to another, has considerable interstate economic impact in terms of reservoir recreation and potentially high hydroelectric impact as well. As such, during prolonged drought, there exists considerable potential for conflict between the upper basin states for retention of remaining storage.

In some cases, a microcosm of the upstream-downstream tradeoffs discussed in the previous section also exists between reservoirs, where higher river stages are needed to support water supply or irrigation intakes or are required for river recreation between Fort Peck, Garrison, and Oahe reservoirs and between Fort Randall and Gavins Point reservoirs, perhaps detracting from the benefits of retaining storage in the upstream reservoirs.

Table 2-5
Main Stem Reservoir Flow and Storage Resources by State

State	Reservoirs	Gross Storage	Average Flow
Montana	Fort Peck	18.7 MAF	7.5 MAF/yr.
North Dakota	Garrison Oahe	47.2 MAF	21.0 MAF/yr
South Dakota	Oahe Big Bend Fort Randall Gavins Point	31.3 MAF	23.3 MAF/yr
Nebraska	Gavins Point	0.5 MAF	23.3 MAF/yr
Iowa	none	0	23.3 MAF/yr
Kansas	none	0	23.3 MAF/yr
Missouri	none	0	23.3 MAF/yr

Trade-Offs Over Time

The temporal, as well as the spatial, aspects of reservoir regulation imply important trade-offs between purposes and regions within the basin. This is particularly evident with the timing of seasonal flood control storage and the conversely seasonal accumulation of storage for downstream navigation releases. Another example of these temporally-induced trade-offs are regulation of reservoir levels or releases to encourage fish migration or spawning or preservation of endangered species. Often, the breeding periods for fish and wildlife species are fairly brief, a few months. Specific reservoir levels or releases might need only be required for a short time, but must occur during a specific season.

Threatened and Endangered Species

Threatened and endangered species have become a significant operating consideration for most of the nation's natural resource managers, particularly those in the public sector. This is also true for the Missouri River main stem system. As discussed above, current operational concern for threatened and endangered species has focussed largely on two species, but seems likely to expand to several more. From national trends, it seems likely that the interests of endangered species will increasingly affect the operation of the main stem system. The exact form and impact of the operational changes are as yet uncertain, and might change considerably if the survival of more endangered species are linked to reservoir operations.

Indian Water Rights

Another uncertain factor that might significantly affect the operation of reservoirs in the Missouri River basin is Indian water rights. Already, several tribes in the basin have been awarded title to considerable flows of water (Farney, 1991). Water rights issues have not been a major operational concern with operating the main stem reservoirs in the past. This could change, and could greatly complicate operations.

Chapter 3

Overview of Current Reservoir Operation Plans and their Derivation

This chapter reviews the current operating plan for the main stem system and the methodologies employed in its development over time. This chapter then summarizes the efforts taken to revise and update the system's operating plan, including the current update and revision effort.

CURRENT OPERATION PLAN DEVELOPMENT

The current operation of the main stem system has evolved over more than half a century of operations on the river. This evolution has benefitted from the judgement of many talented engineers and long-standing simulation modeling efforts.

Early Operations

The main stem reservoirs were completed over a 24-year period, from 1940 until 1964. The operational beginning of each reservoir is indicated in Table 3-1. During this period, the operation of these reservoirs became increasingly integrated as new reservoirs were completed and as a result of the accumulation of experience and the increased opportunities afforded by coordinating the operation of such large reservoirs.

Table 3-1
Start of Operations for Missouri River Main Stem Reservoirs

Reservoir	Year Operational
Fort Peck	1940
Garrison	1955
Oahe	1962
Big Bend	1964
Fort Randall	1953
Gavins Point	1955

The main stem reservoirs began integrated operations in 1954, well before the final reservoir became operational in 1964. These early operations were guided by an extensive series of studies concerned with flood control, hydropower production, and water supply for downstream navigation. The development of water resources along the main stem tributaries was also considered, with its effects of reducing inflows, including flood flows, into the main stem system. The first of these long range operational studies was published in 1956. Most of these studies were completed by 1959.

Master Manual and Its Revisions

The Master Water Control Manual for the Missouri River Main Stem reservoirs contains specific guidelines for operating the six-reservoir system (U.S. Army Corps of Engineers, 1979). The Master Manual focuses particularly on the coordination of releases within the reservoir system for the purpose of fulfilling the authorized purposes of the reservoir system. The Master Manual is supplemented by six other volumes, one for each main stem reservoir, which address aspects of system operation specific only to individual reservoirs.

The original master water control manual was published in 1960. The operating plan contained in this original manual was selected specifically to maintain the permanent pool elevations through a repeat of the 1930s critical drought period and flood control storage for the 1881 flood season. In 1973, selected pages of the 1960 manual were revised, and a revised manual was published in 1975. The manual was again republished in 1979, reflecting changes in regulation criteria for flood control. The 1979 Master Manual anticipated the need for future further revisions.

Methods Used for Operations Studies for Coordinated Reservoir Operation

The operation of the main stem reservoirs has been the subject of numerous operational studies for almost forty years. These studies have included both multi-purpose and single purpose studies and studies over the entire hydrologic record (now 92 years) and critical portions of the hydrologic record and re-constructed extreme flood events.

The Missouri River Division's studies of reservoir operations for the original water control manual, during the 1950s, were among the first to employ modern simulation modeling techniques (Hall and Dracup, 1970). Simulation modeling has remained the primary method used to plan the operation of the main stem system.

Several simulation models are available for operations studies for the main stem system. Most operation planning employs a monthly model for long-term planning and medium-term planning. Daily models are employed for streamflow routing and hydropower operations planning over short terms of about a week in duration. A new daily model is currently under development for examination of environmental, flood control, and navigation impacts.

Overall operations are typically judged on the performance of proposed operating policies based on simulation models. These simulations are based on inflow records which extend from 1898 to the present. These records have been corrected for water resource development on the system's tributaries over this period.

For the most part, operational simulation studies of coordinated main stem operations for water supply and drought are also tested for the "critical period" of the 1930s drought.

Flood studies have been based on a number of floods experienced. In particular, the reconstructed 1881 flood was used to establish the size of flood control pools. The amount of flood storage in the system is seen as more than sufficient for floods that have occurred during the post-1898 period for which detailed inflows are available.

MAJOR ELEMENTS OF CURRENT OPERATION STRATEGY

This section reviews the major features of the current operating plan for the main stem system. In addition, there are a number of relatively minor features which affect short-term and local aspects of reservoir operations. For assessment of operations on a monthly scale, these lesser features are neglected. This section begins with an overview of the system's operating strategy, followed by "rules" which guide decisions to release water from the system at Gavins Point and which guide decisions for balancing total system storage among the six reservoirs. This discussion is a summary of more detailed presentations produced by the Missouri River Division (U.S. Army Corps of Engineers, 1979, 1990b, 1991a).

Prioritization of Purposes

The current Master Manual (U.S. Army Corps of Engineers, 1979, pp. IX-1, 2) prioritizes the purposes of main stem operations as follows:

1. Flood control
2. Upstream irrigation and other upstream consumptive uses
3. Downstream municipal and industrial water supply and water quality
4. Releases from Gavins Point for hydropower and navigation
5. Hydropower
6. Recreation, fish, and wildlife.

These priorities motivate current operational policies.

Operating Strategy Overview

The current operating plan for the main stem system is pool-based with supplemental rules for releases from each pool. Each of the six reservoirs is divided into four storage pools:

Exclusive Flood Control,
Flood Control and Multiple Use,
Carryover Multiple Use, and the
Permanent Pool.

The extent of these pools is summarized in Tables 3-2 and 3-3.

Table 3-2
Pool Allocations for Each Reservoir, in MAF (rounded)

(From 1990-91, MRD Annual Operating Plan, U.S. Army Corps of Engineers, 1991a)

Reservoir	Total Storage	Exclusive Flood Control	Flood Control & Multiple Use	Carryover Multiple Use	Permanent Pool
Fort Peck	18.7	1.0	2.7	10.8	4.2
Garrison	23.9	1.5	4.2	13.2	5.0
Oahe	23.3	1.1	3.2	13.6	5.5
Big Bend	1.9	0.1	0.1	0.0	1.7
Fort Randall	5.6	1.0	1.3	1.7	1.6
Gavins Point	0.5	0.1	0.1	0.0	0.3
Total:	73.9	4.7	11.6	39.3	18.3

Table 3-3
Pool Allocations for Each Reservoir, in percent (rounded)

(after Plate 11, U.S. Army Corps of Engineers, 1991a)

Reservoir	Total Storage	Exclusive Flood Control	Flood Control & Multiple Use	Carryover Multiple Use	Permanent Pool
Fort Peck	100	5.2	14.5	57.7	22.5
Garrison	100	6.2	17.6	55.3	20.9
Oahe	100	4.7	13.6	58.3	23.4
Big Bend	100	3.2	6.2	0.0	90.5
Fort Randall	100	17.7	23.7	30.5	28.1
Gavins Point	100	12.2	18.7	0.0	69.1
Total:	100	6.3	15.8	53.2	24.7

Exclusive Flood Control storage is the highest elevation pool and is used exclusively to regulate flooding events in the basin. The time frame for utilization of this storage is event-based. Flood waters are diverted into the pool during a flood event, and these waters are then released quickly from the pool after the flood has subsided. The emptying of the exclusive flood control pool is to be as rapid as possible, constrained only by the release capacity of the reservoirs, and local and regional flooding and channel capacity problems downstream. The intent of this exclusive storage is for regulation of extreme and unexpected floods. Only slightly over six percent of total main stem storage is for exclusive flood control.

Flood Control and Multiple Use storage is intended to operate on the reservoir system's annual drawdown-refill cycle. This pool has the second highest elevation in each reservoir. Each year, this pool is intended to be filled by "normal" flood flows. These "conserved" flood waters are then used for water supply, navigation, hydropower, and other downstream purposes. The intent is that reservoir levels fluctuate within this pool during normal years. This pool is sometimes called the "normal operating zone." This "normal operating zone" consists of 11.6 million acre-feet of storage, roughly sixteen percent of total system storage.

Carryover Multiple Use storage is intended to accommodate multi-year shortages of water, shortages beyond the "normal" drawdown-refill cycle. This is storage "carried over" from wet years to supply navigation, water supply, hydropower, and other uses in drier years. This is essentially drought storage. Retention of this storage during wet years also contributes to recreational and hydropower uses. Carryover storage is the largest single pool, representing over 50% of all reservoir storage, almost 40 million acre-feet. This storage is concentrated disproportionately in the three uppermost reservoirs.

Permanent Pool storage is intended to remain inactive. This lowest pool in each reservoir serves to set minimum reservoir levels for recreation and hydropower uses. In addition, during extreme drought, the existence of water in a substantial permanent pool allows some flexibility to supply releases for high-valued downstream uses and hydropower. The size of the present permanent pool level was established by simulation as the minimum pool during the critical drought period spanning the 1930s.

The sections below describe some of the release rules which serve to coordinate the filling and depletion of these pools. Figure 3-1, from the 1990-91 annual operating plan, depicts the normal annual cycle of reservoir operations on the main stem. Given the importance of releases from the main stem reservoirs to downstream uses, the following sections are organized to first discuss rules for releases from the entire system, considered as a unit. This is followed by rules used to allocate remaining storage among the six reservoirs and plan releases between reservoirs.

Navigation Operation Rules

Releases for navigation are based on total storage in all reservoirs. These releases are made initially from the Gavins Point reservoir. There are two ways of reducing releases for navigation from releases in a normal year. The navigation season can be shortened or the average release rate can be curtailed. Conversely, during wet years, the navigation season can be lengthened or average releases increased.

Average releases during the navigation season are set twice during the year. Downstream target flows are also established twice during the year, in late March and early July, based on March 15 and July 1 total system storage levels, respectively. Releases vary when combined with downstream inflows to provide flows which vary between "full service" and "minimum service" levels. These "service levels" are storage-based as determined using Table 3-4 below. The service level varies linearly between minimum and maximum levels, depending on total system storage. If total system storage approaches the permanent pool level (18.3 MAF), navigation releases are to be suspended when navigation releases would threaten other reservoir purposes (U.S. Army Corps of Engineers, 1990b).

Table 3-4
Relation of Navigation Service Level to System Storage

(from p. IX-8 of the Main Stem Master Manual)

Date	System Storage (MAF)	"Service Level"
March 15	>54.5	35,000 cfs (full-service)
	46.0 - 54.5	29,000 cfs + 706*(Storage - 46.0 MAF)
	18.3 - 46.0	29,000 cfs (minimum service)
	< 18.3	no navigation service
July 1	>59.0	35,000 cfs (full-service)
	50.5-59.0	29,000 cfs + 706*(Storage - 50.5 MAF)
	18.3 - 50.5	29,000 cfs (minimum service)
	< 18.3	no navigation service

From these "service levels" target flows are established at several points downstream. Reservoir releases from the main stem are then made to achieve these target flows, when combined with other downstream inflows. Target flows for points downstream are established using Table 3-5.

To meet these target flows at several downstream locations requires that releases from Gavins Point be coordinated with inflows downstream. Since the Gavins Point reservoir is rather small, releases from upstream reservoirs must also be scheduled to help satisfy navigation releases.

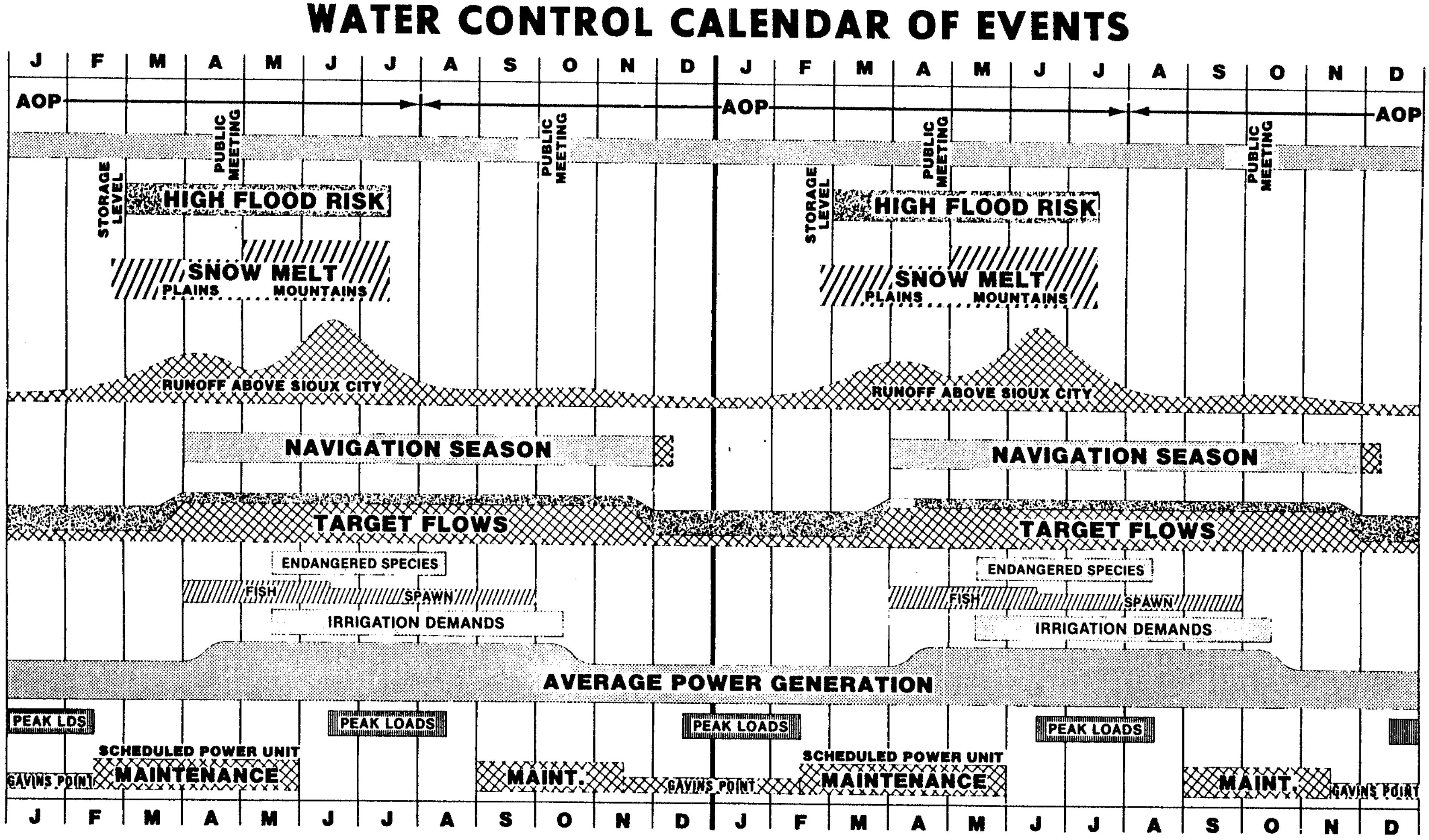

Figure 3-1

Water Control Calendar of Events
(from U.S. Army Corps of Engineers, 1991a)

Table 3-5

Target Discharge Relation to Navigation Service Level

(from p. IX-8 of the Main Stem Master Manual)

Location	Target Discharge
Sioux City	Service Level - 4,000 cfs
Omaha	Service Level - 4,000 cfs
Nebraska City	Service Level + 2,000 cfs
Kansas City	Service Level + 6,000 cfs

Note: Service Level is defined in Table 3-4.

The rule establishing the length of the navigation season appears in Table 3-6, assuming the navigation season begins on April 1. The decision to shorten the navigation season from its "normal" eight-month length is taken in early July, based on total system storage at the beginning of July, well after the beginning of the navigation season. Releases extending the "normal" eight-month navigation season are scheduled in years with above normal inflows, where such releases will not significantly draw the reservoirs into carryover storage and ice conditions permit continued navigation.

It is generally thought that a navigation season of less than six months is not economically viable for the commercial shipping firms operating on the river.

Since navigation releases have typically exceeded those needed for water supply and instream flows downstream of the main stem reservoirs, there are not specific release rules for these other uses during the navigation season.

Table 3-6

Navigation Season Length Relation to Total System Storage

(after p. IX-9 of the Main Stem Master Manual)

System Storage on July 1 of Season (MAF)	Length of Navigation Season (months)
≥ 41	8
40-41	7 3/4
39-40	7 1/2
37.5-39	7 1/4
36.5-37.5	7
35-36.5	6 3/4
33.5-35	6 1/2
32-33.5	6 1/4
30-32	6
27.5-30	5 3/4
25-27.5	5 1/2
18.3-25	5 1/4
< 18.3	no navigation service

Other Releases Downstream of the Main Stem System

Aside from navigation, release considerations for water supply, flood control, and hydropower also affect release decisions from Gavins Point, out of the main stem system downstream. These considerations vary seasonally. The general pattern of downstream releases is depicted in Figure 3-2.

Flood Control

Flood control considerations in Gavins Point releases vary seasonally. During the winter, when ice jams and related flooding are a concern, releases downstream of Gavins Point are usually restricted to a maximum of 20,000 cfs (1.2 MAF/month), but can increase to as high as 23,000 cfs (1.4 MAF/month) during relatively ice-free winter periods or as low as 15,000 cfs (0.9 MAF/month) under particularly severe ice conditions.

During the spring and summer, when the river is free of ice, snow-melt and large storms pose a flooding risk. During this period, seasonal and exclusive flood storage are employed in real time to regulate flood flows downstream of the system and create seasonal and carryover water storage for water supply, recreational, and navigation purposes. Some attempt is also made to regulate normal upper basin inflows that might contribute to downstream floods that primarily originate from precipitation downstream of the main stem system.

During droughts, when there is sufficient empty reservoir storage, regulation of spring and summer floods poses little problem. Release limits during the winter ice-bound season are important in most years, since they limit the ability of system operators to evacuate storage for later floods. Consequently, the flood control and multi-purpose use pools (the "normal operating zone"), which is to be cleared by March 1 of each year to accommodate spring and summer floods, must be largely emptied by the beginning of December, depriving the system of much operating flexibility should spring and summer flood flows be inadequate to replenish this pool.

Water Supply

Water supply releases from Gavins Point are required to maintain river stages above intake levels downstream of the reservoir system, as well as to provide water quantity for withdrawals. Minimum releases of between 6,000 and 10,000 cfs (0.36 to 0.6 MAF/month) are required year-round to protect water supply intakes downstream (U.S. Army Corps of Engineers, 1991a, pp. 12 and 15).

Hydropower

Releases for other purposes are typically scheduled to be routed through turbines to generate electric power. On a daily time scale, releases typically are scheduled to maximize peak-time power production. As can be gathered from Figure 3-1, most hydropower production from releases from the entire system is made during the spring, summer, and fall months. This coincides with the summer energy demand peak for air conditioning.

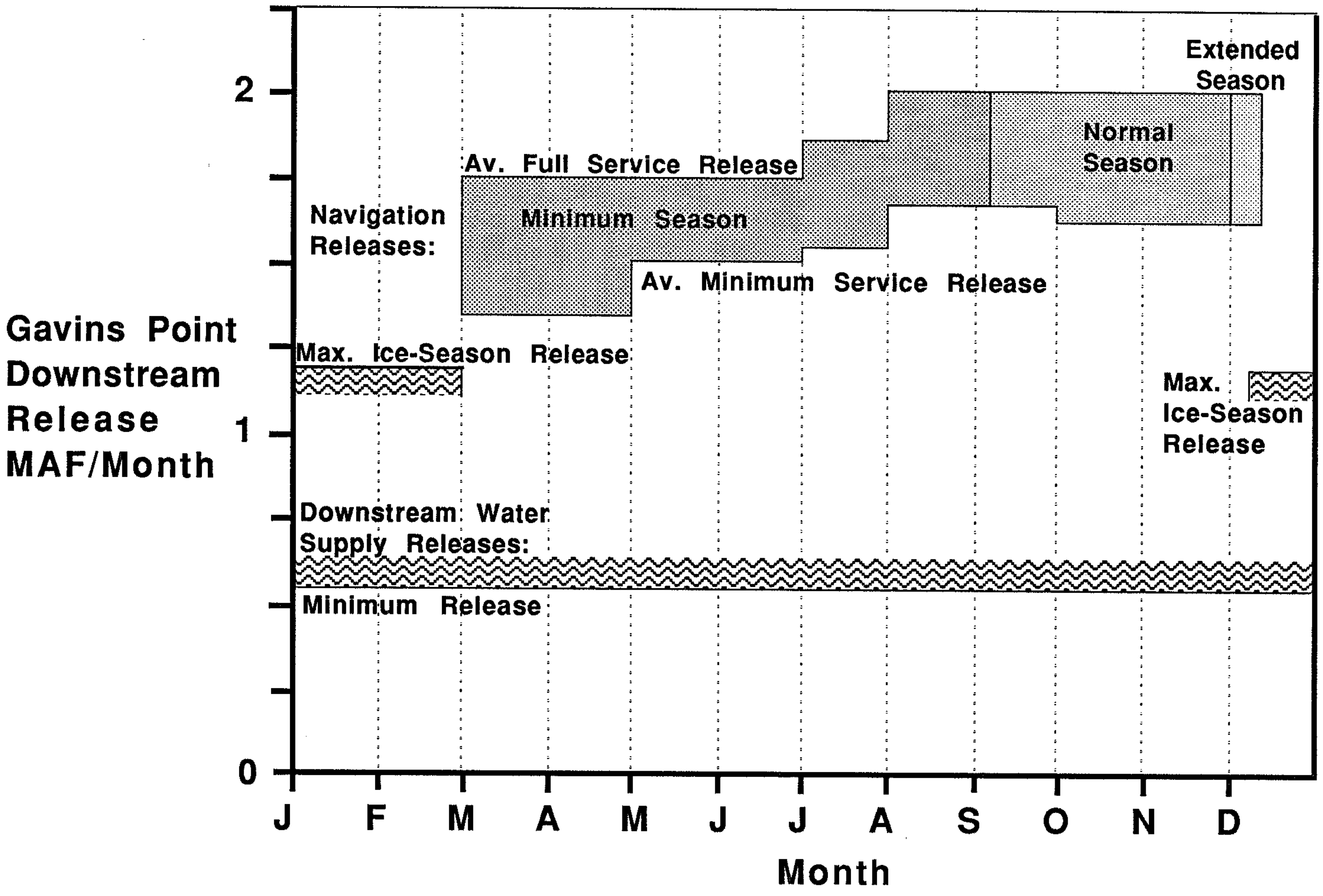

Figure 3-2

Current Downstream Release Guidelines from Main Stem System

Water Quality

Water quality control downstream of the reservoir system is concerned mostly with dissolved oxygen concentration and the dilution of waste heat from downstream thermal power plants. For the most part, these concerns are met by the minimum releases needed to support water supply intakes downstream.

Reservoir Balancing Rules

Operating rules used to allocate total system storage among individual reservoirs will be termed reservoir balancing rules. A number of considerations interplay to result in the overall allocation of total storage to individual reservoirs. Operators seek to shed excess water from the system during the navigation season.

Flood Control Rules

Several flood control rules affect the balancing of storage between reservoirs. First, water encroaching into exclusive flood control pools must be evacuated as quickly as possible, consistent with flood protection downstream.

Second, the flood control and multi-purpose pools should all be evacuated by March 1 of each year. Given maximum downstream release limits during the winter months, these pools must be substantially reduced by the onset of winter ice.

Third, there are flood control limits on flows between some of the reservoirs. Under ice-free conditions, releases from Fort Peck are restricted to less than 35,000 cfs (2.1 MAF/month) to prevent minor local flooding. Between the other reservoirs, maximum ice-free releases are somewhat below the 100,000 cfs (6 MAF/month) channel capacity before these reservoirs were constructed. Exceptions are releases from Garrison and Fort Randall, which must be kept beneath 65,000 cfs (3.9 MAF/month) and beneath 40,000-50,000 cfs (2.4-3.0 MAF/month), respectively, due to channel deterioration and floodplain encroachment since pre-project conditions.

Ice conditions severely reduce channel capacities within the reservoir system. With the onset of ice-cover formation, releases from Fort Peck must be limited to 10,000 cfs (0.6 MAF/month) but can be gradually increased to 15,000 cfs (0.9 MAF/month) after a stable ice cover has been formed. Initial ice formation also limits releases from Garrison reservoir to 20,000 cfs (1.2 MAF/month), which can generally be raised to 35,000 cfs (2.1 MAF/month) after the ice cover has stabilized.

There is a tendency to utilize flood storage capacity in Fort Peck, Garrison, and Oahe reservoirs over that in downstream reservoirs. This allows for greater re-regulation downstream and better maintains hydropower heads in the lower reservoirs. Within the three upper reservoirs, there is some attempt made to keep an equal percentage of flood control storage available in each reservoir. Chapter 10 of the Master Manual (U.S. Army Corps of Engineers, 1979) provides much greater detail on flood control operations.

Given the short-term and often localized nature of flood inflows to the system, flood control operations remain rather flexible, responding to localized and idiosyncratic flood conditions. In winter, the formation and nature of ice cover on the river and tributaries compound the need for flexibility. The exclusive flood control storage pools in each reservoir and flood storage capacity in some reservoirs on tributaries add additional flexibility to flood control operations. The flexible nature of flood control operations is well-described in Chapter 10 of the Master Manual (U.S. Army Corps of Engineers, 1979).

Tributary Inflows

As indicated in Table 2-1 and Figure 2-2, substantial tributary inflows enter between and above the main stem reservoirs. These are especially important where the inflows are a large proportion of the storage immediately downstream, as is the case with Fort Peck, Garrison, Fort Randall, and Gavins Point reservoirs. These are not rules, per se, but is an important factor in the implementation of reservoir balancing rules.

The extensive reservoir development on tributaries to the main stem, has several effects on regulation of the main stem. The coordination of flood control on these tributary reservoirs with main stem system operations improves the ability of the main stem reservoirs to service multiple purposes without slighting flood control operations. Storage deficits in tributary reservoirs also subtract from both flood and normal inflows to the main stem system; when full, the ten largest tributary reservoirs contain 6 MAF of water.

Minimum Pool Rules

Releases from each reservoir should be such that the permanent pools of each reservoir remain intact. These minimum pool elevations protect some of the infrastructure and recreational activities operating on the reservoirs and provide minimal head for hydropower releases.

Hydropower Operations

During the spring, summer, and fall, releases for navigation provide much of the system's hydroelectric power production. This production comes not only from the lowermost reservoir (Gavins Point), but also comes from releases from Fort Randall, Big Bend, and Oahe reservoirs. Given the large downstream release volumes required during these seasons, storage from upstream reservoirs is required. Since the lowest three reservoirs have relatively little storage, much of the water destined for navigation uses must eventually be released from Oahe reservoir. Releases from these reservoirs can be timed to accommodate daily, weekly, and monthly variations in power demands, with releases from Gavins Point somewhat smoothed to match downstream navigation and stage requirements.

During the winter, there are significant flood control constraints on maximum releases to downstream of the system. This reduces the ability of the lower reservoirs to produce hydropower. Yet the system's uppermost reservoirs, Fort Peck and Garrison, will typically be rather full and not suffer ice-related constraints on releases. Therefore, winter hydropower releases are made primarily from the uppermost reservoirs, with some additional releases from Oahe. These winter releases further serve to fill storage in Oahe for use during the coming navigation season.

A similar balancing of hydropower operations is employed with Fort Randall reservoir during the fall. Here, the Fort Randall reservoir is drawn down into the carryover storage pool during the fall by reducing releases upstream at Big Bend and Oahe. This reduces fall hydropower production and retains storage in these higher reservoirs. This drawdown of the Fort Randall reservoir is replenished during the non-navigation season by releases upstream. This procedure effectively shifts some hydropower production from the fall to winter months, while maintaining navigation flows downstream of the main stem system. The extent of the Fort Randall drawdown is limited by environmental, aesthetic, and recreational considerations to roughly 900,000 acre-ft of storage within the carryover multiple use pool.

These complementary releases between reservoirs over different seasons are one of the primary benefits of reservoir balancing operations. In addition, these operations tend to retain high reservoir levels in Fort Peck and Garrison reservoirs during the peak recreation and fish spawning seasons.

Minimum Release Rules

There are a number of water intakes for municipal and irrigation uses located on river reaches between reservoirs that rely on river stages being above certain levels. These intakes typically require year-round minimum releases of:

- 3,000 cfs (0.2 MAF/month) from Fort Peck,
- 10,000 cfs (0.6 MAF/month) from Garrison, and
- something less than 10,000 cfs (0.6 MAF/month) from Fort Randall and Gavins Point.

Fish and Wildlife Considerations

The system has had success in the past at varying reservoir levels between reservoirs to encourage the spawning of fish and the nesting of birds. In the case of fish, this has entailed raising water elevations above normal levels during specific seasons of some years. Different reservoirs are kept at prespecified higher than normal levels in different years to increase fish populations in a number of reservoirs without requiring additional water storage systemwide.

Some Other Considerations

There are a number of short-term considerations that affect releases within the reservoir system. These include diurnal or daily variation in releases to accommodate recreation and fishing during the day and on weekends during the summer and a number of other factors. Most of these short-term operations have little affect on releases averaged over monthly periods.

Flexibility

Many of the rules discussed above are essentially constraints on system operation. The "optimization" of operations is then accomplished manually, with the aid of simulation models, by engineers in the Reservoir Control Center, with advice from other groups as discussed in Chapter 2. This form of decision-making, that is not rigidly bound to specific release levels, provides system managers with a degree of flexibility. This flexibility is particularly important for flood control operations, which must respond to less predictable large short-duration events which may be local in nature.

PRESENT PLAN UPDATE

> "With the inherent flexibility of operation of the main stem reservoir system, with the benefits which will be gained from further actual operating experience, and with possible changing emphasis on service to various functions as a result of economic growth, it may be found necessary to revise the plans presented herein from time to time in the future."
>
> *Missouri River Main Stem Reservoir System Reservoir Regulation Manual: Master Manual,* 1979 revision, p. I-1
> U.S. Army Corps of Engineers, Missouri River Division

The need to periodically revise the operation plans for the Missouri River main stem reservoirs has long been recognized. Indeed, there have been many studies since the system's completion intended to improve the technical and economic performance of the main stem system. However, there has been little comprehensive and fundamental re-examination of the main stem system's operations. Indeed, the actual process for comprehensively revising the operating plans for such a large and complex system has not been well established, either for the main stem system or for Federal reservoir systems in general.

The current update was motivated by several factors (U.S. Army Corps of Engineers, 1990a):

"1. It has been 10 years since the last update.
2. The current drought has pointed out that parts of the existing Master Water Control Manual may require change and that a review is in order.
3. Recreation on the reservoirs and the river downstream is becoming an increasingly important industry, which was not the case when the original Master Water Control Manual was written.
4. The current drought has demonstrated the importance of Missouri River water to commercial navigation on the Mississippi River during drought, especially during summer and fall periods.
5. The Master Water Control Manual needs to be updated to include regulation criteria for endangered and threatened species, new data collection methods, and flood history which has occurred since the last update."

Several of these concerns have been discussed in Chapters I and II.

The stated objective of the current update process is to "search for Master Water Control Manual operating criteria that better serve the contemporary uses of the Missouri River than the current operating procedures" (U.S. Army Corps of Engineers, 1990b). The need to keep reservoir operations up to date with evolving social and economic circumstances has been accentuated greatly by the drought which began in 1987. This drought has brought forward several water resource conflicts which were latent in wetter years. However, even without the drought, many of these conflicts would likely emerge eventually, as individual competing water demands continue to increase and multiply.

Specific objectives of the review include (U.S. Army Corps of Engineers, 1990b):

- "Identify alternatives to the existing Water Control plan.
- Evaluate the economic, social, and environmental impacts of the existing and alternative water control plans.
- Address the legal constraints on changes to the operation of the system.
- Establish a basis for identifying the plan that 'best meets the wide variety of contemporary needs served by the main stem system.'
- Identify the plan that 'best meets the wide variety of contemporary needs served by the main stem system.'
- Include the input of the basin states' governors and other interested parties into the review and update process.
- Expedite the process to allow early implementation of recommended operational changes, if existing constraints will allow."

The process to accomplish these specific objectives is seen as having two phases. Phase 1 of the update study was conducted to determine if there was merit to an additional, more detailed Phase 2 analysis.

Phase 1 of Update Study

A draft Phase 1 report for the review and update study was published in May, 1990 (U.S. Army Corps of Engineers, 1990b). This short six-month phase was necessarily preliminary in the sophistication of its economic analysis and data acquisition. The Phase 1 work examined seventy alternatives. Sixty-six of the alternatives considered addressed change in drought operations. These "drought" operation alternatives each reflected a change in one or more of the following parameters:

1. the size of the systems permanent storage pool
2. the navigation season release rule
3. the minimum winter release rate, and
4. the minimum summer, non-navigation, release rate.

Four "flood" alternatives were developed to examine modifications that would primarily change flood control operations.

The Missouri River Division's 724C0100 monthly flow model (Long Range Study, or LRS, Model) was adapted for the hydrologic analysis of these alternatives. Fourteen of the alternatives with combinations of low carryover storage (high permanent pools) and high summer minimum flows were hydrologically infeasible at some point in the 92-year record. It was impossible to maintain these high summer flows without entering the permanent pool of storage.

Of the remaining fifty-six alternatives, economic analysis could only be undertaken for twenty-two alternatives, owing to shortages of data and time required for economic analysis. The results of the preliminary evaluation of these twenty-two alternatives appear in the report (U.S. Army Corps of Engineers, 1990b). Generally, alternatives with higher minimum pool levels (and consequently less navigation) had superior economic performance.

The recommendations of the Phase 1 report for Phase 2 alternatives were that:

1. Permanent pool levels between 24 and 35 MAF should be examined.
2. A "full range" of navigation season rules should be examined, including the elimination of navigation on the Missouri River.
3. Winter minimum releases between 9,000 and 12,000 cfs should be examined.
4. Summer minimum releases between 9,000 and 18,000 cfs (and perhaps higher) should be examined.

Recommendations in the Phase 1 report for the evaluation methodology in Phase 2 included:

1. Daily or even hourly hydrologic modeling is needed to estimate some impacts.
2. Endangered species evaluations need to be added.
3. Potential future upstream flow depletions should be considered.
4. Minimum flow requirements need to be estimated for all uses.
5. Additional acquisition and verification of data is needed for estimating many economic impacts, particularly for water supply and power impacts.
6. For drought events, public welfare and industrial impacts might be sufficiently severe to judge some alternatives on their performance during the worst year, rather than averaging performance over all years in the hydrologic record.
7. Estimation of economic impacts should include broader regional, or secondary economic impacts.
8. Alternatives which "maximize" various system outputs should be identified.

Later Phases of the Update Study

Following Phase 1, a scoping phase, an additional Technical Evaluation Phase is currently underway. This phase consists of additional scoping studies; data collection; development of additional economic, simulation, and modeling tools; and analysis of alternatives using these additional tools and data. This phase has a projected duration of about 20 months.

After the Technical Evaluation Phase, a Trade-Off Analysis and Decision Making phase of roughly 4 months is scheduled. This phase should narrow the selection of alternatives, followed by a detailed evaluation of a limited number of alternatives, and selection of a single preferred alternative. The final projected phase of the update study is Master Water Control Manual Presentation, Review, Revision, and Publication. This phase consists of the drafting and comprehensive review of the revised master manual. The expected duration of this phase is about 6 months. Concurrent with the development of the revised Master Manual is the preparation of an environmental impact statement (EIS). This procedure is already underway with completion expected at the end of 1992. The procedure includes public meetings and circulation and revision of the draft EIS.

Chapter 4

HEC-PRM Application and Comparison of Results with Current Operation Plans

This chapter introduces application of HEC-PRM to the main stem system, presents some of its major results, and compares these results with current operating plans. The intent here is to show the critical utility of HEC-PRM results for examining current operating practices and to introduce a procedure which will be continued in Chapter 5, whereby HEC-PRM results will be used to suggest modifications to current operating plans. Throughout this chapter, it should be recognized that HEC-PRM results used here are preliminary. Because of the many figures in this chapter, all figures are collected and presented at the end of the chapter.

BACKGROUND AND PURPOSE OF HEC-PRM

The Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM) is an optimization model which seeks to minimize a complex linear objective function for multi-reservoir systems subject to flow and storage constraints. Mathematically, it represents a class of network flow programming, commonly used to solve large logistical, warehousing, and transportation problems in the public and private sectors.

The purposes of HEC-PRM are to provide insight into the optimal operation of reservoir systems and to provide screening-level evaluation of reservoir system modifications that would have implications for reservoir operations. To date, HEC-PRM has been applied on the Missouri River main stem and Columbia River systems.

Like any optimization model, HEC-PRM must simplify the reservoir operation problem into a form that can be solved by a computer. For HEC-PRM, some important simplifications include:

- all inflows are known with certainty during the modeled period (This gives the model the opportunity to look ahead to optimize current releases knowing future inflows.);
- evaporation and seepage must be approximated by linear relationships;
- the objective function must be the sum of linear penalty functions;
- hydropower penalties must be approximated by linear relationships; and
- all operating objectives must be included in the model quantitatively to be considered.

While few reservoir operations problems will conform exactly to these simplifications, the model still retains an ability to represent many of the most important aspects of most reservoir problems and should be able to provide at least qualitative insight into the problem of optimizing reservoir operations. Indeed, for large reservoir systems, there is no alternative optimization methodology presently available which would not require similar or greater assumptions. The importance of these assumptions can be tested using simulation models.

Some caveats for interpreting HEC-PRM results are:

- alternative, equally optimal operating solutions can exist (although no operating solution will be better),
- model results will be sensitive to the penalty functions used, and
- some of the simplifications mentioned above might be important.

More detailed discussions of HEC-PRM appear in several Hydrologic Engineering Center reports (U.S. Army Corps of Engineers, 1991b, d).

HEC-PRM APPLICATION TO THE MAIN STEM SYSTEM

The HEC-PRM application to the Missouri River main stem system is described and test results are discussed in the Hydrologic Engineering Center report (U.S. Army Corps of Engineers, 1991b). The particular penalty functions used in the model were developed by the Institute for Water Resources (U.S. Army Corps of Engineers, 1991c).

The HEC-PRM application models the six main stem reservoirs and flows at an additional six locations downstream with a monthly time-step. The six downstream locations modeled are: Sioux City, Omaha, Nebraska City, Kansas City, Boonville, and Hermann. St. Louis has been added as a seventh downstream node to later versions of this HEC-PRM model. Inflows into the reservoirs and entering downstream of the main stem reservoirs are incorporated into the optimization model. Evaporation is assumed to be a linear function of reservoir storage for each reservoir and hydropower penalties are piecewise linearized by having separate piecewise linearized penalties for hydropower releases and hydropower heads at each reservoir. Penalty functions for all other purposes are also developed and piecewise linearized for all reservoir storages and releases and downstream locations. All piecewise linearized portions of the objective function must be mathematically convex. The sum of these piecewise linearized penalty functions, over all purposes, is then used as the objective function for HEC-PRM.

Several periods have been modeled, including the 92-year historic flow record used in this report. The particular 92-year set of inflows used assumed a particular seasonal pattern of depletions and withdrawals from water resource development on the system's tributaries.

Since no final storage level was specified in the optimization of the 92-year historic flow record, HEC-PRM greatly reduced the reservoir storages during the last two years of the optimization. This greatly increased reservoir releases during these last two years. Since this draining of the system at the end of the modeled period is not desirable in reality, the last two years of HEC-PRM results are ignored for the presentation of results herein. This leaves a roughly 90-year period of optimal storages and releases.

HEC-PRM RESULTS FOR THE MAIN STEM SYSTEM

This section presents the results of the first 90-years of the 92-year HEC-PRM optimization. First, the optimal releases and storages for each reservoir are presented on a monthly basis. Optimized flows downstream are then similarly presented. From the optimal storage results, optimized pool sizes are then developed and presented. This section concludes with some observations on these results.

Optimal Reservoir Releases By Month

The ultimate reservoir operation decision is how much water to release from each reservoir in the system. Figures 4-1 to 4-6 show the quartiles of optimal releases from each of the six main stem reservoirs. For each month of the calender year, the uppermost line (with a square symbol) represents the maximum release from the 90-year optimization run. The filled square indicates the upper quartile (Q3) of releases, exceeded in only 25% of the years. The heavy line with an open square represents the median monthly release; 50% of the monthly releases fall above and below this level. The open diamond represents the lower quartile (Q1) of releases; 25% of releases fall below this level. Finally, the filled diamond represents the minimum release observed during the 90-year optimized period.

In many of the months, several reservoirs show distinct patterns. For Fort Peck (Figure 4-1), high releases are typical for August through February. From April until June, releases are fairly consistently low. For March and July, a wide range of releases are common.

For Garrison (Figure 4-2), May through October releases are consistently high. Releases in other months are typically lower, but more commonly span a wide range.

For Oahe (Figure 4-3), releases typically span a much wider range, with a tighter band of common releases from May until November. Median releases tend to peak in May, dip in November, and maintain a fairly constant level in other months. Oahe releases appear to show the greatest variation of the three largest reservoirs.

Big Bend optimal releases (Figure 4-4) appear to closely follow releases from Oahe. There are no significant tributary inflows into Big Bend and the reservoir has a relatively small storage capacity. Releases from Big Bend almost mimic releases from Oahe for each month.

Fort Randall median optimal releases (Figure 4-5) gently decline from a peak in February until a fairly constant level in June and July. Median optimal releases then jump somewhat for August, declining gently from this second peak until December, from which median releases rise until the February peak. From December through March, a wide range of releases is common, compared to April through November release levels. But for any given month, almost any release level is possible.

Gavins Point optimal releases (Figure 4-6) follow trends similar to those of Fort Randall, since Gavins Point has a relatively small storage capacity; although, there can be significant tributary flows into Gavins Point. Figure 4-7 shows the time series of Gavins Point releases throughout the optimized period. Reduced releases are clearly evident during the two major droughts of record (the 12-year drought of 1930s and the 8-year drought of the late 1950s). Diminished releases are also evident during the relatively isolated dry years of 1919, 1977, and 1980-81. Releases have also been reduced for the beginning of the current drought.

While there seem to be distinct seasonal patterns to typical reservoir releases, there is less apparent consistency in operations between years. Examination of patterns in HEC-PRM storage results helps explain some of these release results.

Optimal Reservoir Storages By Month

Many of the objectives of the main stem system are directly dependent on the storage maintained within the reservoir system. Even objectives that are supported by releases depend on storage to provide releases during periods of drought.

Figures 4-8 to 4-13 depict the typical and extreme seasonal variations in reservoir levels suggested by HEC-PRM for the first 90-years of the 92-year historic record. Reported storages here and elsewhere in this report are storages at the <u>beginning</u> of the month. Clear drawdown-refill cycles are apparent for the three largest reservoirs.

Fort Peck storage (Figure 4-8) has a broad median peak from July until September. The reservoir tends to be drawn down from September until the beginning of January and held at this low level until March, when it begins to fill. The years major months for inflows tend to be during May and June, as the reservoir fills. These heightened inflows, combined with the tendency to reduce releases during May and June, raise reservoir levels rapidly during these months. Similar trends are evident in the quartile and extreme reservoir levels. The band of quartiles about the median storage levels is quite tight for Fort Peck. Except for April, 50% or more of the monthly storage levels fall within 1 MAF.

Garrison storage (Figure 4-9) peaks in August, begins drawing down about a month sooner than Fort Peck and completes its draw-down in March. This takes advantage of the slightly earlier and larger inflows into Garrison. Storage levels at Garrison are much more variable from year to year than at Fort Peck. For most months, the middle 50% of storages levels fall within about a 2 MAF range of the median storage.

Oahe storage (Figure 4-10) shows the <u>least</u> seasonal and over-year variation of the three largest reservoirs. The median seasonal range is only about 1 MAF, with this variation in the median restricted to the April-July season. During April and May, Oahe is drawn down. The reservoir is mostly re-filled by the beginning of July. Between year variation in Oahe storage levels is also relatively small. Over 75% of the monthly storages fall within 1.5 MAF of the reservoir's maximum capacity.

The three lowest reservoirs show very regular and consistent variations in seasonal and over-year storage levels. All storage levels for Big Bend (Figure 4-11) fall within a 150 KAF range. There is a very slight 25 KAF increase in median storage during April, with a complementary drawdown during December. This relatively unchanging storage level and the lack of direct tributary inflow into Big Bend, imply that Big Bend releases must almost equal those from Oahe, as shown earlier.

Fort Randall has a wider seasonal range in storage (Figure 4-12), about 800 KAF, with a maximum between year variation in storage of 800 KAF. Median Fort Randall storage increases in May and held fairly constant until November, when it is quickly drawn down to its lower level.

Gavins Point storage (Figure 4-13) varies less than 100 KAF over the entire 90-year optimized period. The median annual draw-down-refill cycle uses only about 60 KAF of storage. Storage is held at about 430 KAF from August until May. During May, the level is dropped to about 370 KAF where it is held until July. Like Big Bend and Fort Randall, this variation is very consistent between years.

The lowest three reservoirs show very narrow and consistent variation in storage levels. These are also the smallest reservoirs. The greatest variation in reservoir storages appears to be in Garrison, Fort Peck, and Oahe reservoirs, respectively. The time series of storages in these three largest reservoirs appear in Figures 4-14 to 4-16. Responses to the 1930's drought are clearly apparent in all three reservoirs. Response during the 1950's drought is less pronounced. Curiously, the optimal storage levels can apparently dip substantially during isolated drought and non-drought years. The lowest levels for each of the three reservoirs occurs during the 1975-1978 period, perhaps in part to accommodate the 1975 floods and in response to the dry year in 1977. But similar behavior is absent for the flood years of the early 1950s and drought of the late 1950s.

Optimal Downstream Channel Flows By Month

Seasonal patterns for reaches downstream of the main stem reservoirs are depicted in Figures 4-17 to 4-22. Median flows show very little seasonal variation for any reach. However, there can be rather wide variations between years, in response to floods or droughts. These variations are shown more clearly by the time-series plots in Figures 4-23 through 4-28. In some dry and drought years, navigation is clearly reduced or eliminated. There are also many scattered years in which downstream releases from Gavins Point are reduced. Many of these years of reduced downstream releases coincide with flood flows entering downstream of Gavins Point.

Permanent, Carryover, and Annual Operating Pool Sizes

Most reservoirs are operated by dividing their storage capacities into "pools" which represent either the storage employed for specific purposes or the storages used for typical annual drawdown-refill cycles, for over-year carryover storage, and a permanent pool used for recreation, hydropower head, and sediment accumulation. Applying this latter scheme to the HEC-PRM results, one can develop proposed "optimal" pool sizes for typical annual operations, carryover (drought) storage, and permanent storage. Table 4-1 shows how these pool sizes could be estimated from the 90-year HEC-PRM results. This system of pools is similar conceptually to the pool system used for current operations.

The maximum storage capacity was employed at least once over the 90-year optimization for each reservoir. These storages appear in Rows 1 and 8 of Table 4-1.

A 90-year minimum pool size for each reservoir can be estimated by identifying the minimum reservoir storage level for each reservoir from the HEC-PRM results. These are shown in Row 2 of Table 4-1.

The combined carryover and within year drawdown-refill storage from the HEC-PRM results can be found by subtracting the minimum pool storages from each reservoir's maximum storage. This appears in Row 3.

An estimate of the volume of drawdown-refill cycle storage needed for the median year is found by subtracting the minimum median monthly storage from the maximum median monthly storage for each reservoir. These three storages appear in Rows 4-6 of Table 4-1. Row 6 represents the median annual operating pool size for each reservoir.

The size of the carryover multiple use, or drought, pool is then found by subtracting Row 6 from the total storage active during the 90-year simulation, Row 3. This leaves the 90-year carryover storages in Row 7.

This approach to estimating pool sizes should be interpreted somewhat more flexibly from traditional pool sizes. If the optimized record were shorter, it would be less likely to incorporate severe droughts, and consequently would have smaller carryover and greater "permanent" pool sizes. Given a long enough period of optimized operations, the "permanent" pool would be reduced to a level where releases downstream were less valuable than retaining that water in storage during extremely severe droughts. For this reason, the pool sizes developed here are pre-fixed by "90-year" to denote their approximate "recurrence interval." The median year operating pool estimate is much more robust and should not vary appreciably with the length of the inflow record for which the system is optimized, provided the record is over 50 or so years in length.

Table 4-1
Operating Pool Sizes Derived From HEC-PRM Results

		Storage Quantity (MAF):					
	Pool	Ft. Peck	Garrison	Oahe	Big Bend	Ft. Randall	Gavins Point
Row 1:	Maximum Pool of 90-yr. Record	17.699	22.430	22.240	1.813	4.585	0.432
Row 2:	Minimum Pool of 90-yr. Record	10.696	16.308	16.089	1.673	3.287	0.338
Row 3:	Combined Carryover and Within-year Storage (Row 1 - Row 2)	7.003	6.122	6.151	0.140	1.298	0.094
Row 4:	Maximum Median Storage	16.559	21.314	22.240	1.725	4.218	0.432
Row 5:	Minimum Median Storage	14.231	18.626	21.168	1.693	3.305	0.372
Row 6:	Median Year Operating Pool Size (Row 4 - Row 5)	2.328	2.688	1.072	0.032	0.913	0.060
Row 7:	90-Year Carryover Pool Size (Row 3 - Row 6)	4.675	3.434	5.079	0.108	0.385	0.034
Row 8:	Modeled Capacity of Reservoir	17.699	22.430	22.240	1.813	4.585	0.432

Distribution of Storage Among Reservoirs

The results of HEC-PRM appear to have a consistent manner of balancing total storage among the individual reservoirs. For the lowest and smallest three reservoirs, storage levels appear rather fixed for each month, as discussed above. The larger upstream reservoirs show the greatest variation in storage.

The allocation of total storage between the three uppermost reservoirs appears to be fairly consistent, however. As seen in Figure 4-29 for July, allocation of total storage among the three uppermost reservoirs follows a pattern.

The earliest reductions in total system storage from maximum levels (about 69.2 MAF) come from storage in the three lower reservoirs above normal optimized storage levels. The three uppermost reservoirs are retained at full or near-full levels.

As total storage is reduced below roughly 68.7 MAF, Fort Peck storage is decreased, with Oahe and Garrison remaining at full or near-full levels.

For storage levels between about 67.5 and 63.5 MAF, Fort Peck storages remain near-constant at about 16.5 MAF. Oahe storage tends to remain full or near full. But, Garrison levels are steadily diminished.

Further reductions to about 63 MAF of storage are made by continuing reductions of storage at Garrison and beginning to reduce storage at Oahe.

Below total storage levels of about 63 MAF, Garrison levels do not show a systematic decrease, but Oahe and Fort Peck are steadily drawn down.

Other months show very similar patterns of balancing storage between the three uppermost reservoirs.

Some Observations on the HEC-PRM Results

The operation of the three lowermost reservoirs by HEC-PRM appears to be very consistent and based on maintaining seasonally-varying storage levels. However, the operation of the three uppermost reservoirs exhibits considerable variation.

The allocation of total storage among the three uppermost reservoirs does exhibit a pattern, however. This pattern is fairly consistent between months. Thus, if the optimal total system storage can be estimated, there is some basis for estimating the near-optimal allocation of that storage among the the individual reservoirs.

The only operational decision that affects total system storage is releases from Gavins Point. As the time series in Figure 4-7 indicates, there is some pattern to these releases, particularly the reduced releases during drought years.

After making these observations, there still seems to be substantial variation in the HEC-PRM storage and release results. Simulation and perhaps further optimization studies are required to estimate the importance of these unaccounted for variations.

MRD SIMULATION OF CURRENT OPERATIONS

For purposes of comparison, a special run of MRD's monthly reservoir simulation model was undertaken using the same initial storages and inflows employed in the 92-year HEC-PRM application. The results of this run represent the history of flows that would have occurred during the 90-year record if current operating policies and the reservoir system had been in operation during this period.

The inflows used appear not to reflect the most recent accounting for depletions from tributary flows, and so the results from this run are not strictly comparable to those of recent production runs from the monthly simulation model. Nevertheless, the simulation results should give an excellent indication of how the reservoir system would be run by the current operating policies over the 92-year detailed hydrologic record.

A particular problem with the results of this particular simulation run is that storage levels in Fort Peck reach a maximum of 19.3 MAF. This greatly exceeds the actual reservoir capacity of 18.7 MAF (including 1 MAF of exclusive flood control storage). This problem is not necessarily due to any flaws in the MRD simulation model, but probably results from the use of wetter hydrology inputs used in the 90-year Phase I HEC-PRM run in the simulation model. This likely difference with the input hydrology should further temper the preliminary results, comparisons, and operation rules presented in this report.

The MRD simulation model does not output storage results for Big Bend or Gavins Point reservoirs.

COMPARISON OF HEC-PRM AND CURRENT SIMULATED OPERATIONS

The operation rules for the main stem system are rather complex in their details, but with major features as described in Chapter 3. A systematic comparison of main stem operations by the MRD simulation model and the HEC-PRM optimization model is presented below.

Releases Downstream from Gavins Point

Releases from the main stem system at Gavins Point are an important aspect of any operating approach to the Missouri River system. The time-series of releases from Gavins Point as simulated by the MRD monthly model appears in Figure 4-30. This can be compared to HEC-PRM's optimal releases in Figure 4-7. The simulated releases show more consistent lower bounds of releases, but less consistent upper-bounds of releases than the HEC-PRM results.

The close relation of current releases to total storage levels appears in Figure 4-31, a scatter plot of releases from Gavins Point and total storage in the system. These Gavins Point release rules were discussed in Chapter 3.

Subtracting the simulated Gavins Point releases from HEC-PRM's modeled releases shows the differences in operations. The time series of this difference appears in Figure 4-32. HEC-PRM is much quicker to restrict releases downstream during droughts and reduces downstream releases much farther than current simulated operations. This is particularly evident in Figure 4-32 for the 1930s and 1950s droughts.

Figure 4-32 also demonstrates the wider seasonal variation of releases under simulated current operations compared with HEC-PRM optimal operations results. This is clearly evident by comparing the quartile plot of simulated monthly Gavins Point releases, Figure 4-33, with the optimized release quartile plot, Figure 4-6. The seasonal variation in median optimized releases is about 600 KAF/month. The seasonal variation in median simulated releases under current operations is about 1000 KAF/month. The pattern of seasonal peak and trough also differs between HEC-PRM and current operations, depicted in Figure 4-34. HEC-PRM operations peak releases in February and March, during the period of lowest releases under current operations. Simulated current operations peak median releases from August to October.

It appears from this comparison that the HEC-PRM application has excluded ice-related reductions in winter channel capacities and consequent flooding from high winter-time releases. If the HEC-PRM results presented here included these flooding costs, then these high-release winter operations would be seen as potentially more beneficial than the economic consequence of the resulting downstream flooding.

Downstream Channel Flow Statistics

The differences in flow statistics and patterns between HEC-PRM and simulated current operations mirror the differences in releases from Gavins Point. However, the differences are muted increasingly, as tributary inflows accumulate further downstream. Figure 4-35 shows the simulated seasonal pattern of flows under current operations at Sioux City. Figure 4-36 contrasts median seasonal flows at Sioux City for HEC-PRM and simulated current operations.

Seasonal Release Patterns

The pattern of monthly releases from the three largest reservoirs above Gavins Point are depicted in the quartile plots in Figures 4-37, 4-39, and 4-41. Each of these quartile plots is paired with a figure contrasting median monthly releases from HEC-PRM and simulated current operations, Figures 4-38, 4-40, and 4-42. The release patterns for the other two small reservoirs (Big Bend and Fort Randall) are similar to those of Gavins Point, with similar comparisons with HEC-PRM operations.

Simulated current operation of Fort Peck has much less seasonal variation in releases than HEC-PRM operations; compare Figures 4-1 and 4-37. Figure 4-38 shows that April through June HEC-PRM releases are considerably less from Fort Peck than under current operating policies. The pattern of releases between these two policies is somewhat similar, but the amplitude of seasonal variation tends to be much greater for HEC-PRM operations.

The seasonal pattern of simulated current Garrison releases also differs markedly from HEC-PRM operations, comparing Figures 4-2 and 4-39. Median seasonal operations are compared in Figure 4-40. Winter releases from Garrison by HEC-PRM tend to be significantly less than under simulated current operating policies. Spring and summer Garrison releases by HEC-PRM are consequently greater than under current practice. This implies that HEC-PRM supplies less winter hydropower and more summer downstream releases from Garrison than current operations.

Simulated current operation of Oahe employs Oahe storage to increase downstream flows during the navigation-season. This is evident in the pattern of high releases, during the navigation season from Oahe, in simulated current operations, Figure 4-41. Under HEC-PRM operations, greater Oahe releases occur during the winter and at the beginning of the navigation season, but somewhat less during the middle of the navigation season, as seen in Figure 4-42.

Seasonal and Overyear Storage Patterns

Comparisons in the use of storage under simulated current and HEC-PRM operations are made for the four largest reservoirs. The MRD simulation model does not output releases or storages for Big Bend or Gavins Point reservoirs. Like the HEC-PRM results, current operating policy is to keep both these reservoirs near-full, to maximize hydropower head.

HEC-PRM tends to make much greater seasonal use of storage in Fort Peck than the simulation of current policies. The range in median monthly storages under current operations is about 1.4 MAF, Figure 4-43. This contrasts with the pattern in Figure 4-8 for HEC-PRM releases, with a range in monthly medians of 2.3 MAF. HEC-PRM operations tend to begin drawdown of Fort Peck much earlier than under current policies, in September compared to November under current operations. The amounts released from Fort Peck during the September-December season are much greater under HEC-PRM operations as a consequence of this difference in the amplitude and phasing of Fort Peck's drawdown-refill cycle between the two operations, Figure 4-44.

Seasonal variations in Garrison storages also differ in HEC-PRM operations from simulated current policies, comparing Figures 4-45 and 4-9. The amplitude of the median drawdown-refill cycle is slightly less for current operations, 2.2 MAF compared to 2.6 MAF for HEC-PRM operations. The peak is slightly more pronounced in HEC-PRM results, Figure 4-46. However, the phasing of the drawdown-refill cycle for Garrison is quite similar for the two sets of model results.

The simulation of current operation of Oahe differs dramatically from HEC-PRM operations, comparing Figures 4-47 and 4-10. The peaks and troughs of the drawdown-refill cycles are reversed between the two operations, Figure 4-48. The amplitude of the annual median drawdown-refill cycle is also much less, 1.7 MAF versus 1.1 MAF for HEC-PRM operations. Most dramatically, HEC-PRM operation of Oahe maintains consistently higher storage levels than simulated current operations.

Fort Randall operation both by HEC-PRM and simulated current practice are highly consistent between years, Figures 4-49 and 4-12. However, the pattern of operations differs significantly. Current operations, as discussed in Chapter 3 and evident in the simulation results, tend to draw Fort Randall down in the fall and replenish this storage during the winter. HEC-PRM does the opposite, replenishing storage during the spring and drawing the reservoir down during the winter, Figure 4-50.

The simulated total storage in the main stem system under current operating policies is shown in Figure 4-51. A comparison with HEC-PRM operation is shown in Figure 4-52, a time series plot of HEC-PRM total storage minus total storage from the simulated current policies. During the great majority of the simulated 90-years, HEC-PRM operations maintain somewhat greater storage levels than simulated current operating policies. During drought periods, the overall effects of which can last well over a decade, HEC-PRM operations maintain storages at much greater levels than current policies. This, of course is a consequence of HEC-PRM's reduced releases from Gavins Point during drought periods.

Permanent, Carryover, and Annual Operating Pool Sizes

Current operating policies are largely pool-based, i.e., founded on the establishment of fairly rigid permanent, carryover, annual operating, and exclusive flood control pools in each reservoir. Table 4-2 compares the pool sizes stated for current operations (U.S. Army Corps of Engineers, 1979) with the pool sizes estimated using the optimized storages from the HEC-PRM model. The pool sizes from the HEC-PRM results are taken from Table 4-1.

The major difference in the two sets of pool sizes is the size of the minimum pool, the "permanent pool" of the current Master Manual and the "90-year minimum pool" from the HEC-PRM results. The HEC-PRM minimum pool is 30.1 MAF larger (2.64 times greater) than the current "permanent pool." The bulk of this increased minimum storage is in the three uppermost reservoirs and Fort Randall.

The larger minimum pool sizes for the HEC-PRM and constant size of total reservoir capacity together imply that the operating (carryover and annual operating) pools for the HEC-PRM results must be smaller than for current operations. The great majority of increase in the minimum pool size (about 85%) comes from a decrease in the carryover pool size. Carryover storage is greatly reduced in the three upper reservoirs and Fort Randall. Carryover storage is slightly increased for Big Bend and Gavins Point.

The remainder of the increased minimum pool size comes from a 39% reduction in the annual operating pool size, from 11.6 MAF to 7.1 MAF overall. This large reduction comes mostly from reductions in the annual operating pool for Garrison and Oahe reservoirs. HEC-PRM operations have considerably less variation in Oahe reservoir levels than current operations (1.1 vs. 3.2 MAF). Reductions in the annual operating pools for Fort Peck and the three lowest reservoirs are relatively small.

The exclusive flood control pools were held at those of the current operating policy for HEC-PRM, given the short-episodic nature of the floods they are intended to accommodate. A monthly model was felt to be insufficient to incorporate the rapid reservoir filling and evacuation from such floods.

Perhaps a better comparison of pool levels for current policies versus HEC-PRM results is to repeat the calculations of pool sizes used for the HEC-PRM results using the 90-year simulation of current operation policies. This is done in Table 4-3 for the four reservoirs whose storages are output by the MRD simulation model. HEC-PRM and simulated current pool sizes are then compared in Table 4-4.

When the inflows used for the HEC-PRM model are entered into the MRD simulation model, the maximum storage levels in the three largest reservoirs greatly exceed the maximum storage capacities used in the HEC-PRM model. For Fort Peck and Oahe, the MRD simulated storages occasionally exceed the gross storage capacities given for these reservoirs in the current Master Manual. Overall, the MRD simulation assumes, implicitly, 5.1 MAF of system storage above that assumed in the HEC-PRM model. As stated before, these discrepancies probably result from the hydrologic input into HEC-PRM being relatively "wet," because of a different consideration of depletions from tributary flow in the two models.

Given these caveats, the median operating pool sizes for the two sets of results are quite similar. The overall sizes of the median operating pools differ only by 0.2 MAF. The HEC-PRM results tend to use the upper two reservoirs (Fort Peck and Garrison) more for annual operations, and keep Oahe and Fort Randall at more constant levels, over seasons.

Again, HEC-PRM employs much less carryover storage than the MRD simulation, only 28% as much carryover storage as apparent from the MRD simulation results. Consequently, in the last two columns of Table 4-4, the HEC-PRM results have much higher 90-year minimum pool levels.

Table 4-2
Current and HEC-PRM Pool Allocations for Each Reservoir
(in MAF, rounded, from 1990-91, MRD Annual Operating Plan and HEC-PRM results)

Reservoir	Total Storage	Exclusive Flood Control	Current Flood Control & Multiple Use	HEC-PRM Median Year Operating Pool	Current Carryover Multiple Use	HEC-PRM 90-Year Carryover	Current Permanent Pool	HEC-PRM 90-Year Minimum
Fort Peck	18.7	1.0	2.7	2.3	10.8	4.7	4.2	10.7
Garrison	23.9	1.5	4.2	2.7	13.2	3.4	5.0	16.3
Oahe	23.3	1.1	3.2	1.1	13.6	5.1	5.5	16.1
Big Bend	1.9	0.1	0.1	0.03	0.0	0.1	1.7	1.7
Fort Randall	5.6	1.0	1.3	0.9	1.7	0.4	1.6	3.3
Gavins Point	0.5	0.1	0.1	0.06	0.0	0.03	0.3	0.3
Total:	73.9	4.7	11.6	7.1	39.3	13.7	18.3	48.4

Table 4-3
Operating Pool Sizes Derived From 90-year Simulated Current Operation Results

	Pool	Storage Quantity (MAF): Ft. Peck	Garrison	Oahe	Big Bend	Ft. Randall	Gavins Point
Row 1:	Maximum Pool of 90-yr. Record	19.283	23.951	24.179	N.A.	4.519	N.A.
Row 2:	Minimum Pool of 90-yr. Record	3.807	5.158	5.832	N.A.	2.382	N.A.
Row 3:	Combined Carryover and Within-year Storage (Row 1 - Row 2)	15.476	18.793	18.347	N.A.	2.137	N.A.
Row 4:	Maximum Median Storage	16.398	20.433	19.927	N.A.	3.643	N.A.
Row 5:	Minimum Median Storage	14.946	18.090	18.192	N.A.	2.382	N.A.
Row 6:	Median Year Operating Pool Size (Row 4 - Row 5)	1.452	2.343	1.735	N.A.	1.261	N.A.
Row 7:	90-Year Carryover Pool Size (Row 3 - Row 6)	14.024	16.450	16.612	N.A.	0.876	N.A.

N.A. = not available from simulation run.

Table 4-4

Simulated Current and HEC-PRM Pool Allocations for the Four Largest Reservoirs

(in MAF, rounded, from 90-year MRD simulation run, Table 4-3, and HEC-PRM results)

Reservoir	Simulated Maximum Storage	HEC-PRM Modeled Storage	Simulated Median Year Operating Pool	HEC-PRM Median Year Operating Pool	Simulated 90-Year Carryover	HEC-PRM 90-Year Carryover	Simulated 90-Year Minimum	HEC-PRM 90-Year Minimum
Fort Peck	19.3	17.7	1.5	2.3	14.0	4.7	3.8	10.7
Garrison	24.0	22.4	2.3	2.7	16.4	3.4	5.2	16.3
Oahe	24.2	22.2	1.7	1.1	16.6	5.1	5.8	16.1
Fort Randall	4.5	4.6	1.3	0.9	0.9	0.4	2.4	3.3
Total:	72.0	66.9	6.8	7.0	47.9	13.6	17.2	46.4

Patterns of Releases over Seasons between Upper and Lower Reservoirs

As discussed in Chapter 3, the intent of current operations, is to peak (increase) releases from the upper reservoirs (Fort Peck and Garrison) during the winter months and releases from the lower reservoirs during the navigation season. This method conveniently provides both navigation flows and year-round hydropower operations. Examination of the seasonal releases in Figures 4-37, 4-39, and 4-41 represents such an operation and the seasonal pattern of storages in Figures 4-43, 4-45, and 4-47. A smaller-scale shifting of storage is evident for Fort Randall's operations.

HEC-PRM operations are rather different in the seasonal operation of the large reservoirs. HEC-PRM makes much greater use of Fort Peck and Garrison to supply navigation-season flows and retains Oahe at relatively high levels year-round. This is evident from the seasonal plots of HEC-PRM releases and storages (Figures 4-1 to 4-3, 4-8 to 4-10, respectively) as well as from the comparison of median year operating pools in Table 4-4. In is unknown at this time exactly how seasonal hydropower production patterns would be affected by such operations. However, by maintaining generally higher storage levels and hydropower heads, HEC-PRM operations should be able to produce the same power levels with lower overall releases. The flood control implications for operations suggested by HEC-PRM that should be tested by simulation studies.

Patterns of Distributing Total Storage between Upper Reservoirs

The patterns of "balancing" total reservoir storage between the three largest reservoirs also differs between simulated current policies and HEC-PRM results. HEC-PRM balancing of total storage has a distinct non-linear pattern that varies for each reservoir (Figure 4-29). The simulation of current operations shows a very different, linear balancing of total storage, Figure 4-53. This linear balancing seems consistent between months.

CONCLUSIONS

Before drawing tentative conclusions from the HEC-PRM results and the comparisons of current and HEC-PRM operating procedures, a few cautionary points should be re-stated about the nature of HEC-PRM and results. First, HEC-PRM does not, and could not, model all aspects of the Missouri River Main Stem reservoir operation problem. Simplifications are required especially regarding the ability of HEC-PRM to have perfect forecasts of future inflows, the approximate nature of the penalty (objective) functions used, and the monthly time-step of the model. In particular, the penalty functions used for the Phase I HEC-PRM results used here are preliminary. As an example, the Phase I penalty functions apparently did not include special penalty functions for flooding during the season when ice reduces channel flow capacities on the river. This ice-related reduction in channel capacity is much of the rationale for current within-year operations.

Keeping these reservations in mind, distinct patterns have been seen in HEC-PRM's operation of the modeled main stem system. These HEC-PRM operations are also found to be somewhat different from the simulated current operating policies over the same 90-year period. Two uses can be made of the extensive presentations and comparisons in this chapter:

1. Comparisons with current operating policies can be used to suggest economically desirable adjustments in current operating policies. Such modifications to existing policies could consist of using HEC-PRM results to help "re-calibrate" existing operating procedures. In this case, for instance, the HEC-PRM results would seem to suggest more rapid reduction of navigation service and season with decreases in total storage.

2. The HEC-PRM results presented here can be used to help construct perhaps entirely different rules for operating the reservoir system. The reservoir balancing rules suggested by HEC-PRM are rather different in form from those resulting from current operations.

The following chapter provides a more detailed discussion of these operating rule implications of the HEC-PRM results.

Of course, any modification of existing operating policies or new operating policies suggested by HEC-PRM results should be further tested and refined with the use of more detailed simulation models and studies. HEC-PRM requires a number of simplifications, and most reservoir operations are of sufficient importance, that these additional studies are justified and indeed required to more truly optimize a reservoir system.

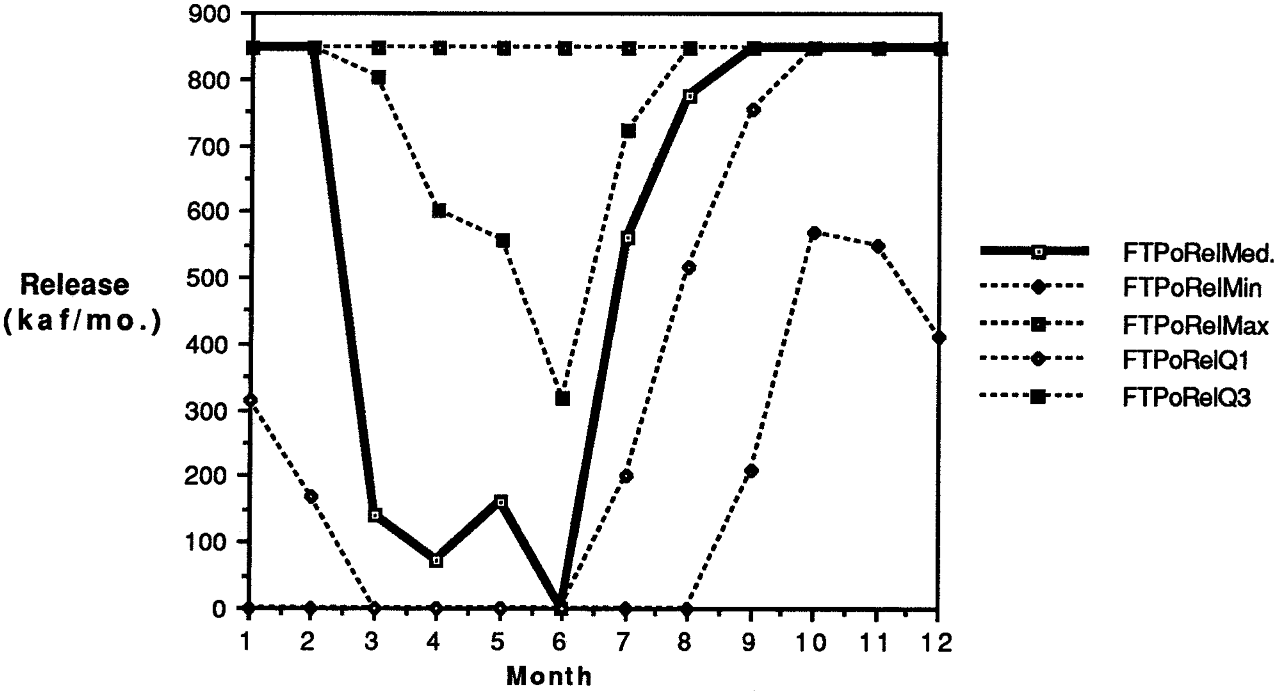

Figure 4-1
Fort Peck Optimal Releases By Month

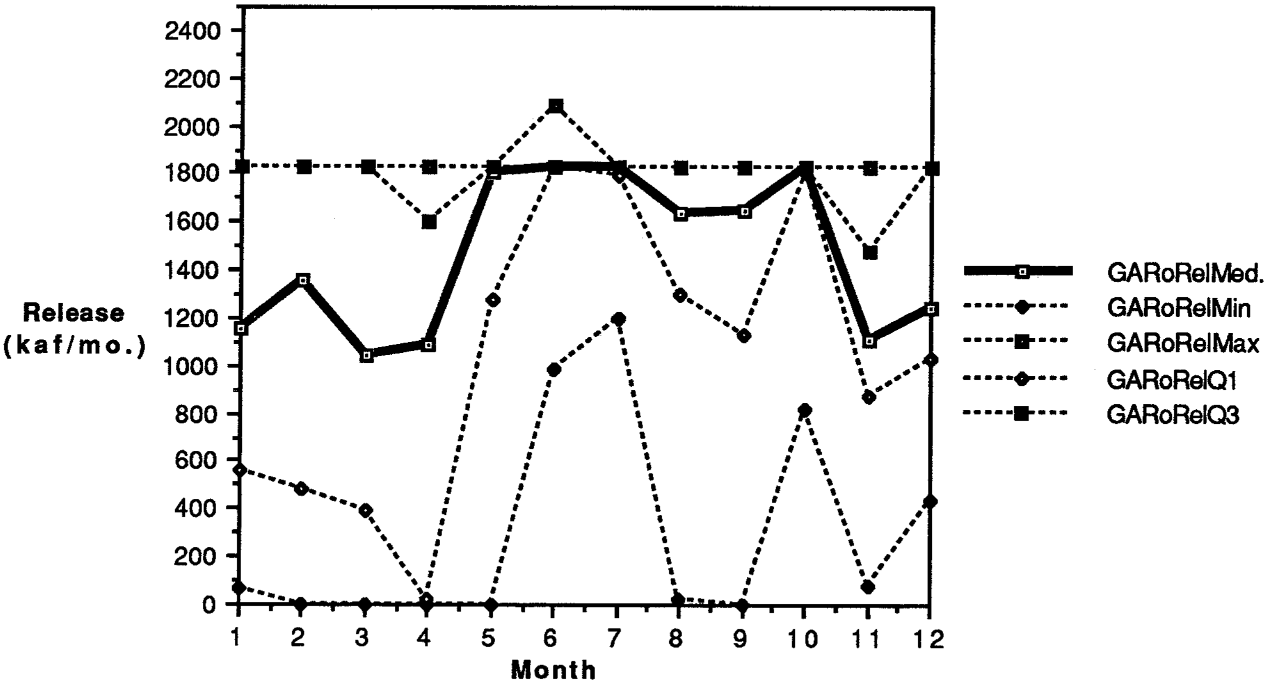

Figure 4-2
Garrison Optimal Releases By Month

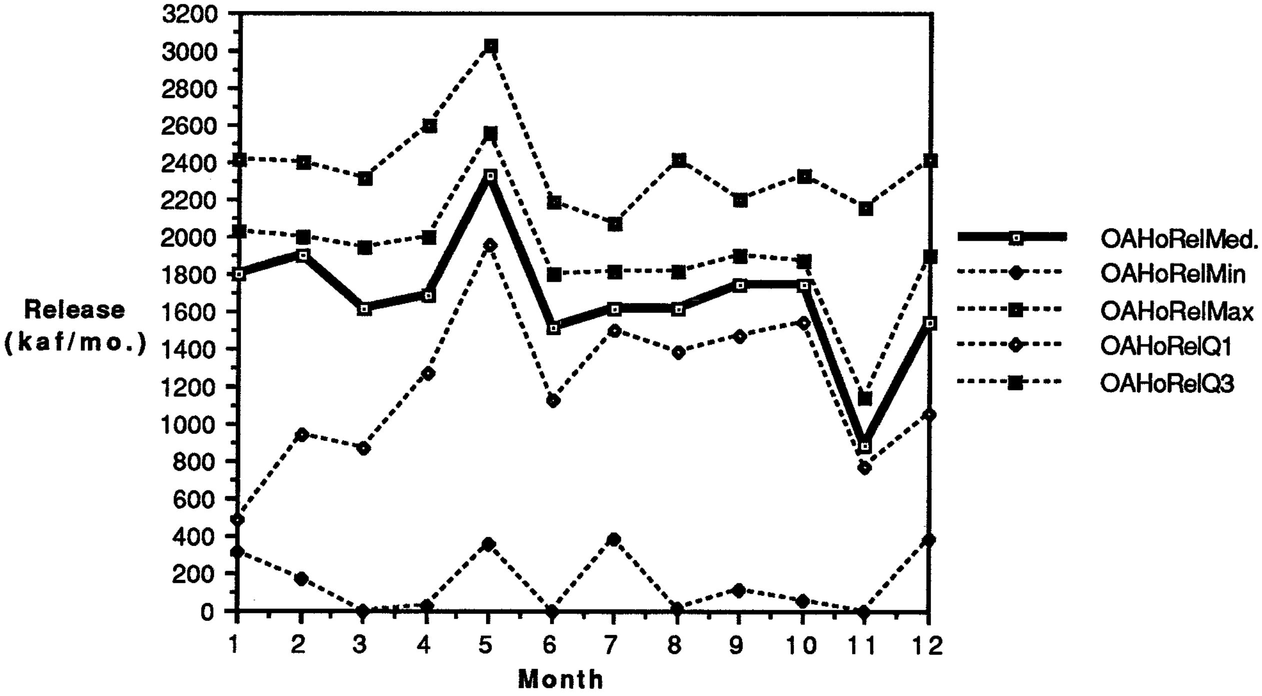

Figure 4-3
Oahe Optimal Releases by Month

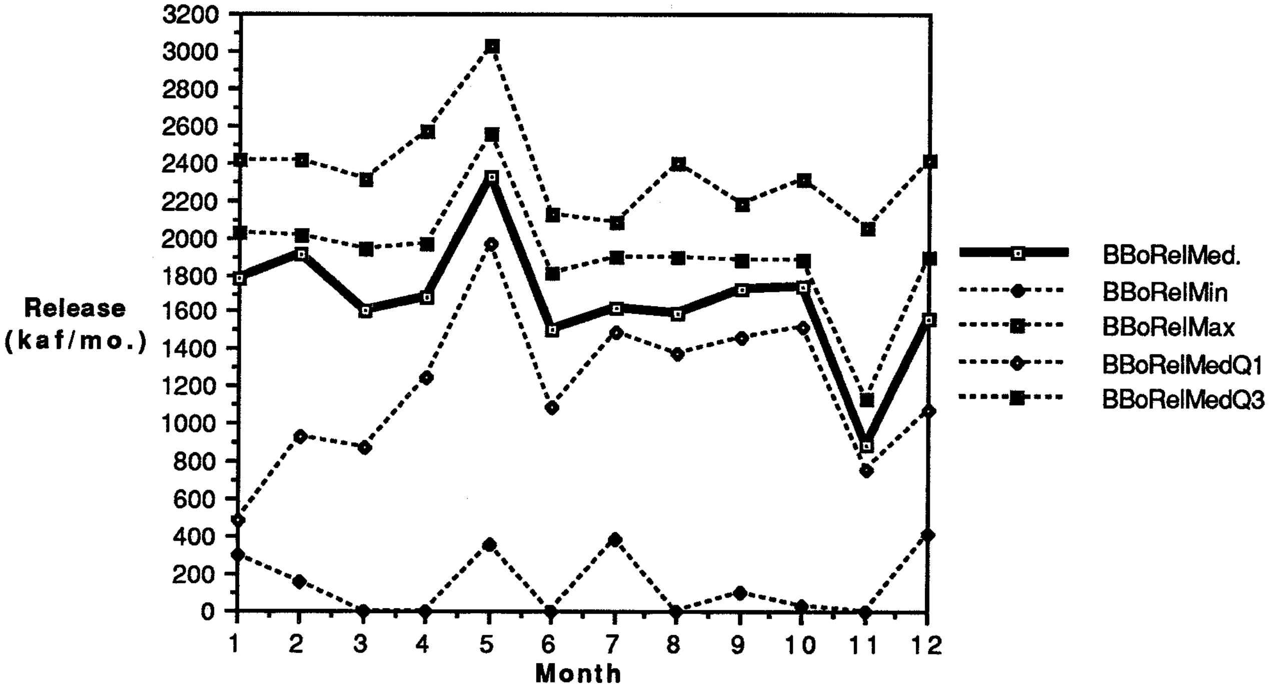

Figure 4-4
Big Bend Optimal Releases By Month

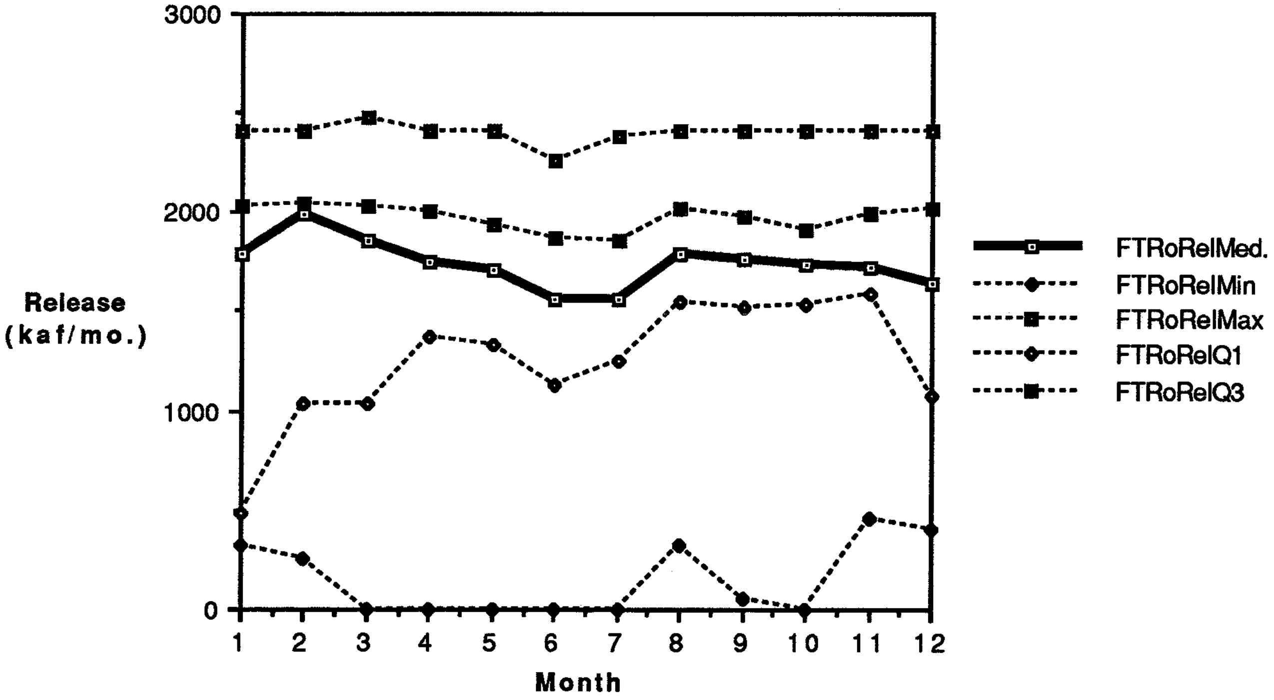

Figure 4-5
Fort Randall Optimal Releases By Month

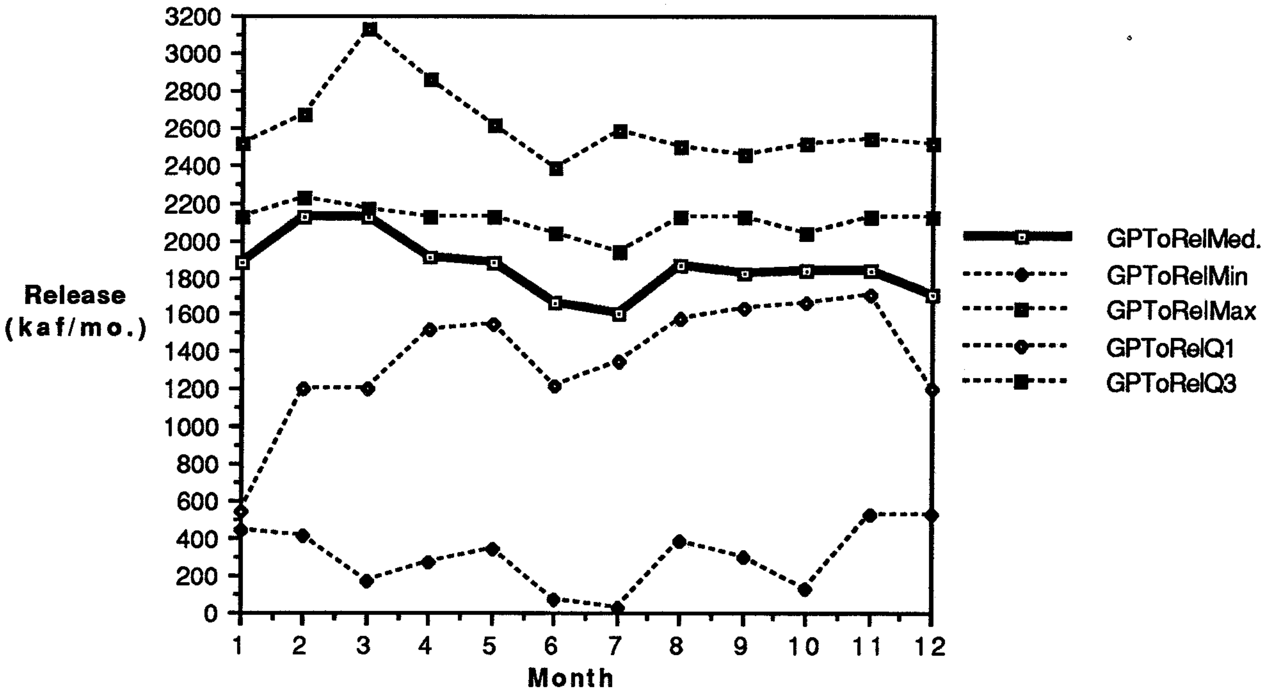

Figure 4-6
Gavins Point Optimal Release By Month

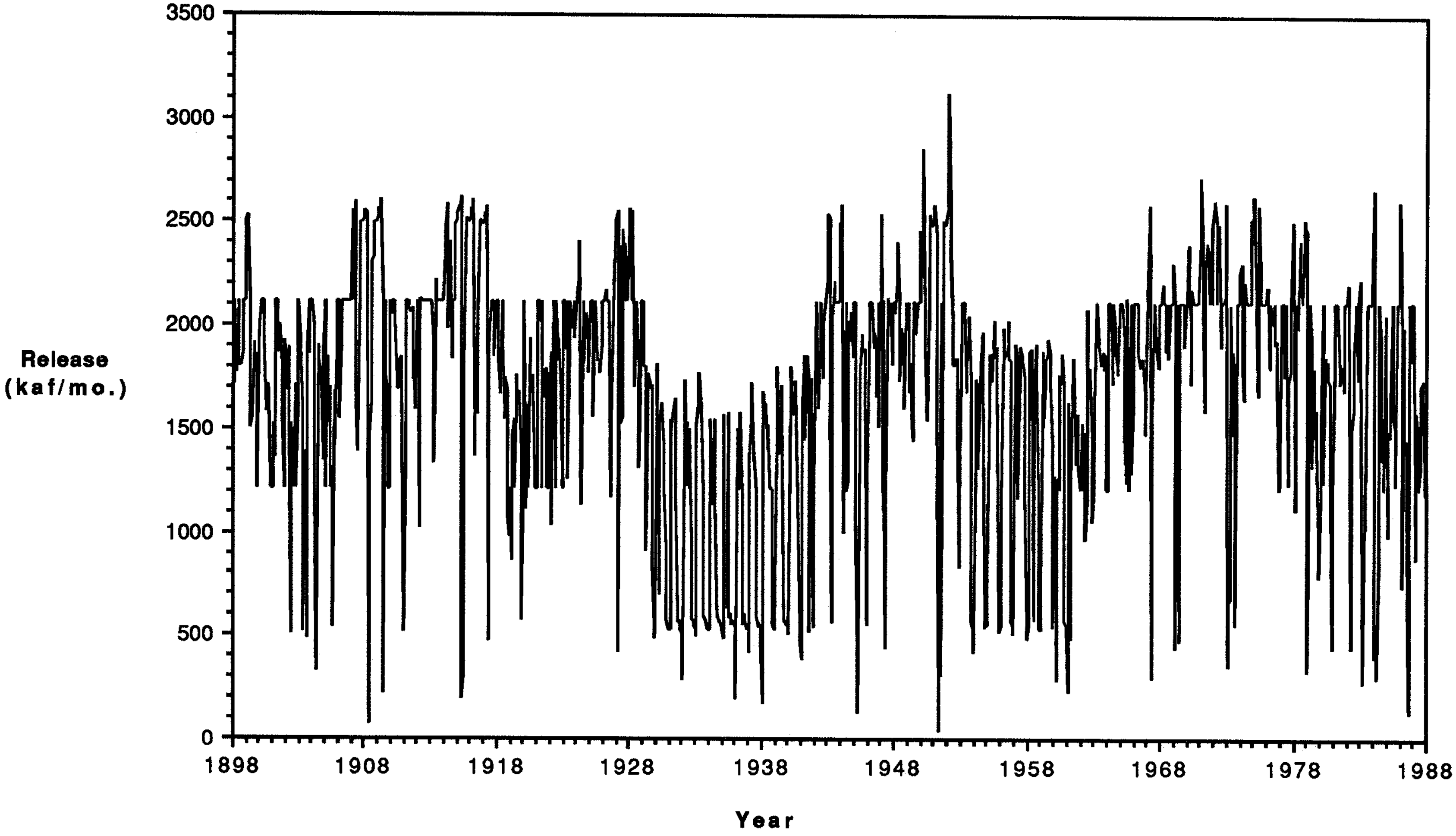

Figure 4-7

Time Series of Optimal Gavins Point Releases

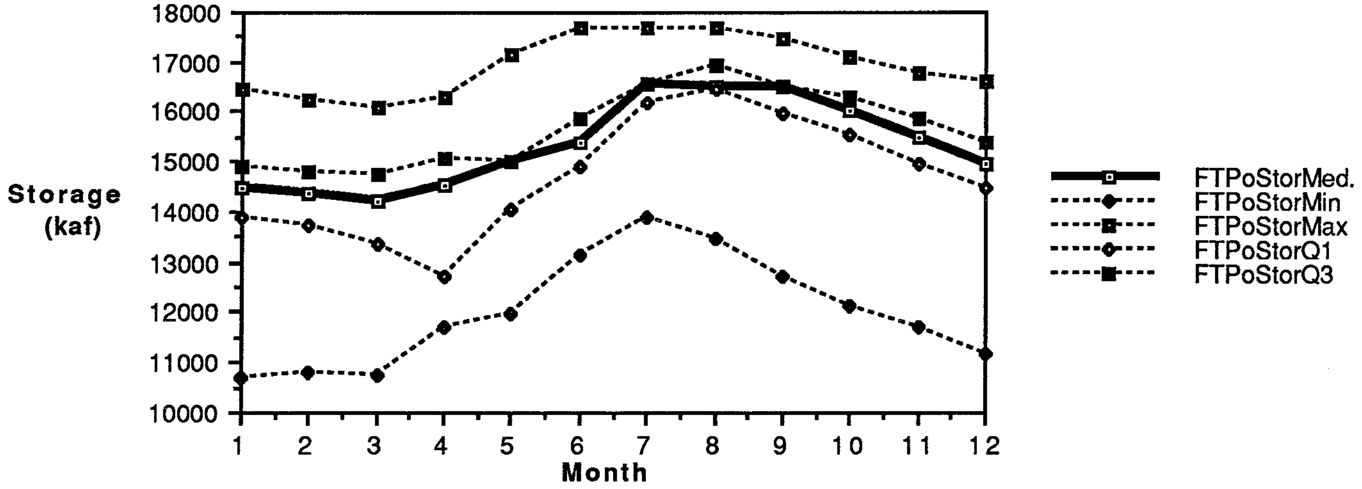

Figure 4-8
Fort Peck Optimal Storages By Month

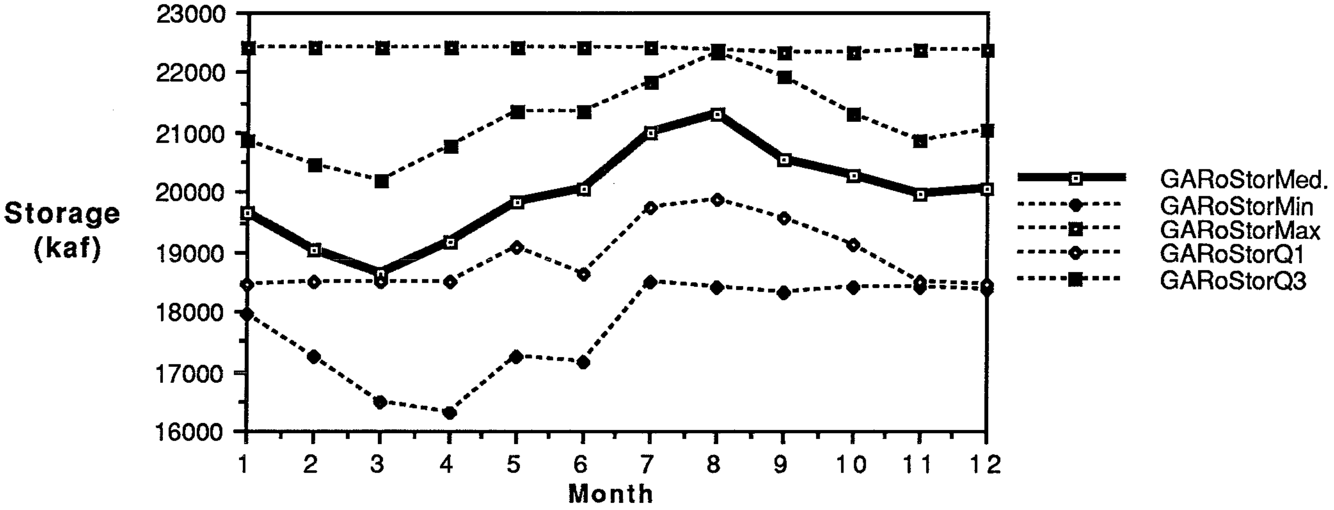

Figure 4-9
Garrison Optimal Storages By Month

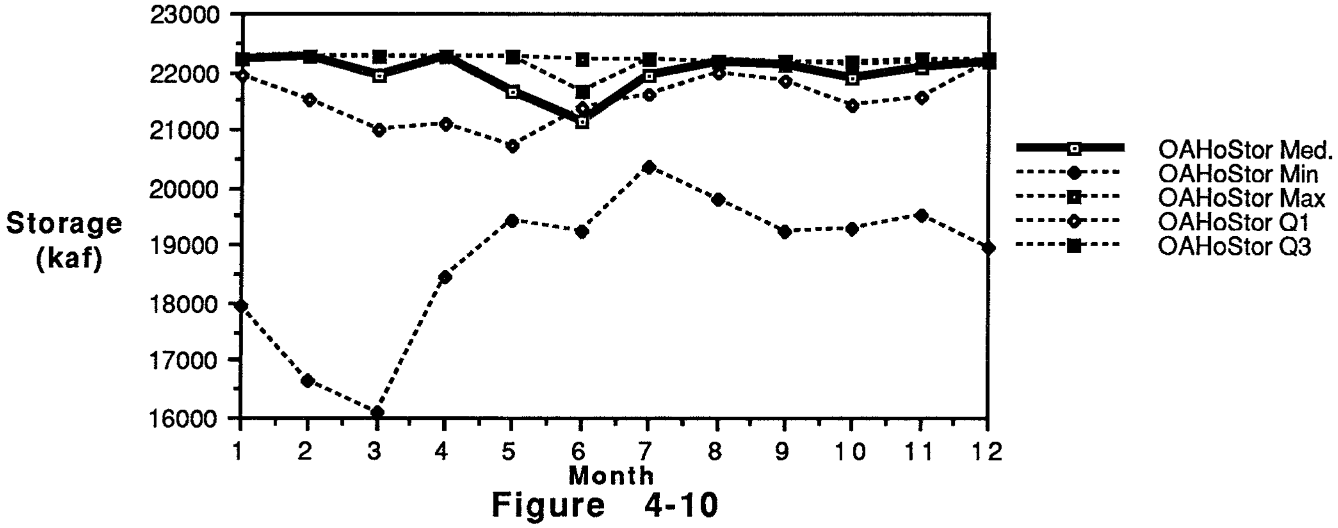

Figure 4-10
Oahe Optimal Storages By Month

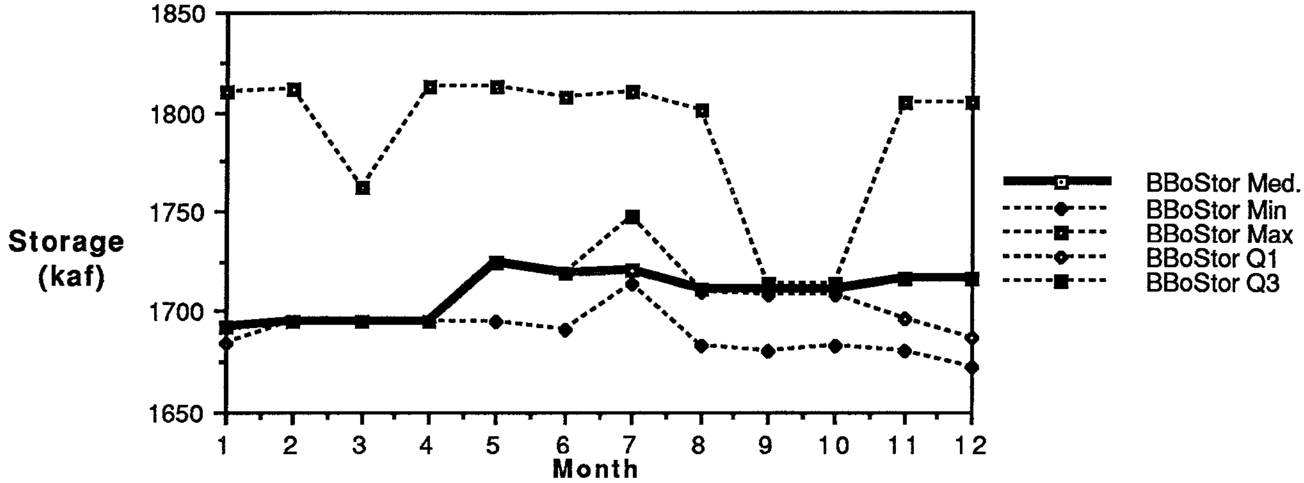

Figure 4-11
Big Bend Optimal Storages By Month

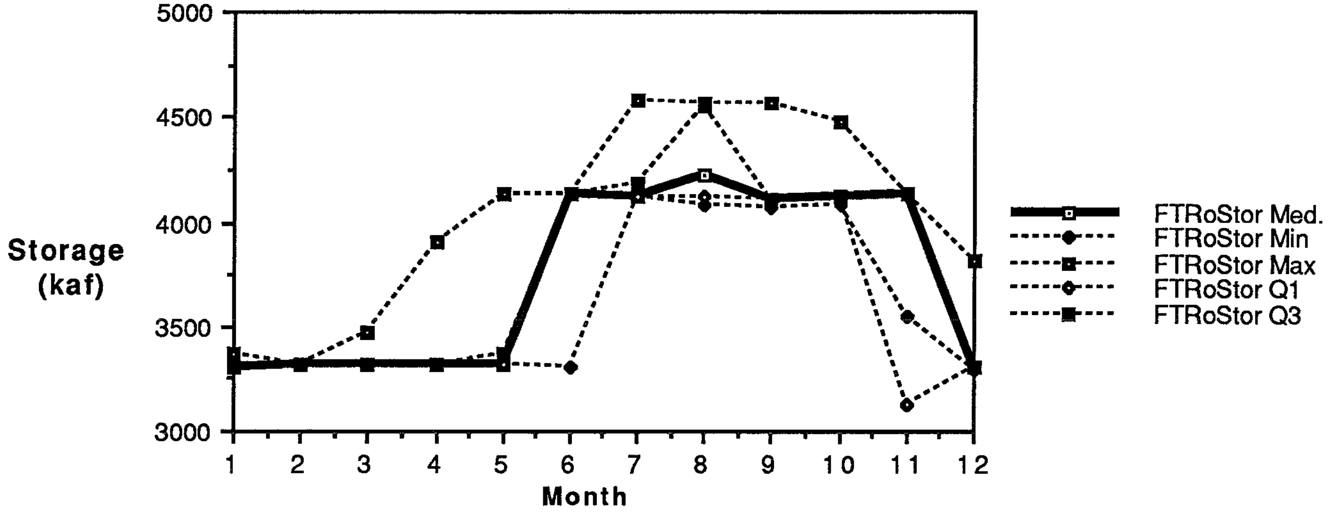

Figure 4-12
Fort Randall Optimal Storages By Month

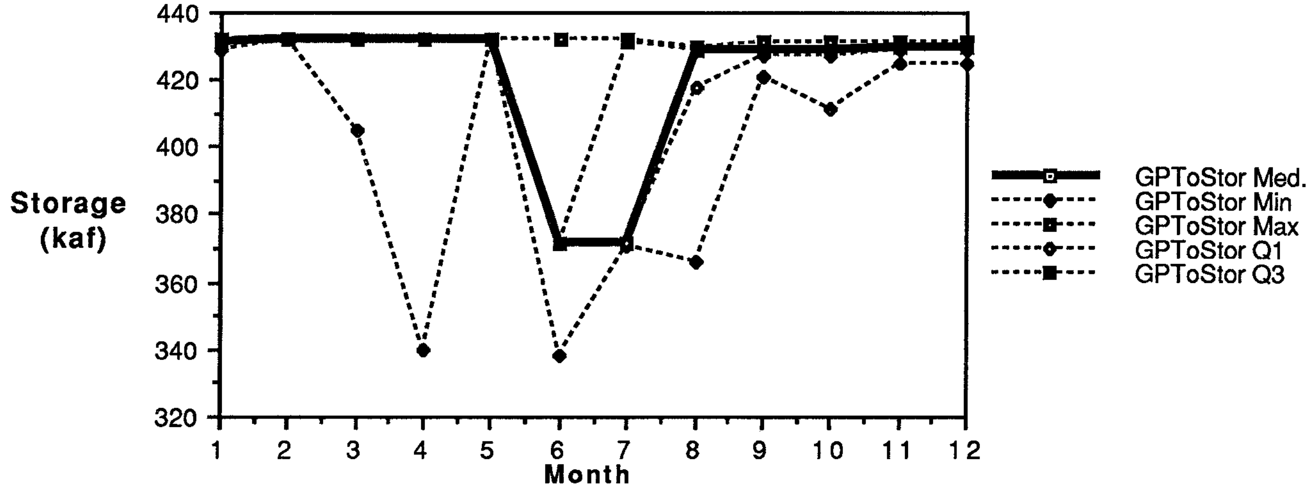

Figure 4-13
Gavins Point Optimal Storages By Month

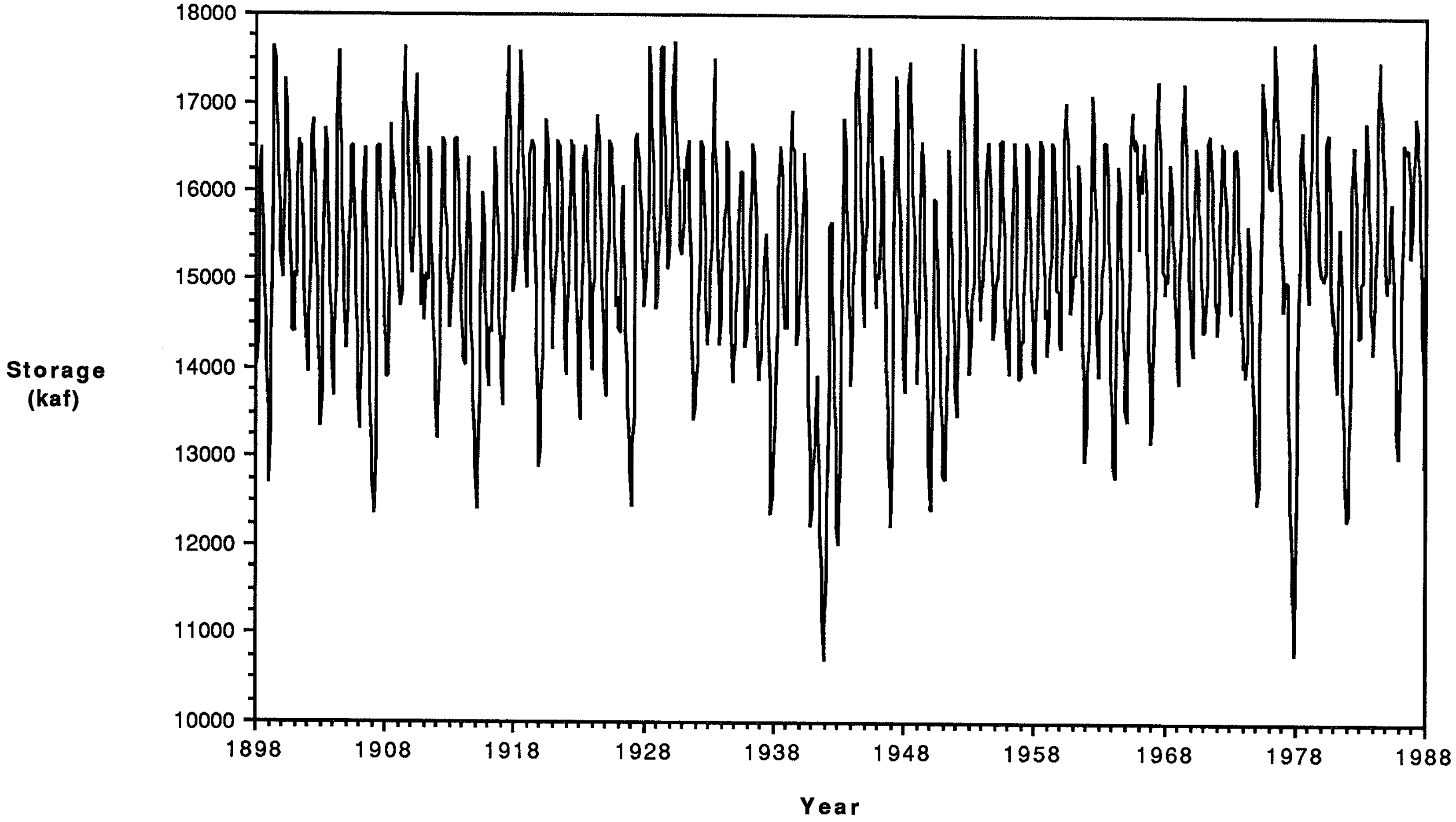

Figure 4-14

Fort Peck Optimal Storage Time Series

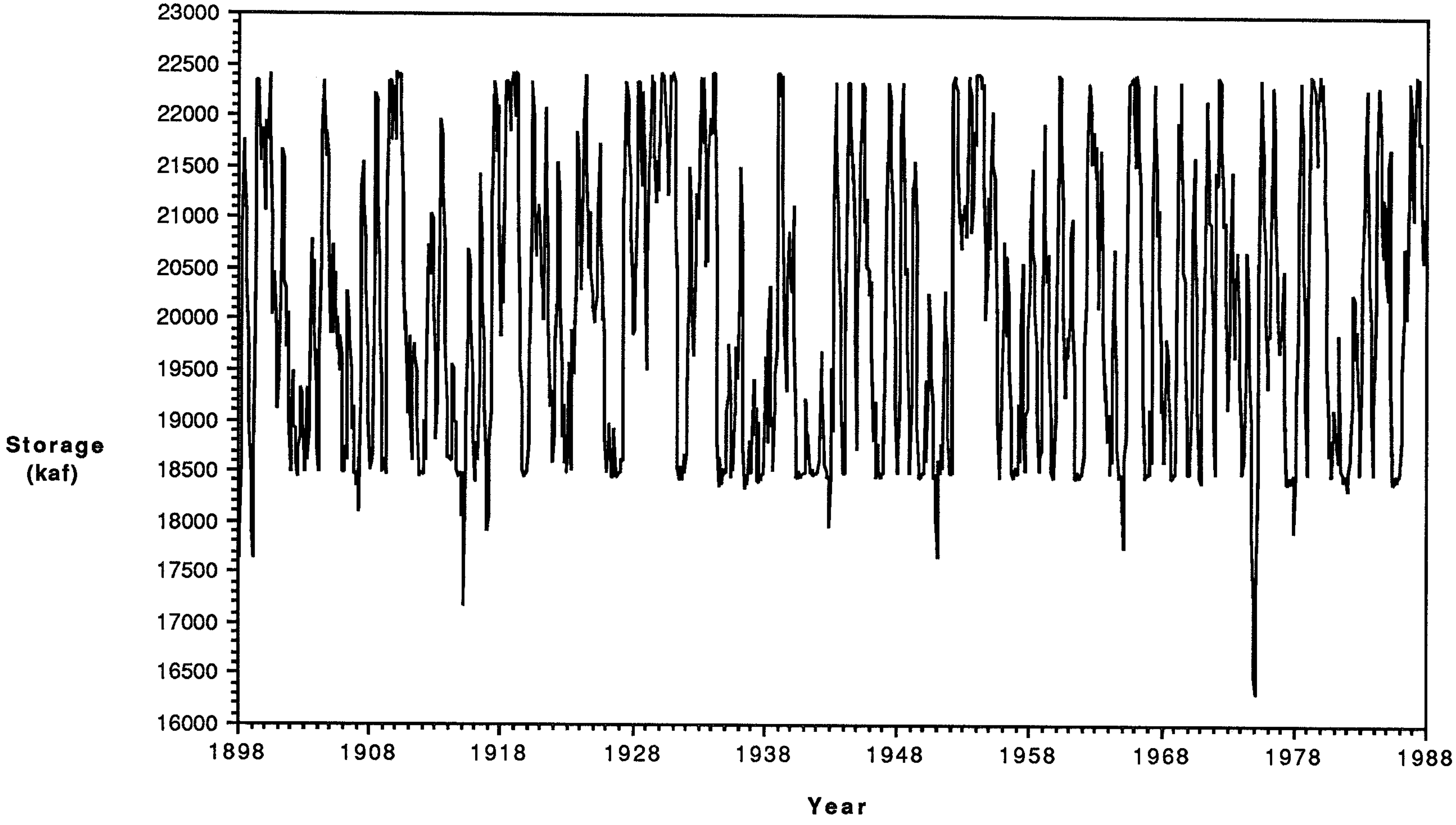

Figure 4-15

Garrison Optimal Storage Time Series

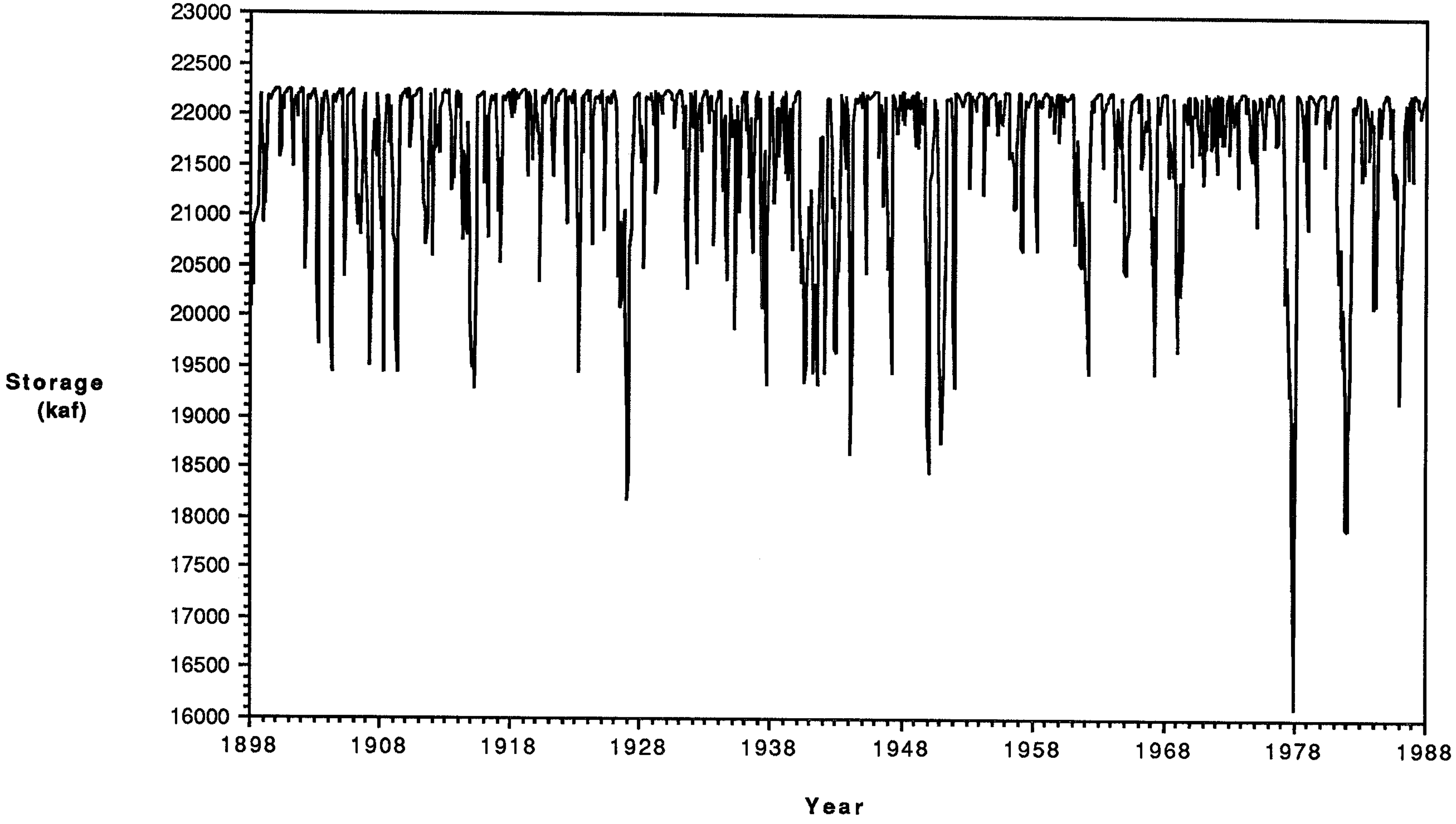

Figure 4-16

Oahe Optimal Storage Time Series

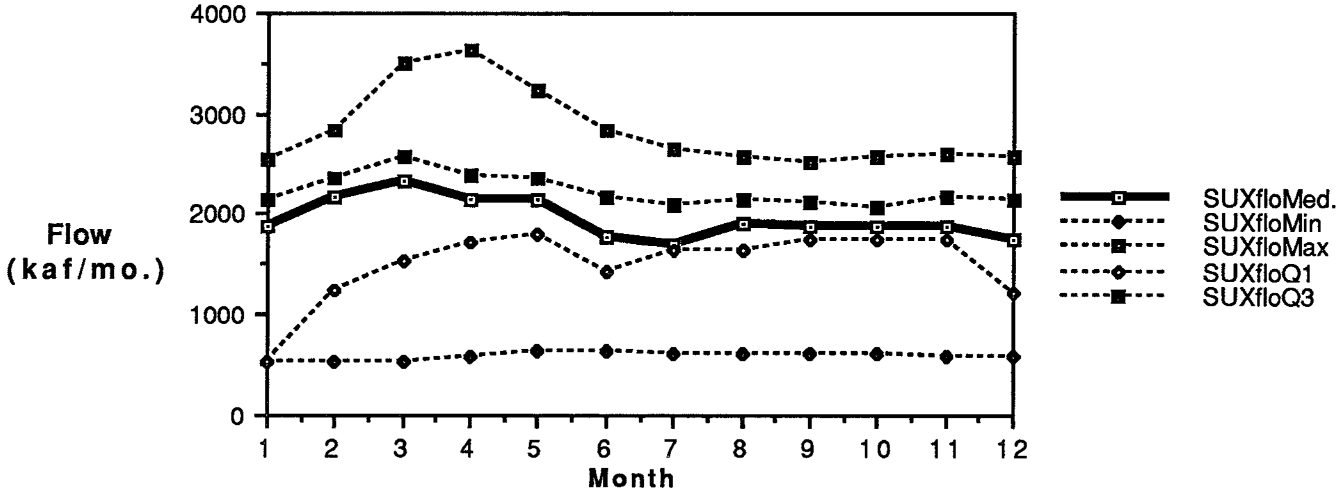

Figure 4-17
Sioux City Optimal Flows by Month

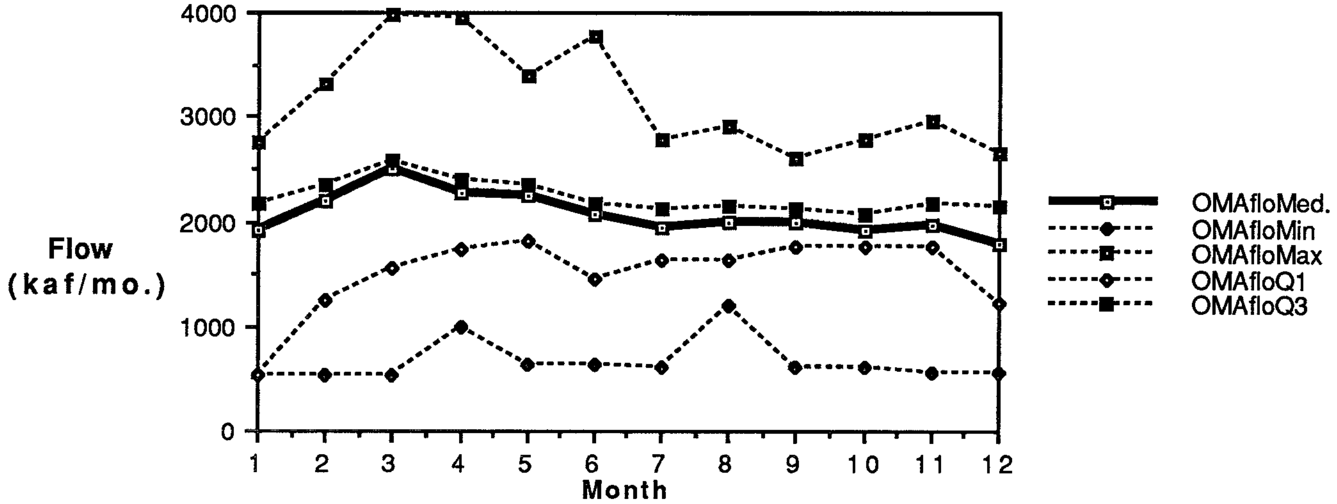

Figure 4-18
Omaha Optimal Flows By Month

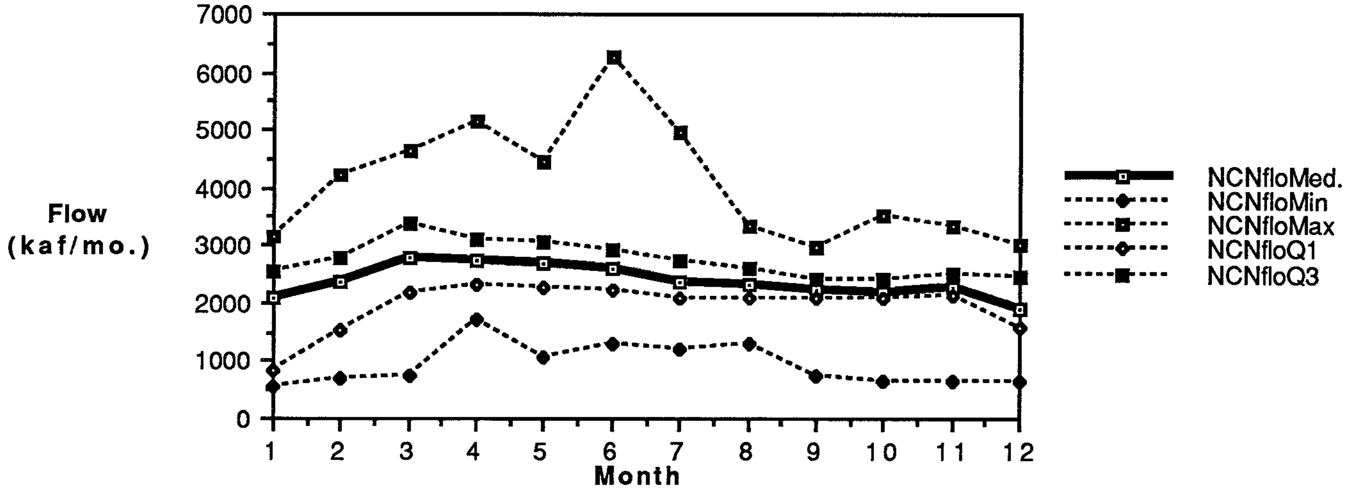

Figure 4-19
Nebraska City Optimal Flows By Month

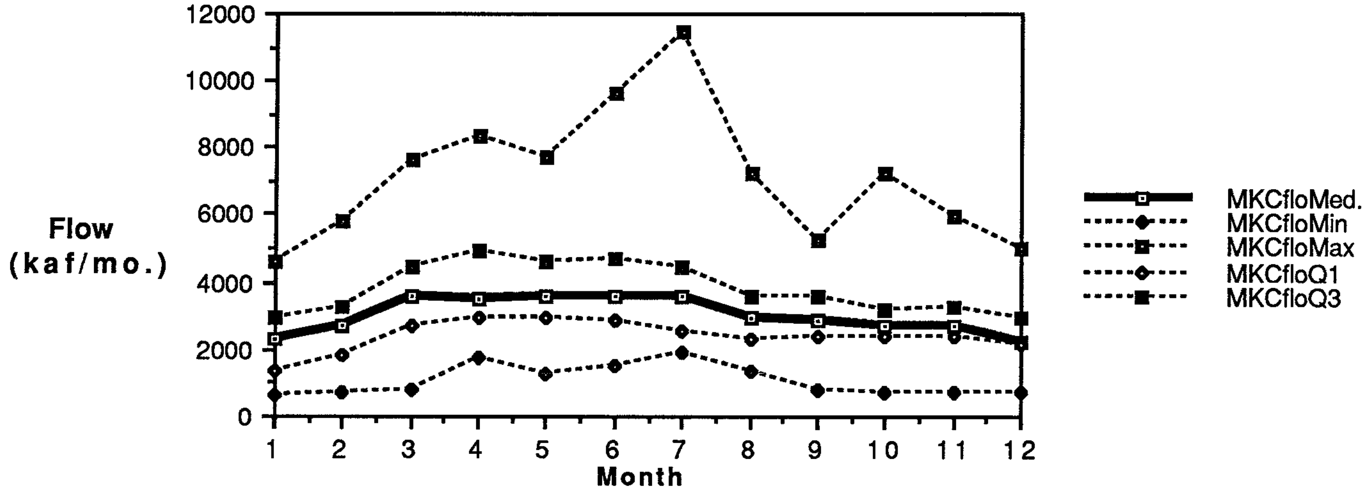

Figure 4-20
Kansas City Optimal Flows by Month

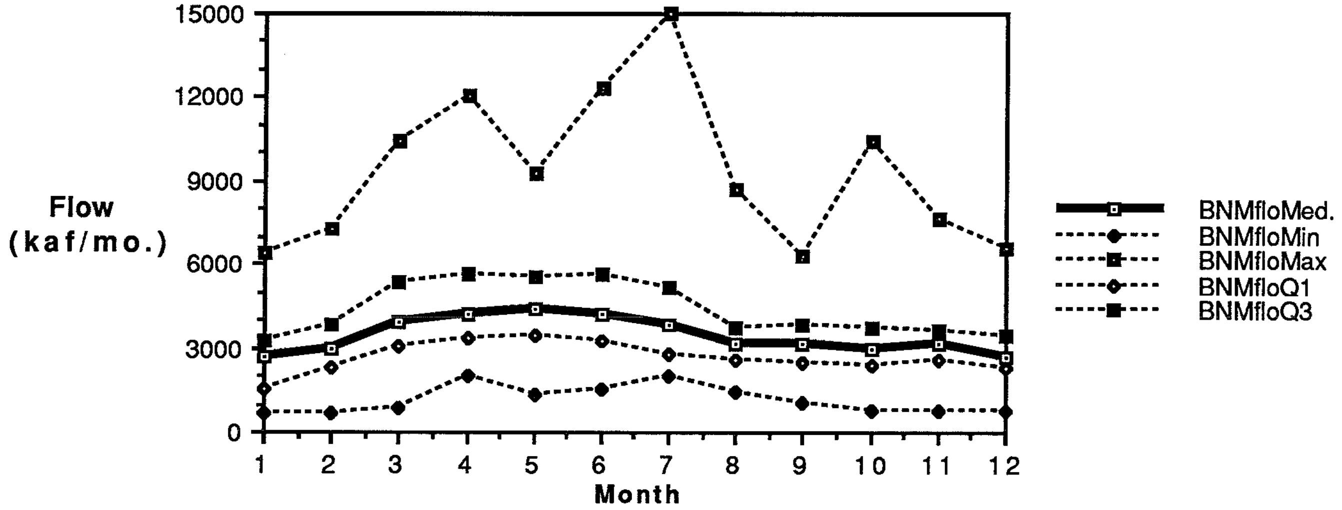

Figure 4-21
Boonville Optimal Flows By Month

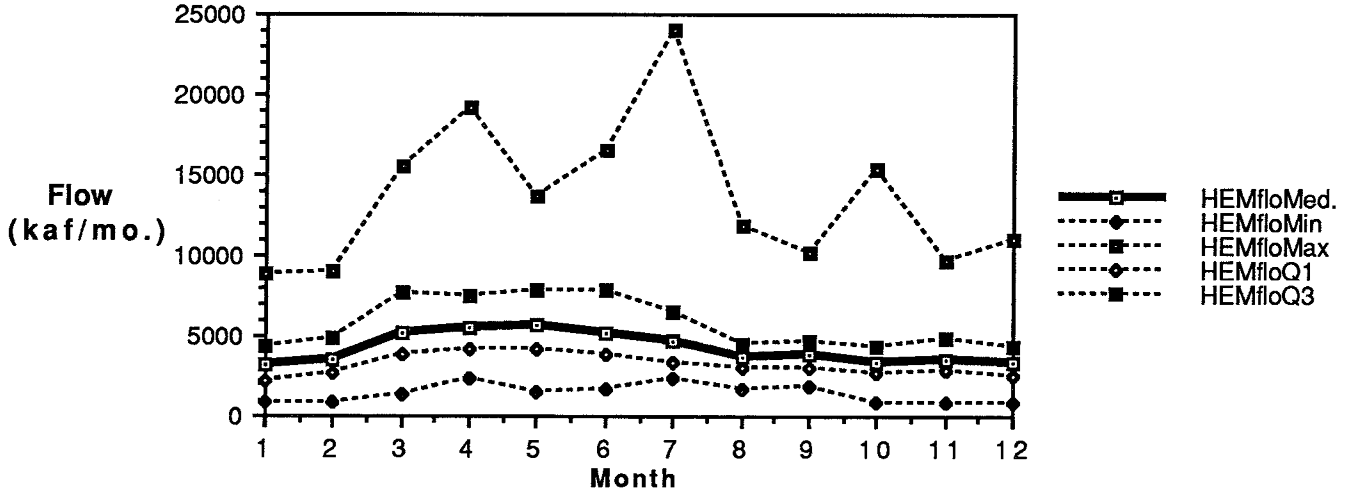

Figure 4-22
Hermann Optimal Flows By Month

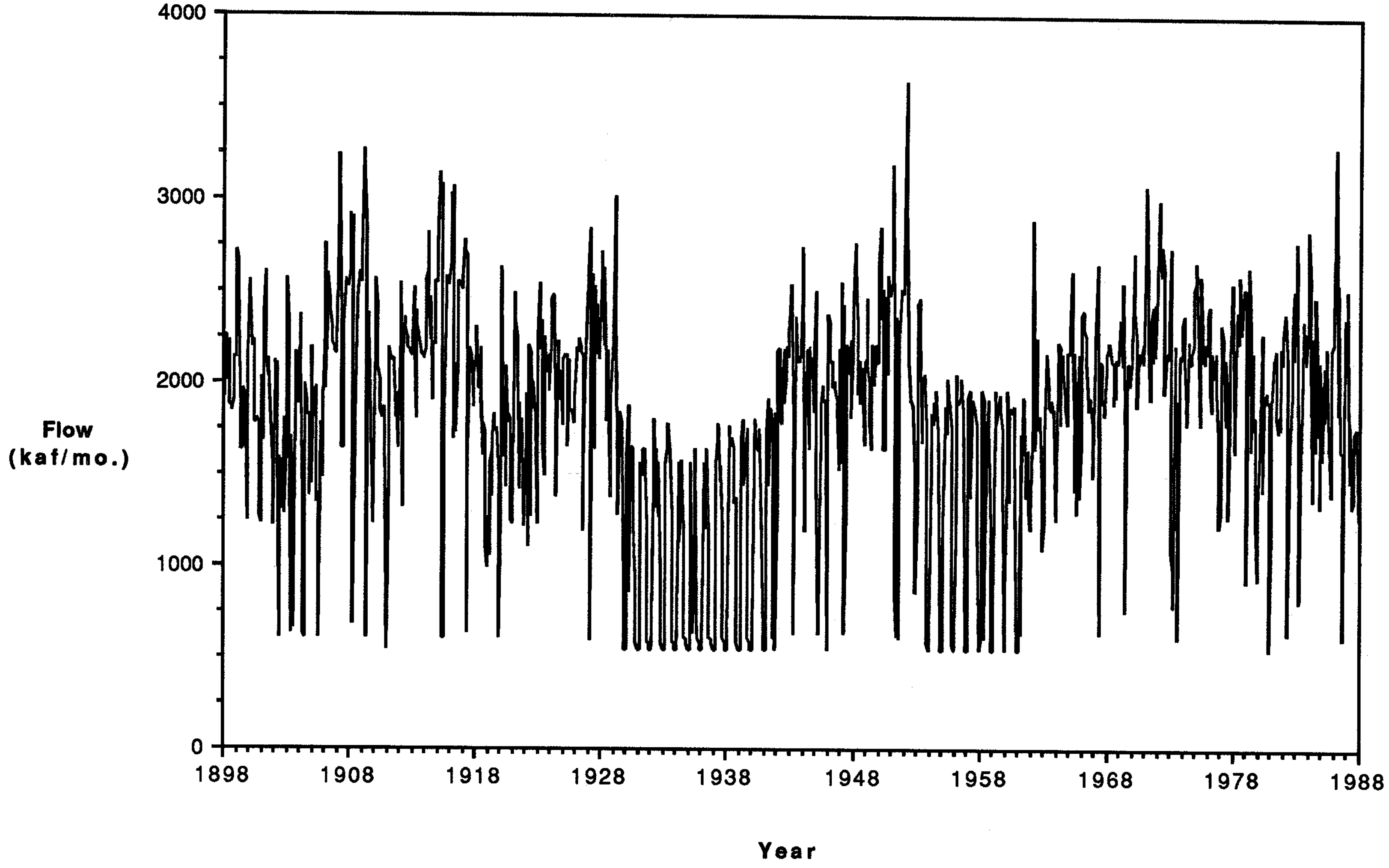

Figure 4-23

Optimal Sioux City Flow Time Series

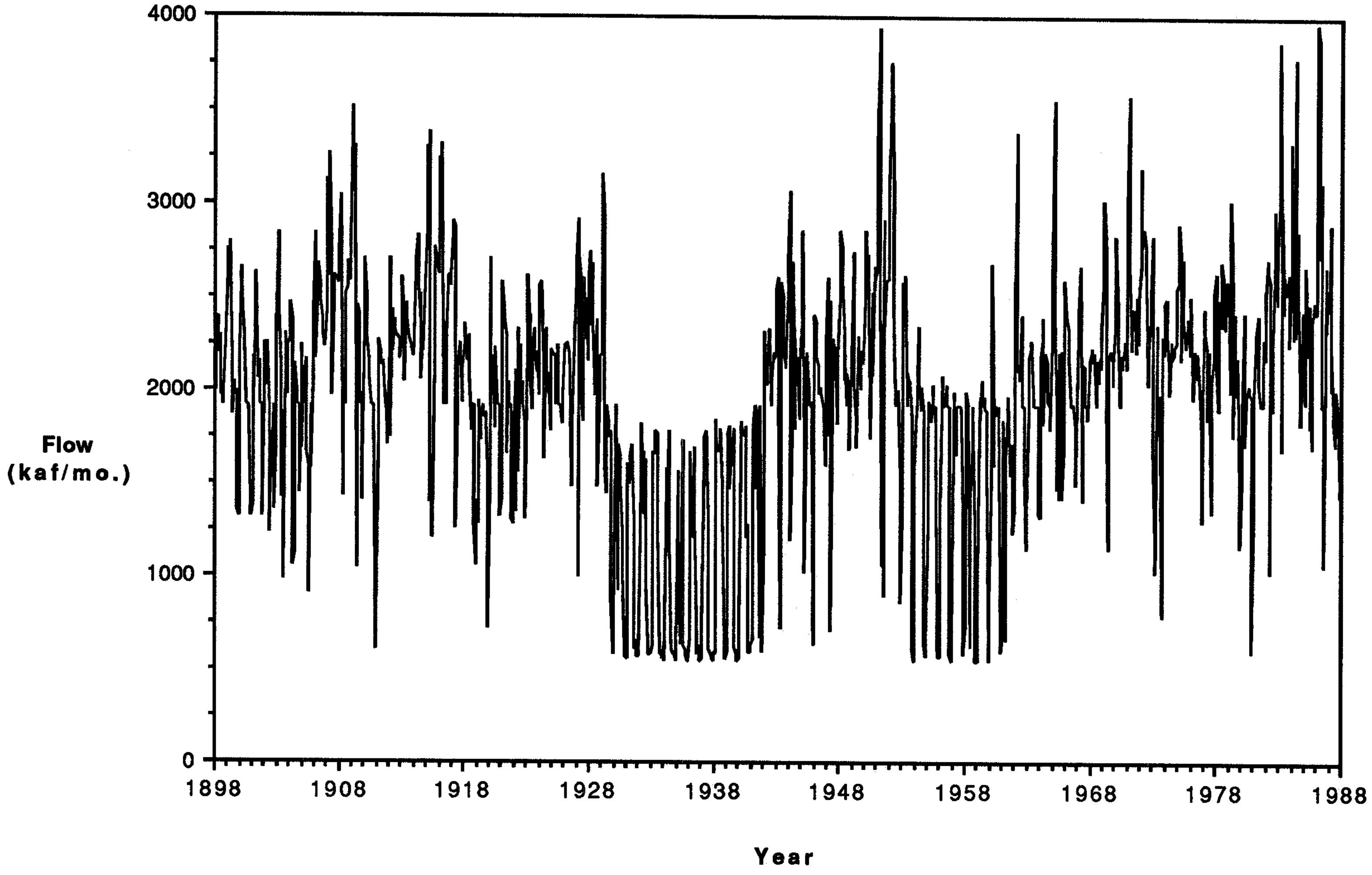

Figure 4-24

Optimal Omaha Flow Time Series

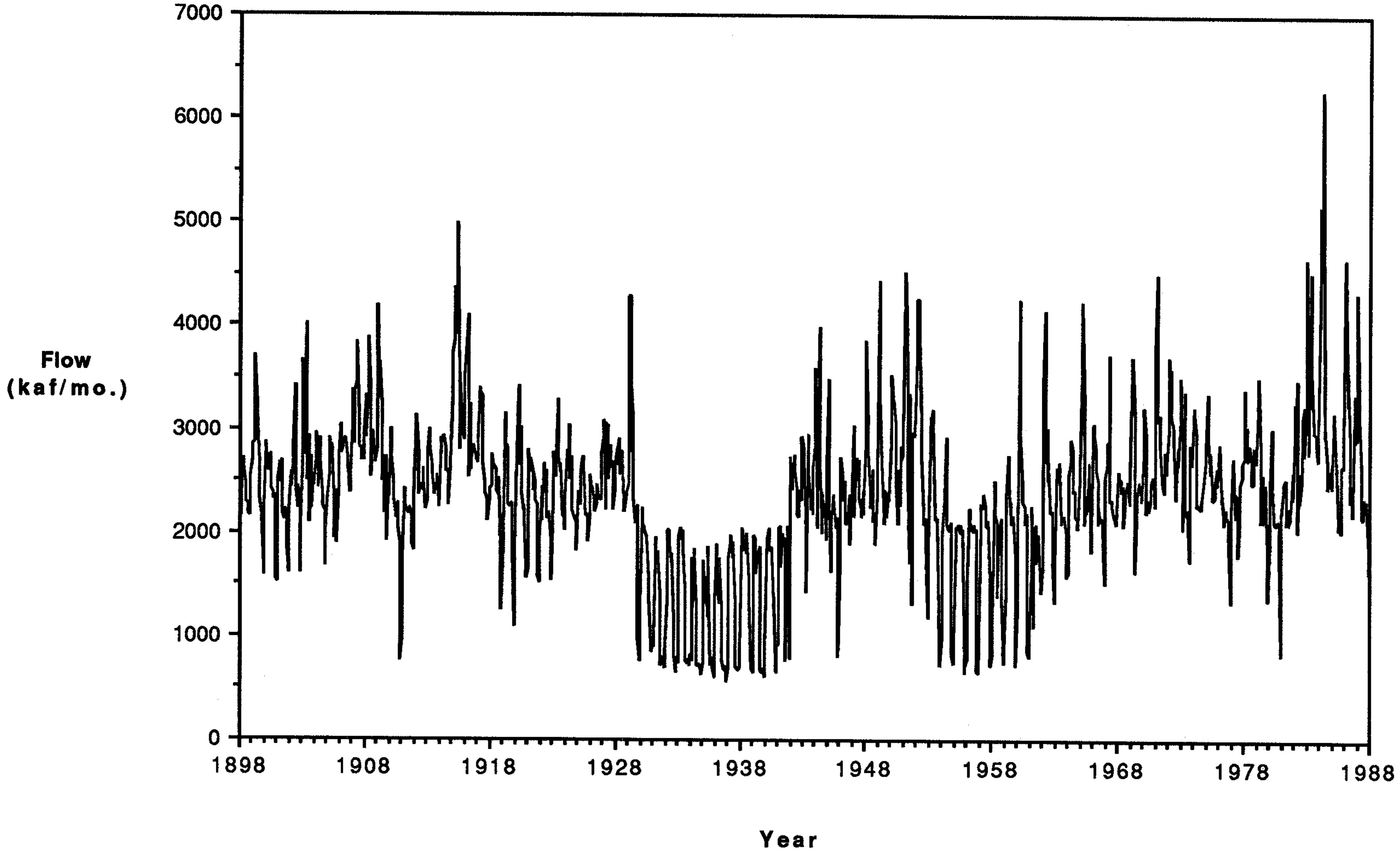

Figure 4-25

Optimal Nebraska City Flow Time Series

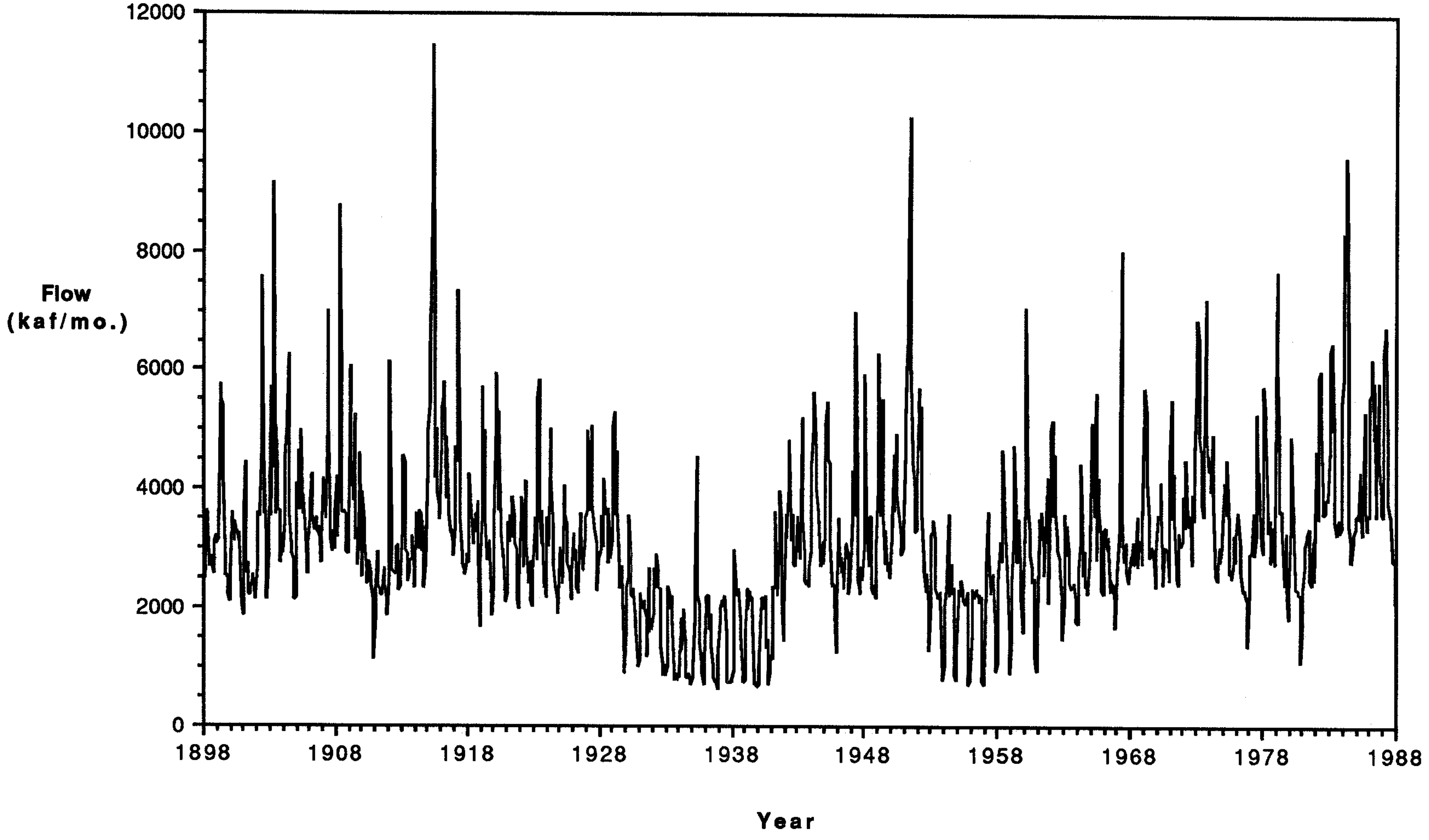

Figure 4-26

Optimal Kansas City Flow Time Series

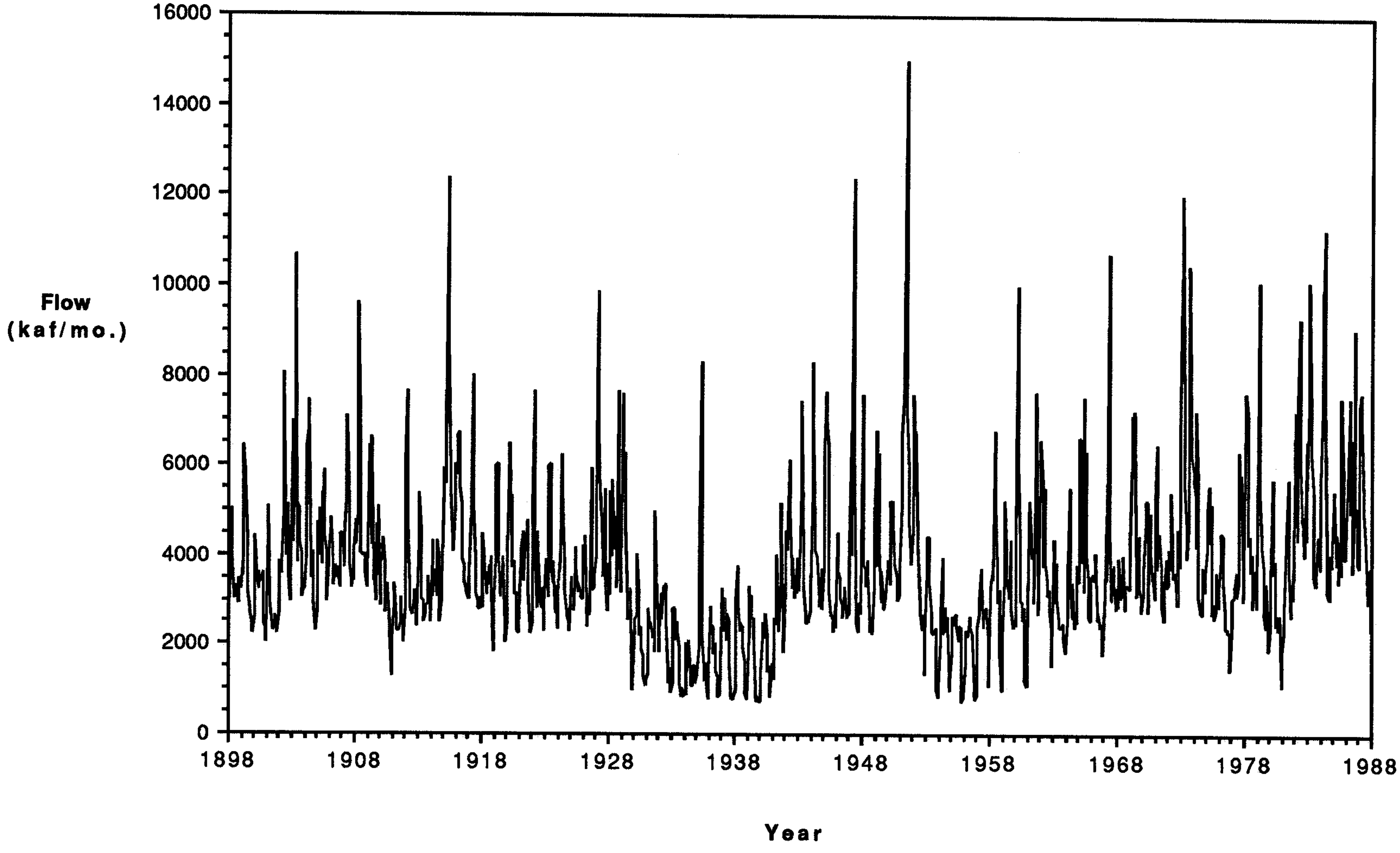

Figure 4-27

Optimal Boonville Flow Time Series

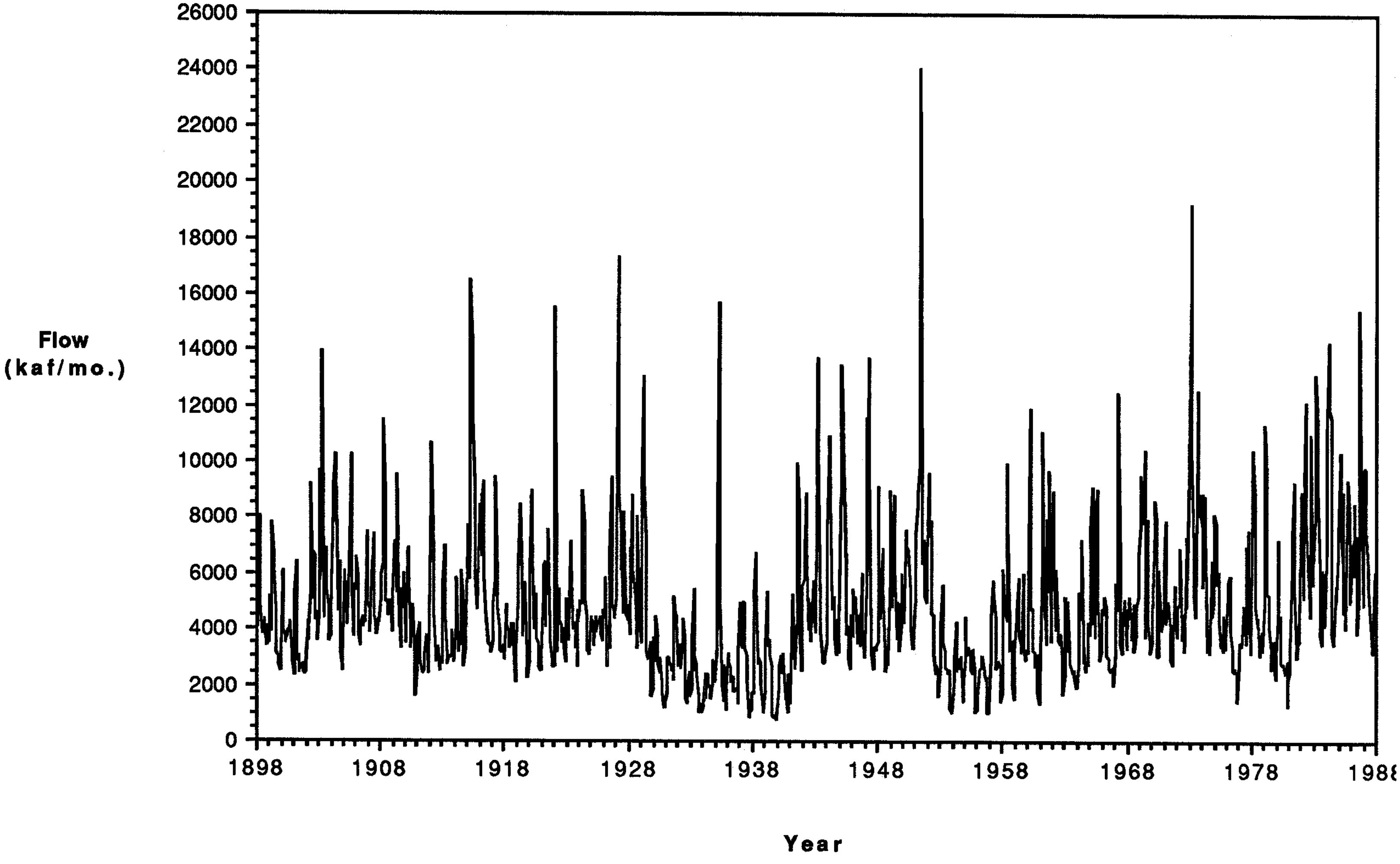

Figure 4-28

Optimal Hermann Flow Time Series

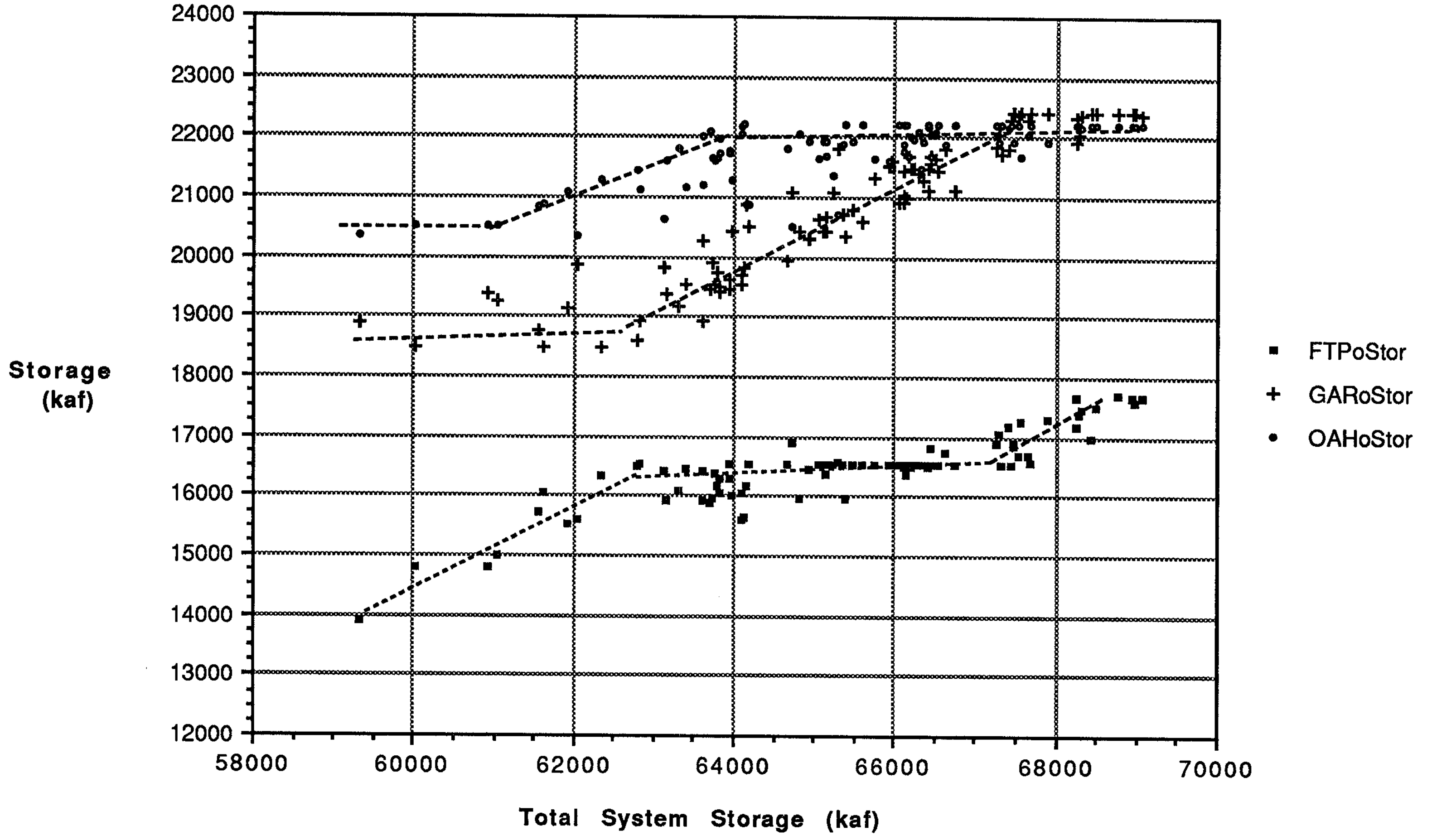

Figure 4-29

July Optimal Storage Relationships

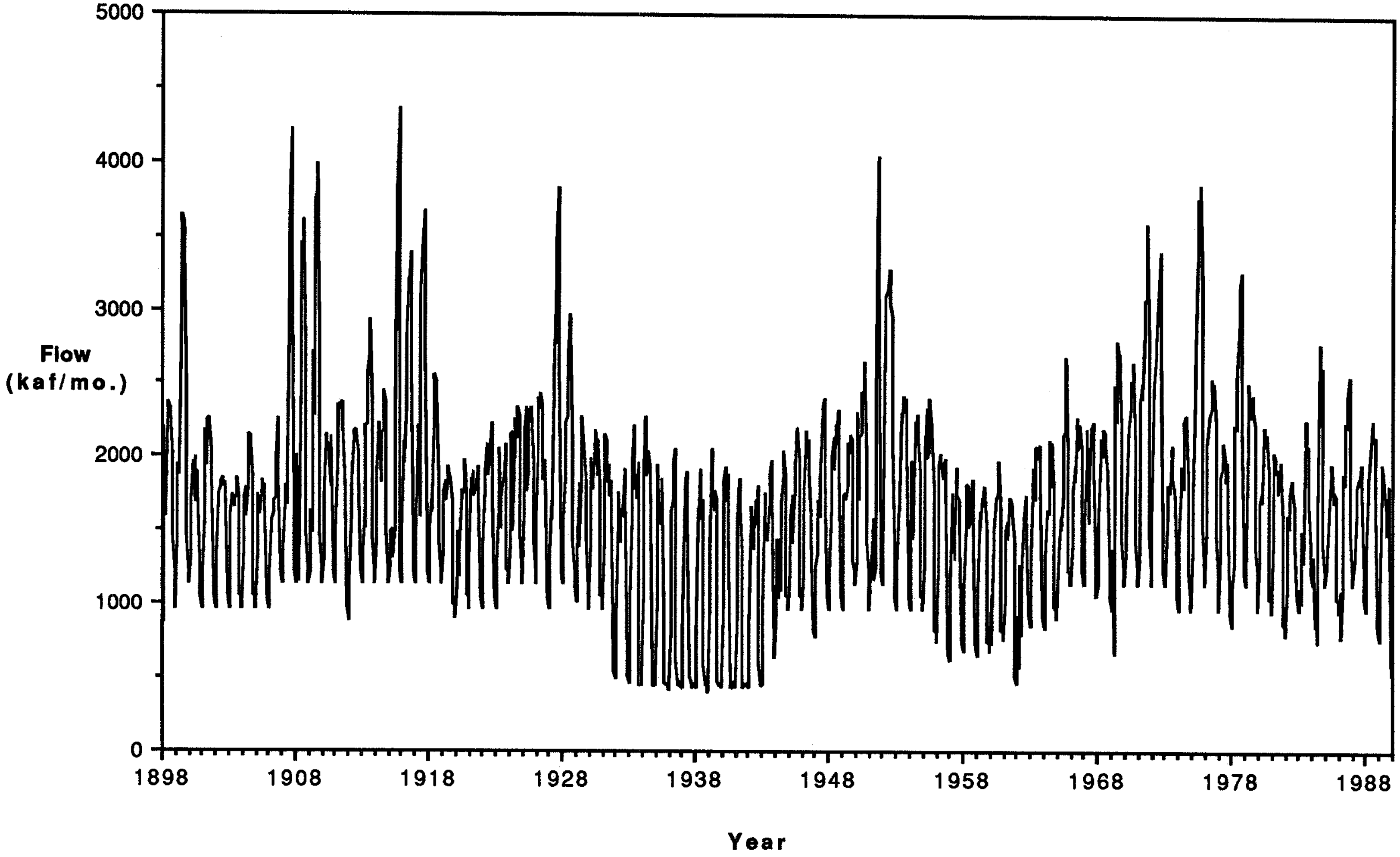

Figure 4-30

Time Series of Simulated Gavins Point Releases

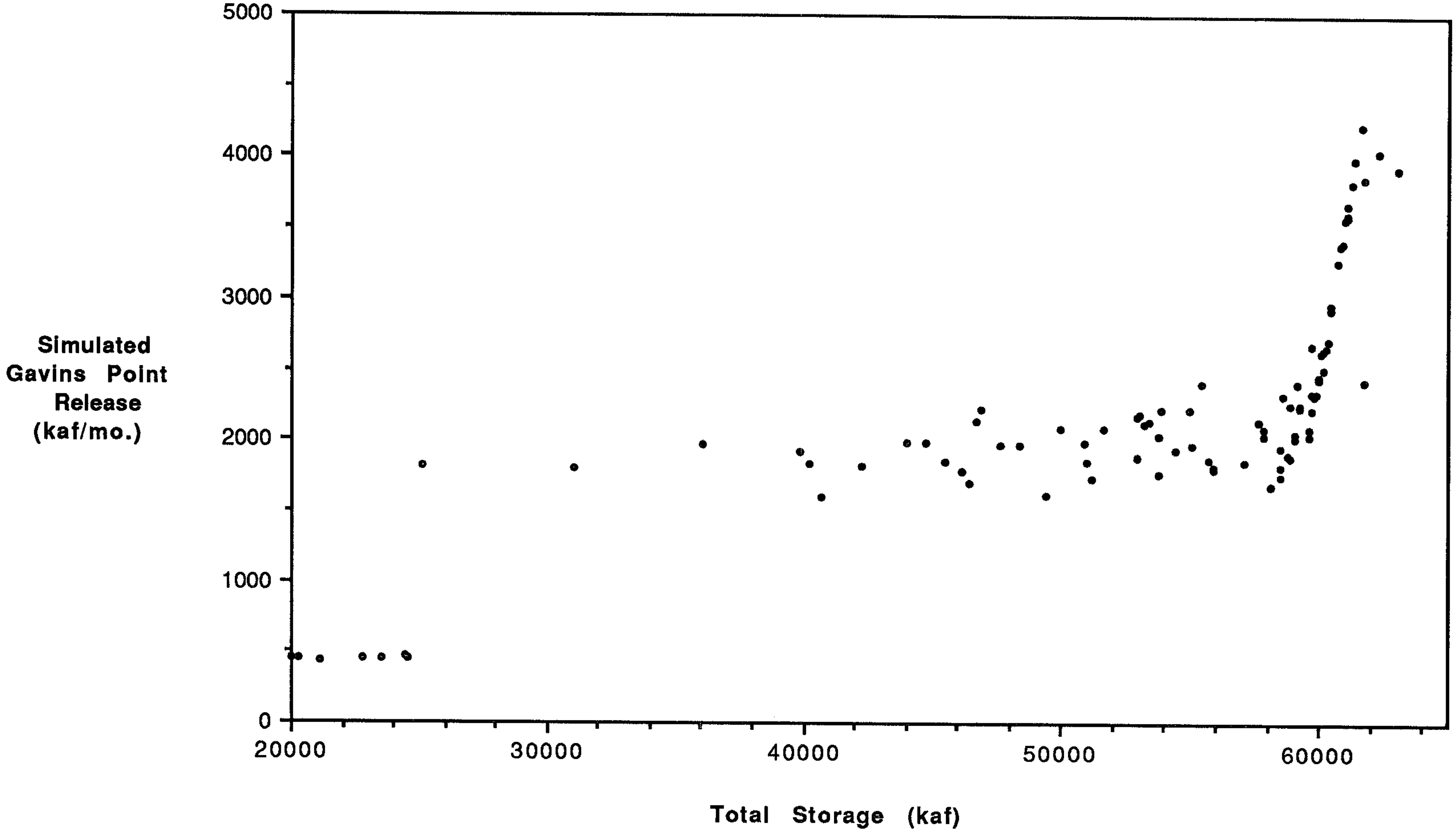

Figure 4-31

Simulated Current Gavins Point Releases Versus Total Storage

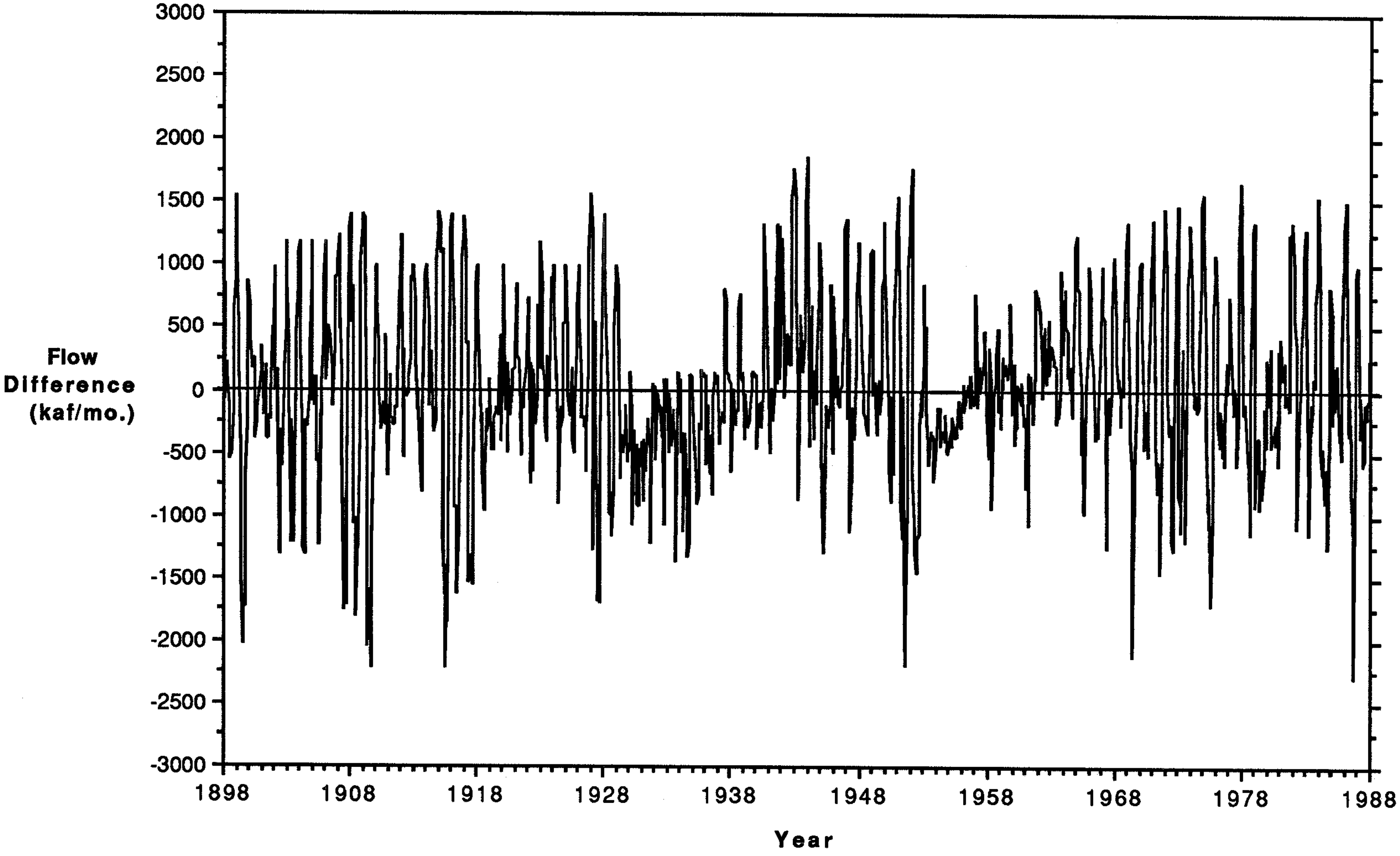

Figure 4-32

Optimal Minus Simulated Gavins Point Releases

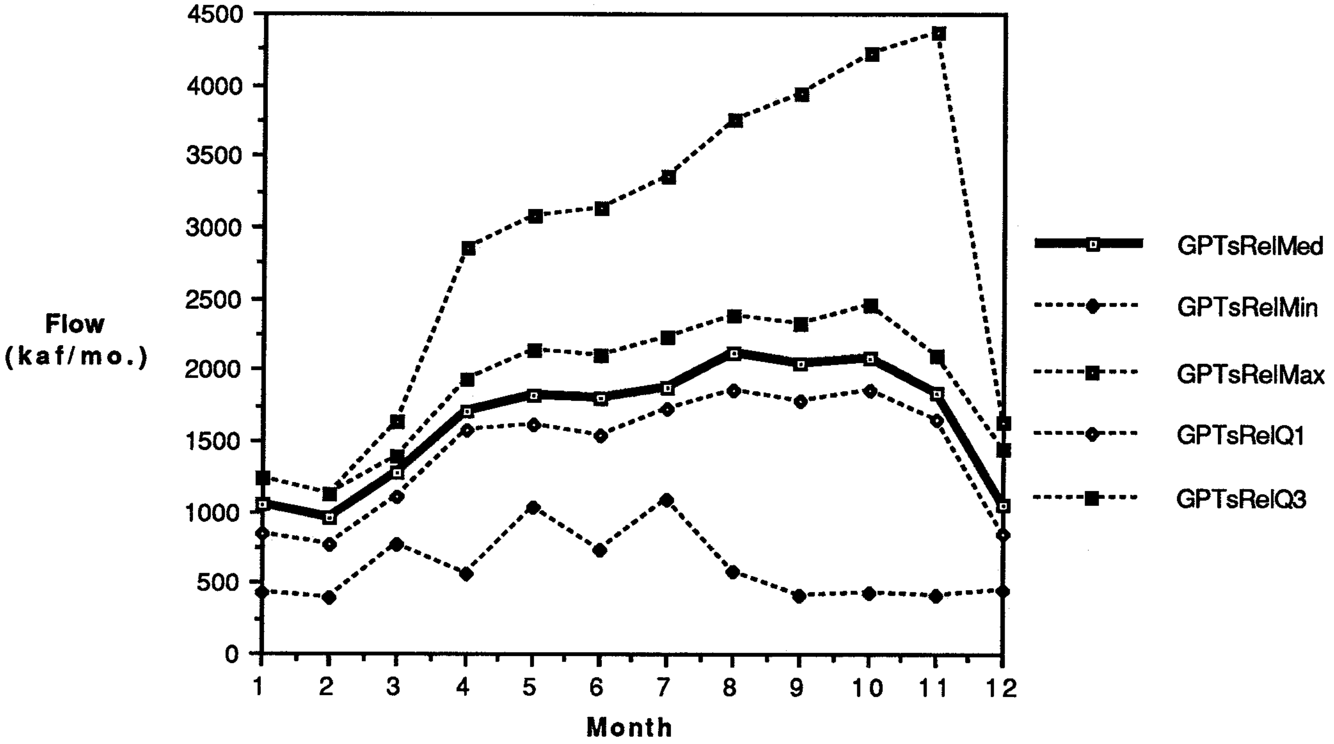

Figure 4-33

Gavins Point Simulated Releases By Month

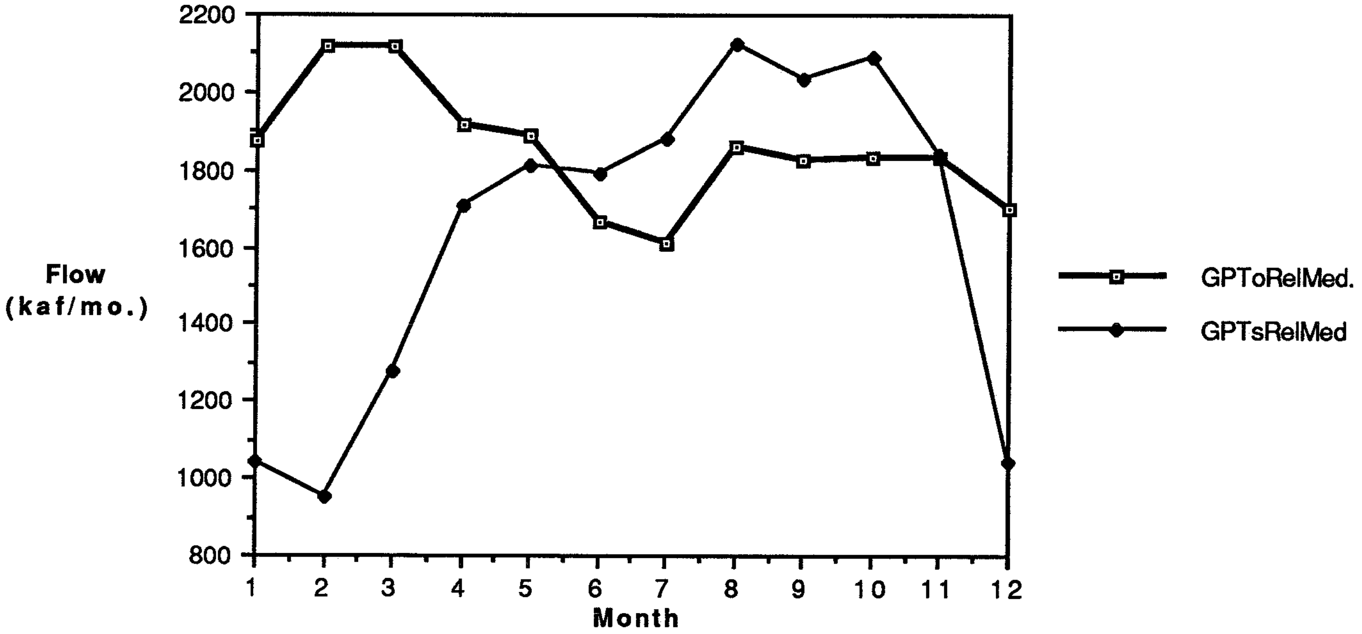

Figure 4-34

Median Optimal and Simulated Gavins Point Releases By Month

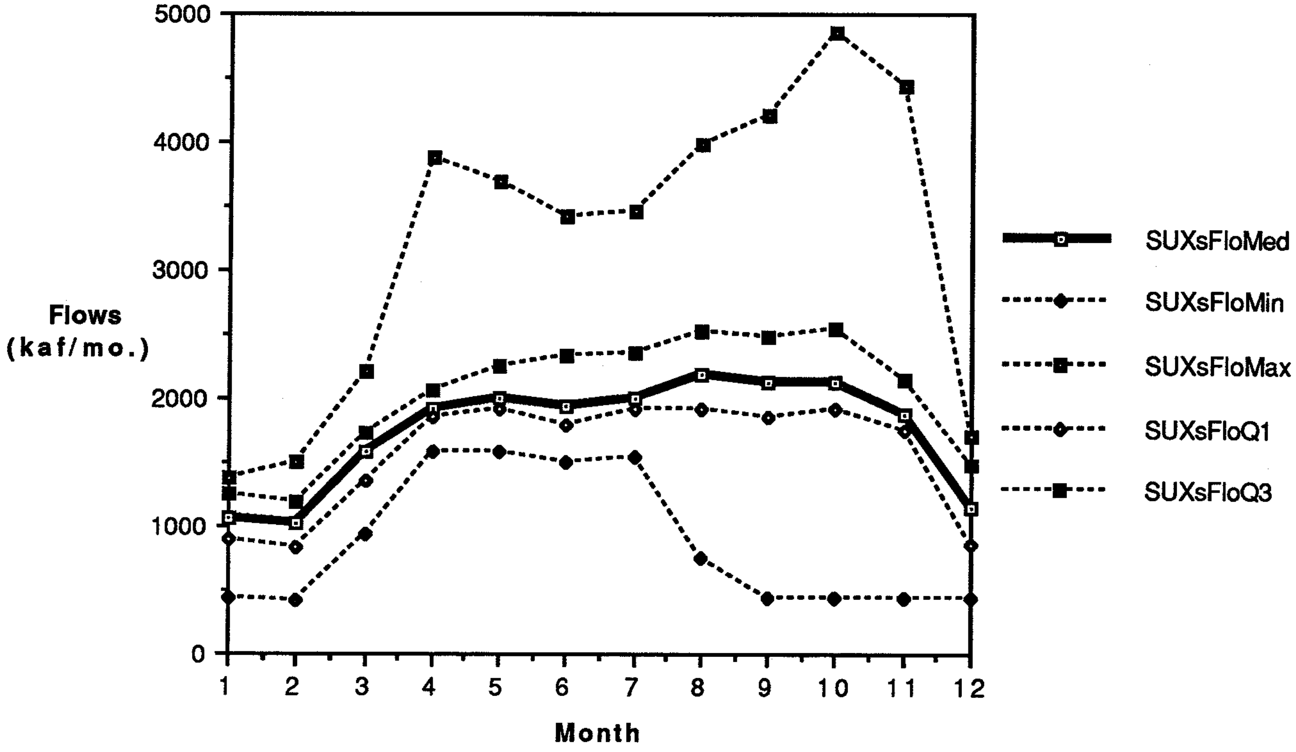

Figure 4-35

Sioux City Simulated Flows By Month

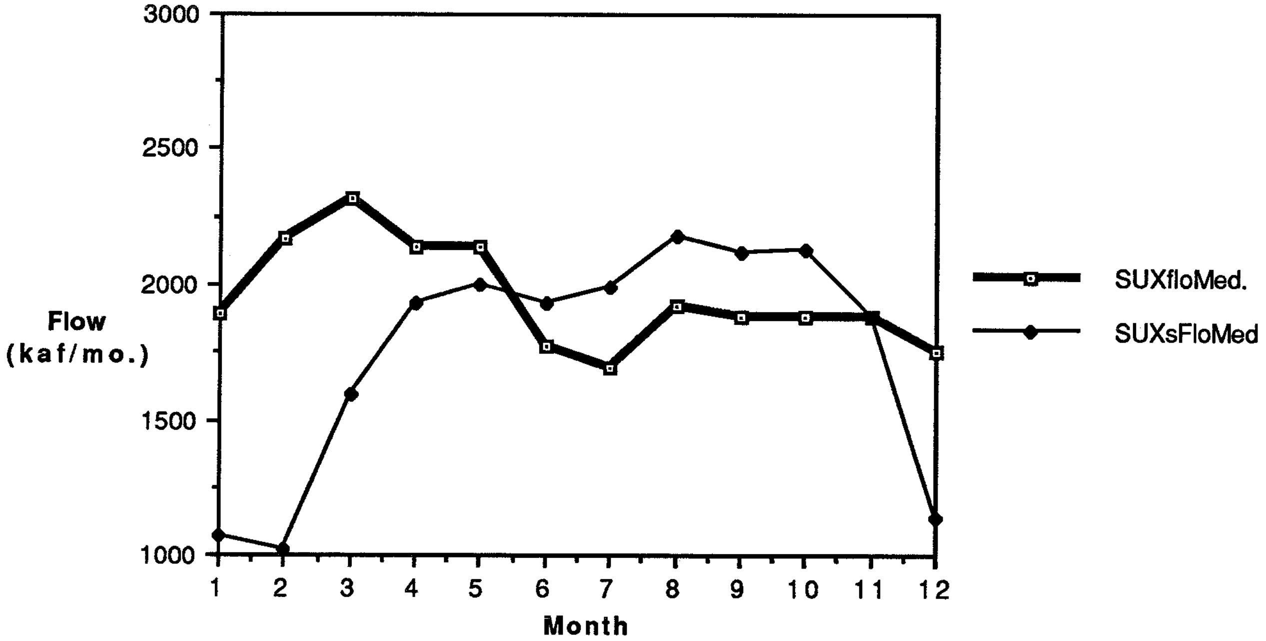

Figure 4-36

Median Sioux City Optimal and Simulated Flows

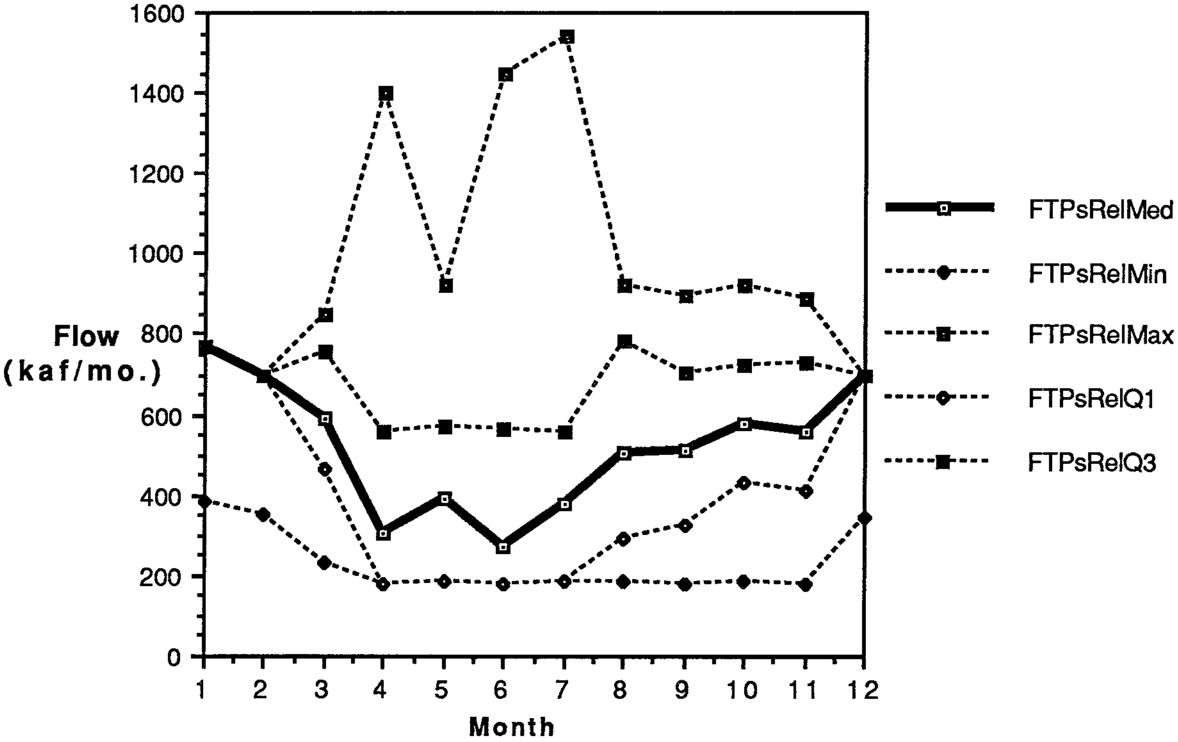

Figure 4-37

Fort Peck Simulated Releases By Month

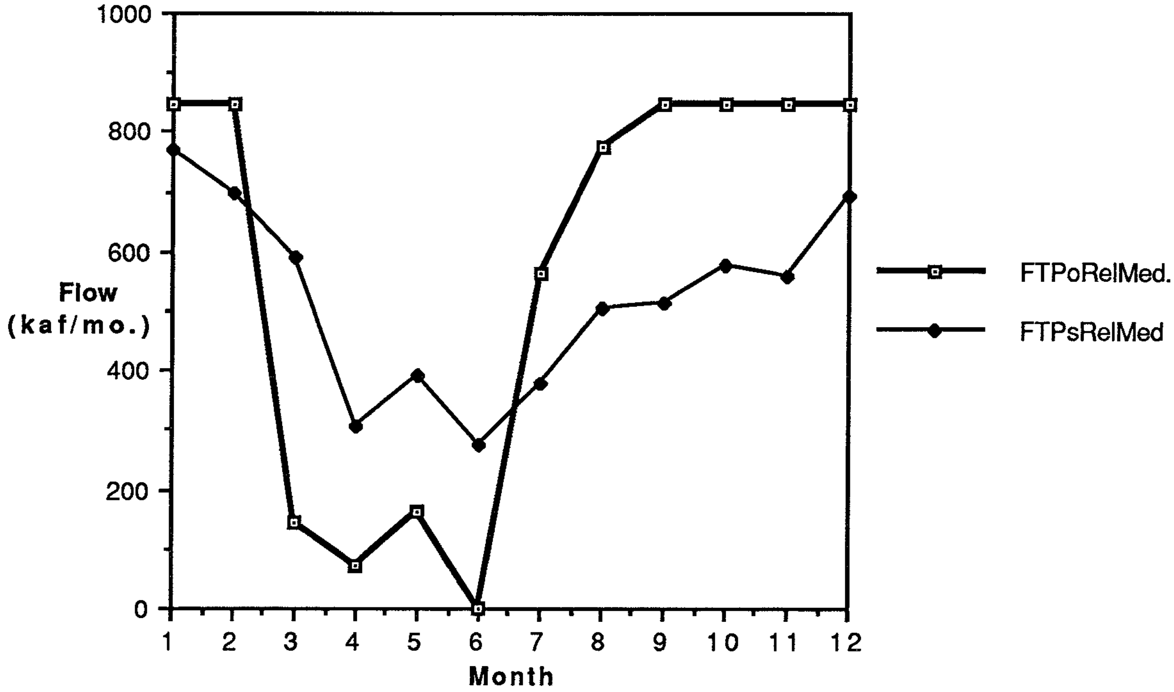

Figure 4-38

Median Fort Peck Optimal and Simulated Releases

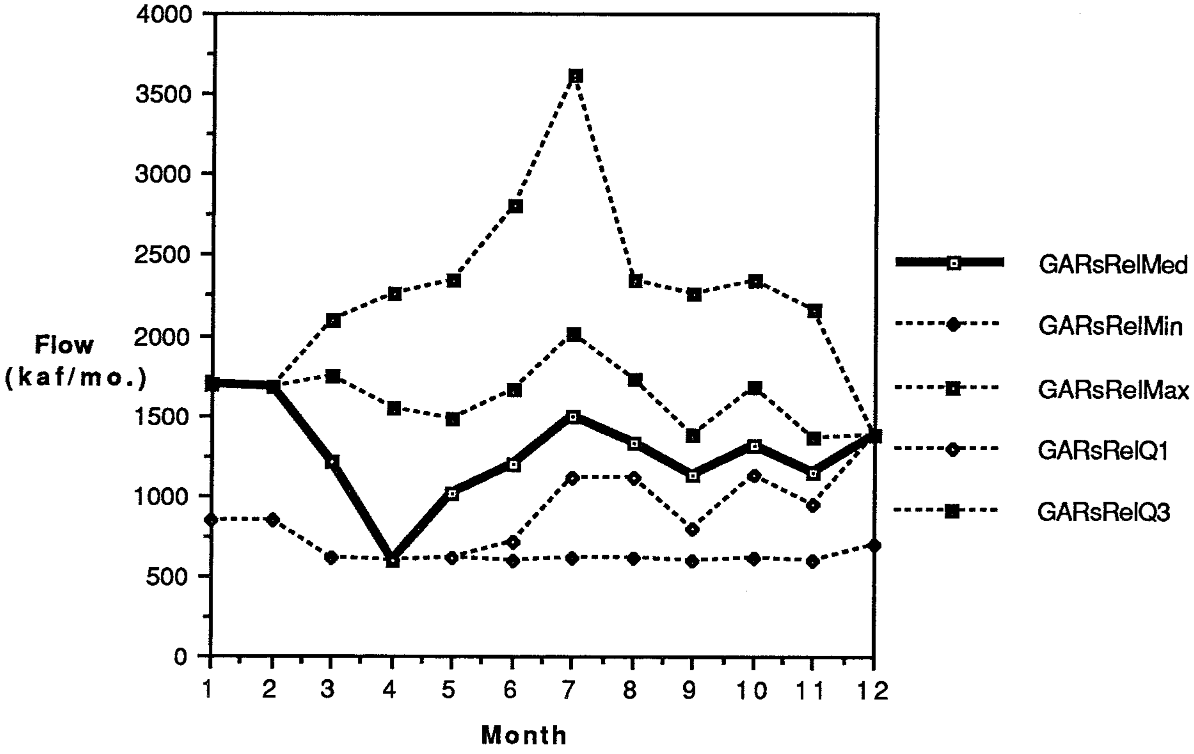

Figure 4-39

Garrison Simulated Releases By Month

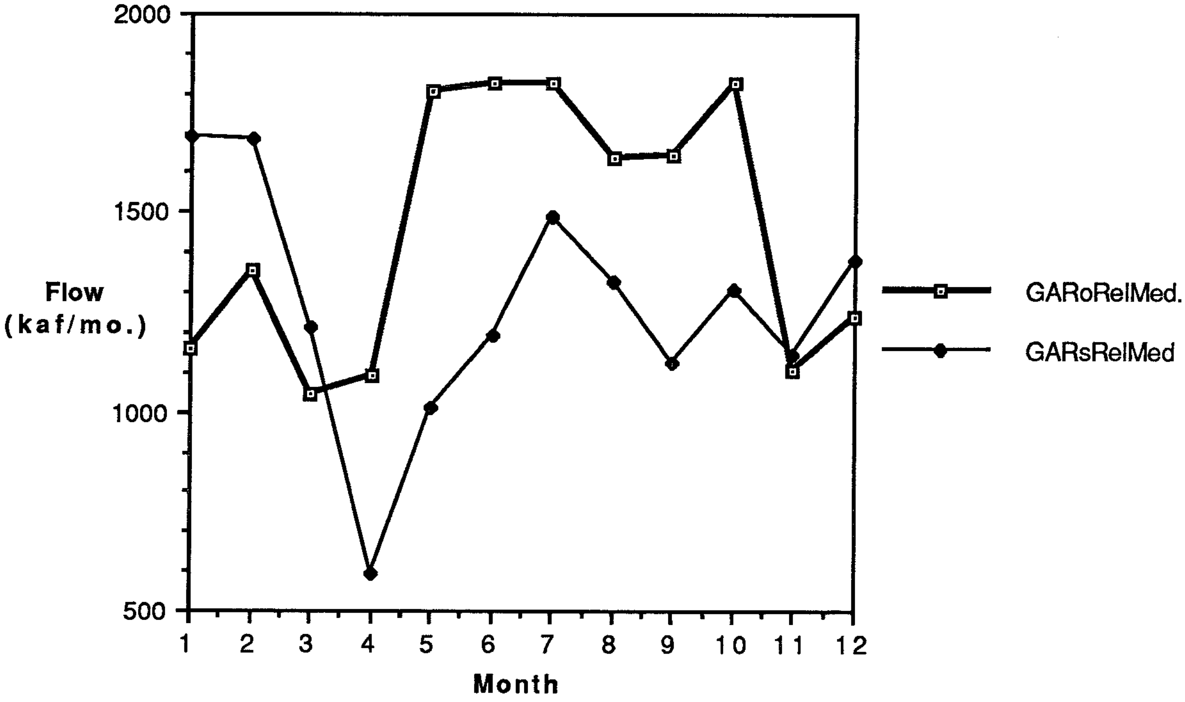

Figure 4-40

Median Garrison Optimal and Simulated Releases

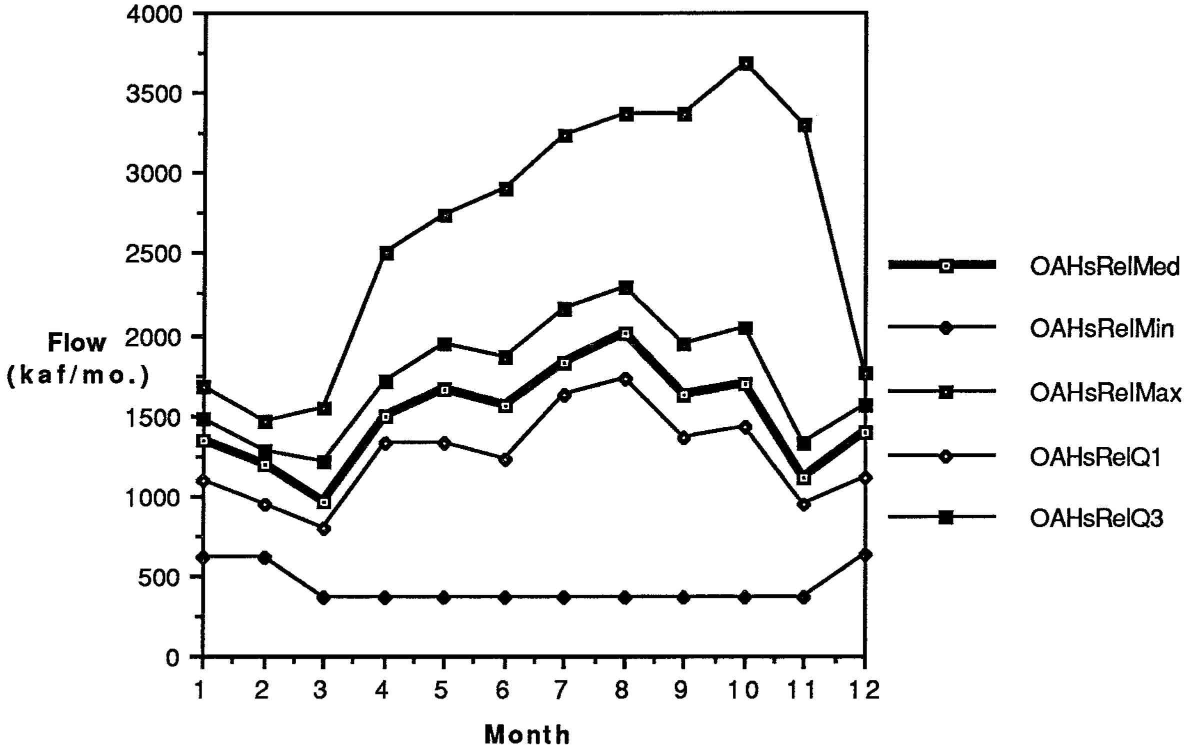

Figure 4-41

Oahe Simulated Releases By Month

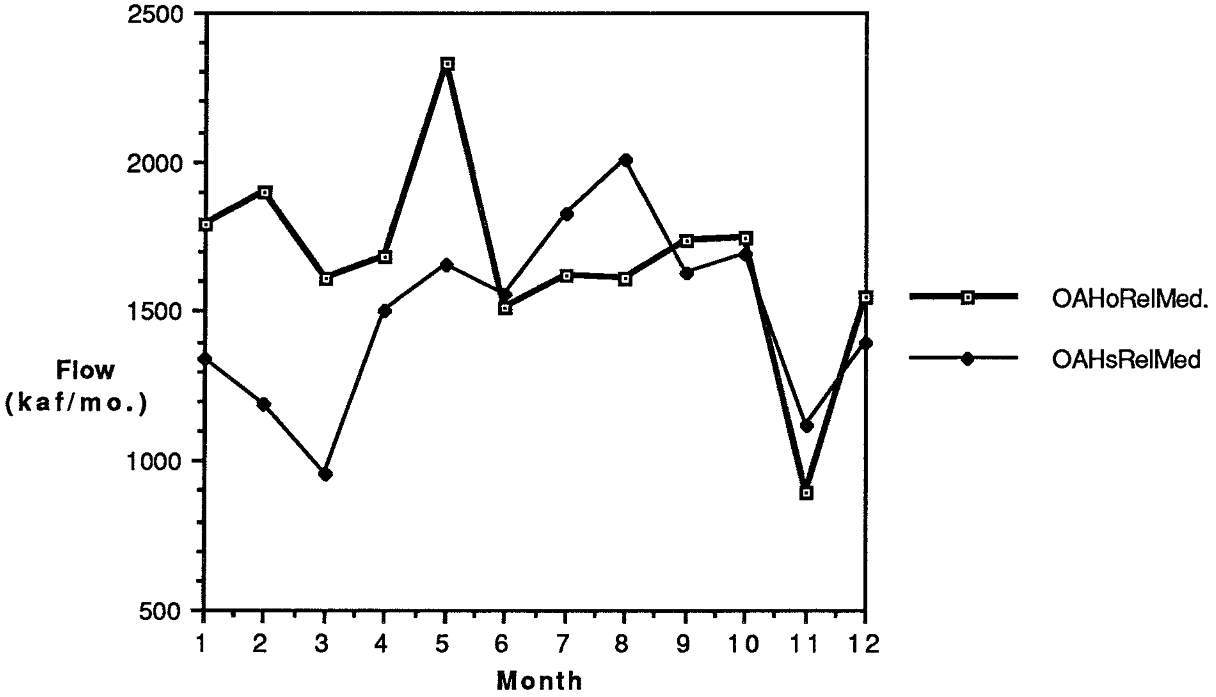

Figure 4-42

Median Oahe Optimal and Simulated Releases

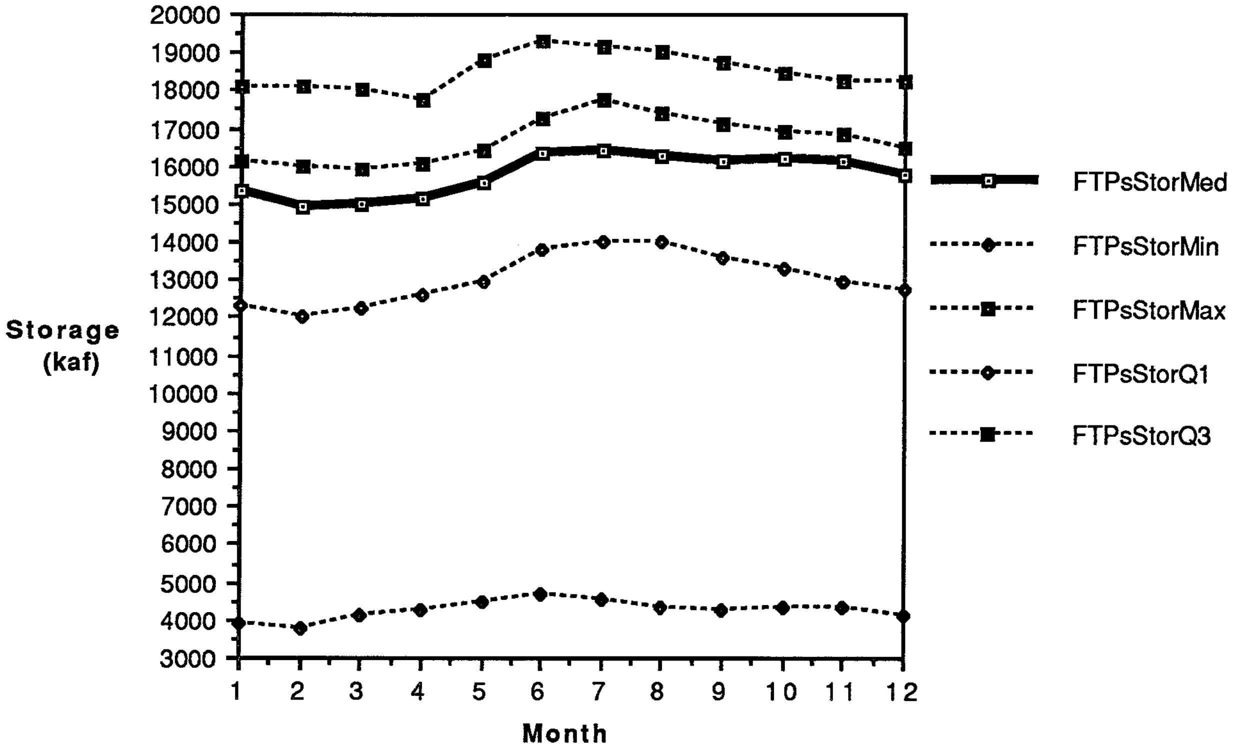

Figure 4-43

Fort Peck Simulated Storages By Month

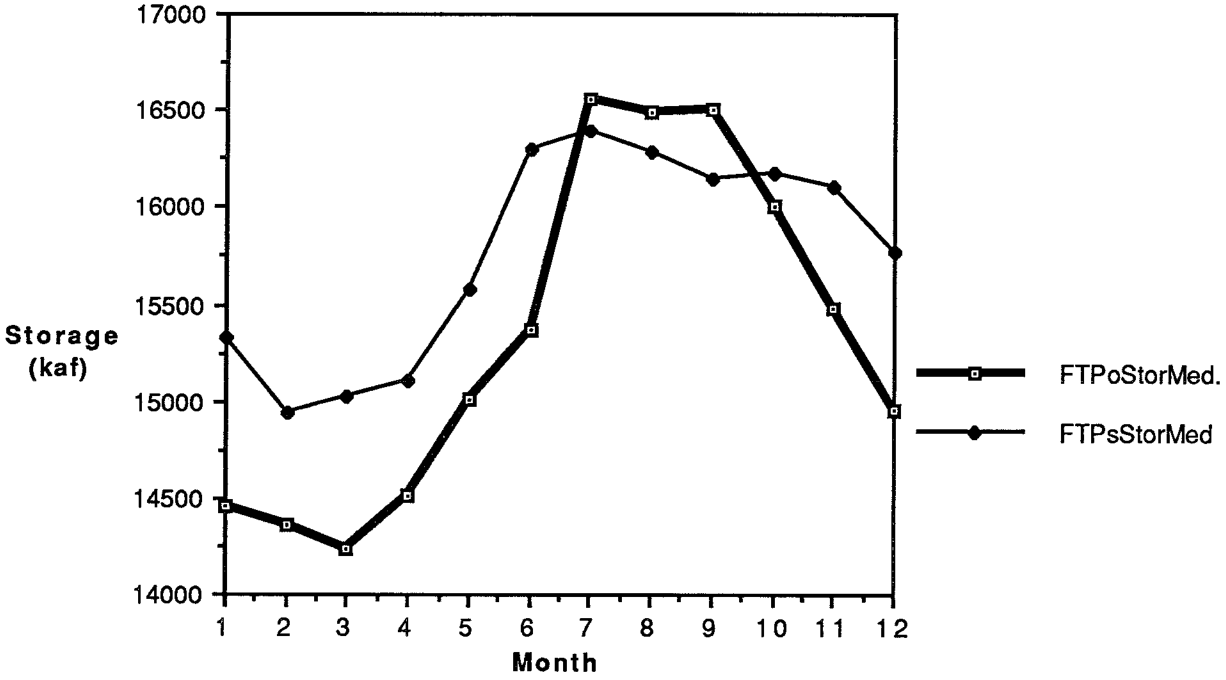

Figure 4-44

Median Fort Peck Optimal and Simulated Storages

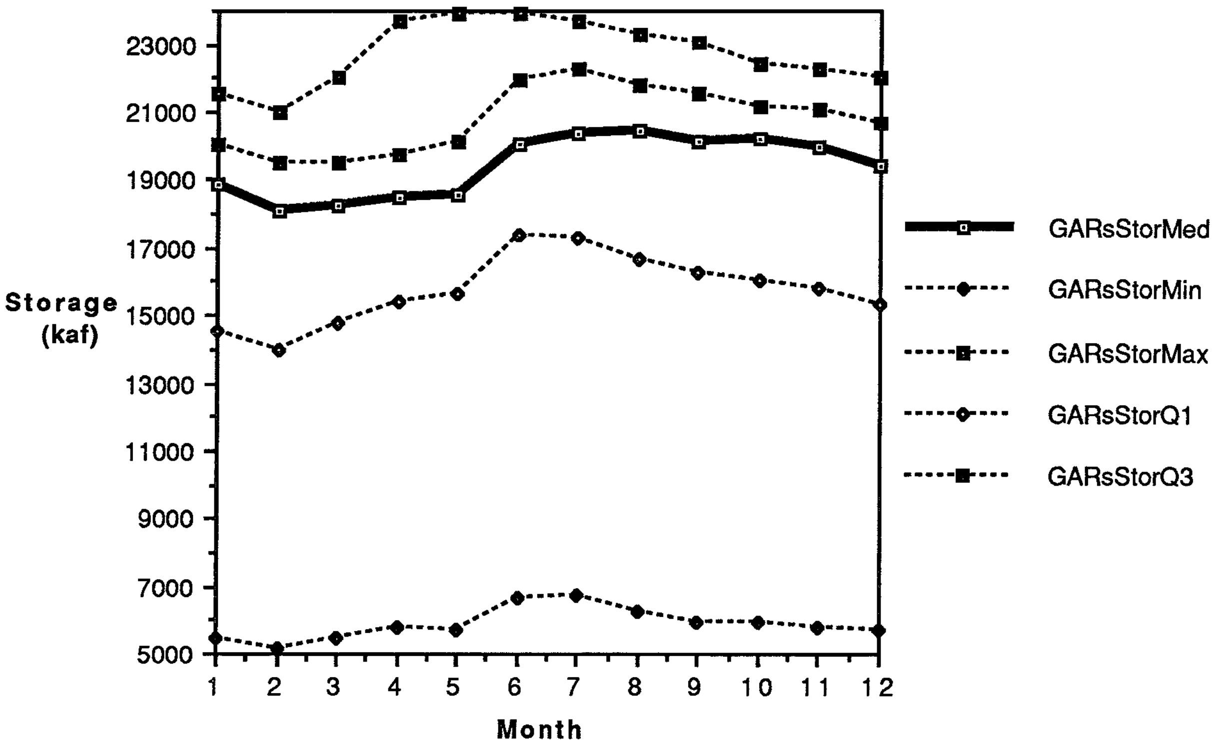

Figure 4-45

Garrison Simulated Storages By Month

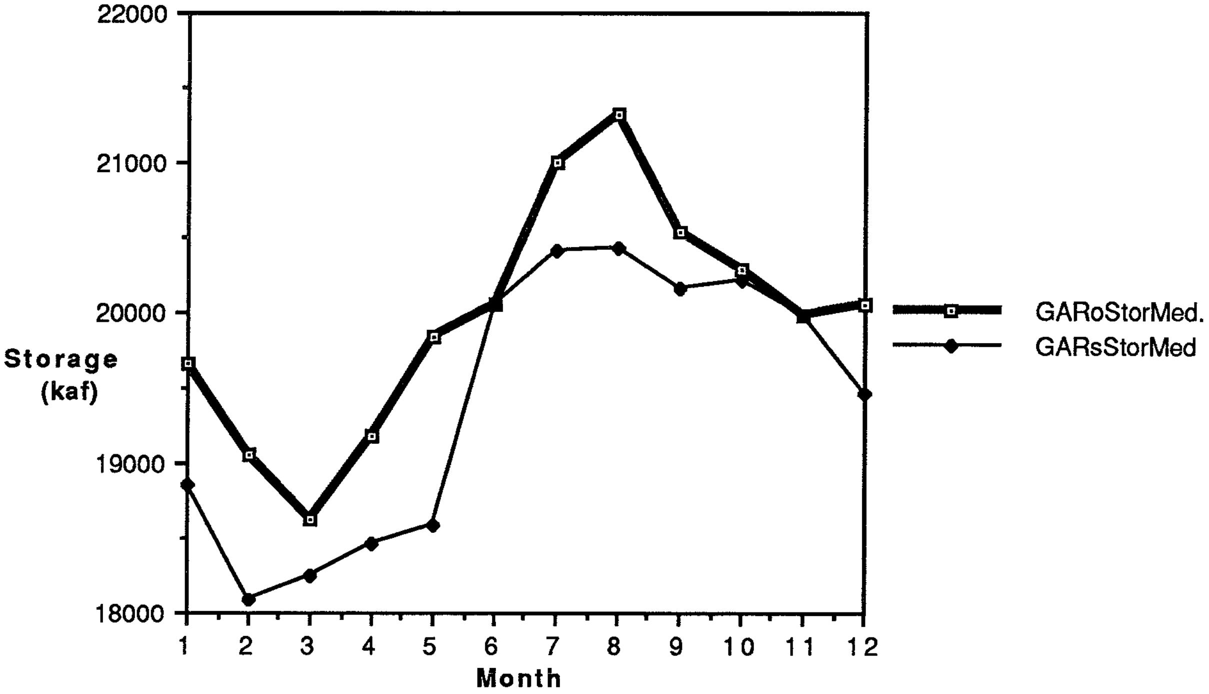

Figure 4-46

Median Garrison Optimal and Simulated Storages

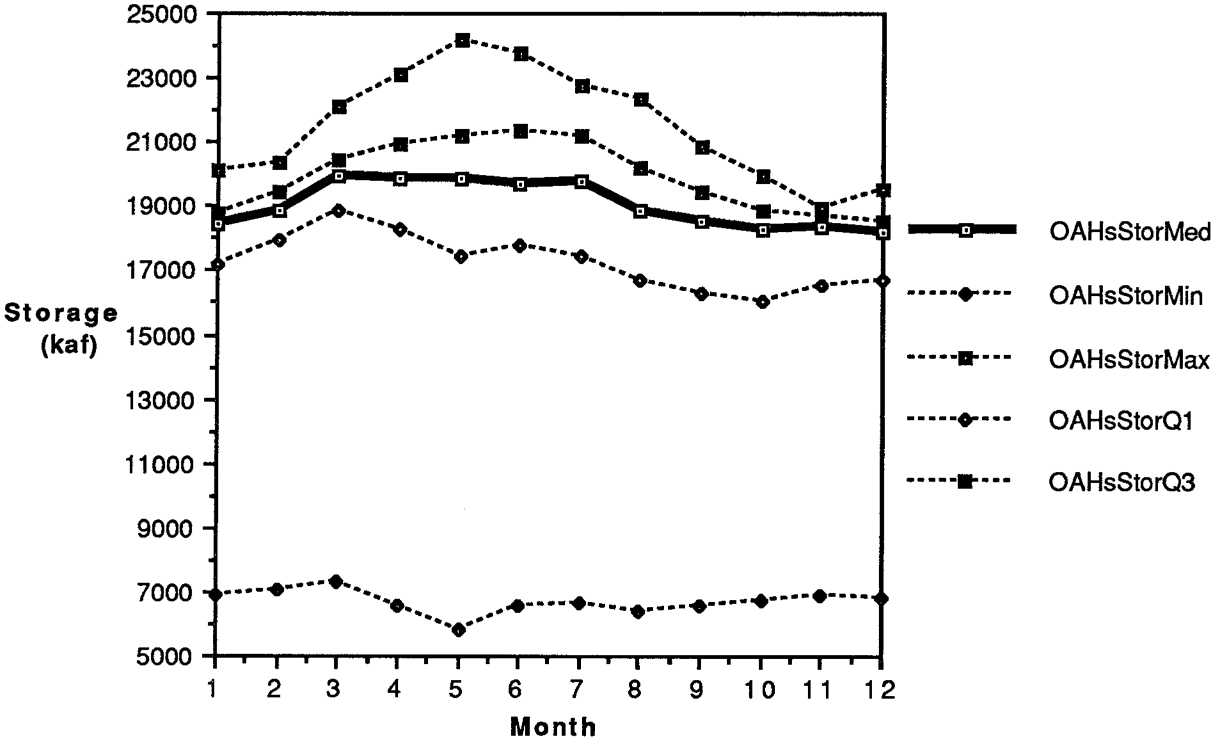

Figure 4-47

Oahe Simulated Storages By Month

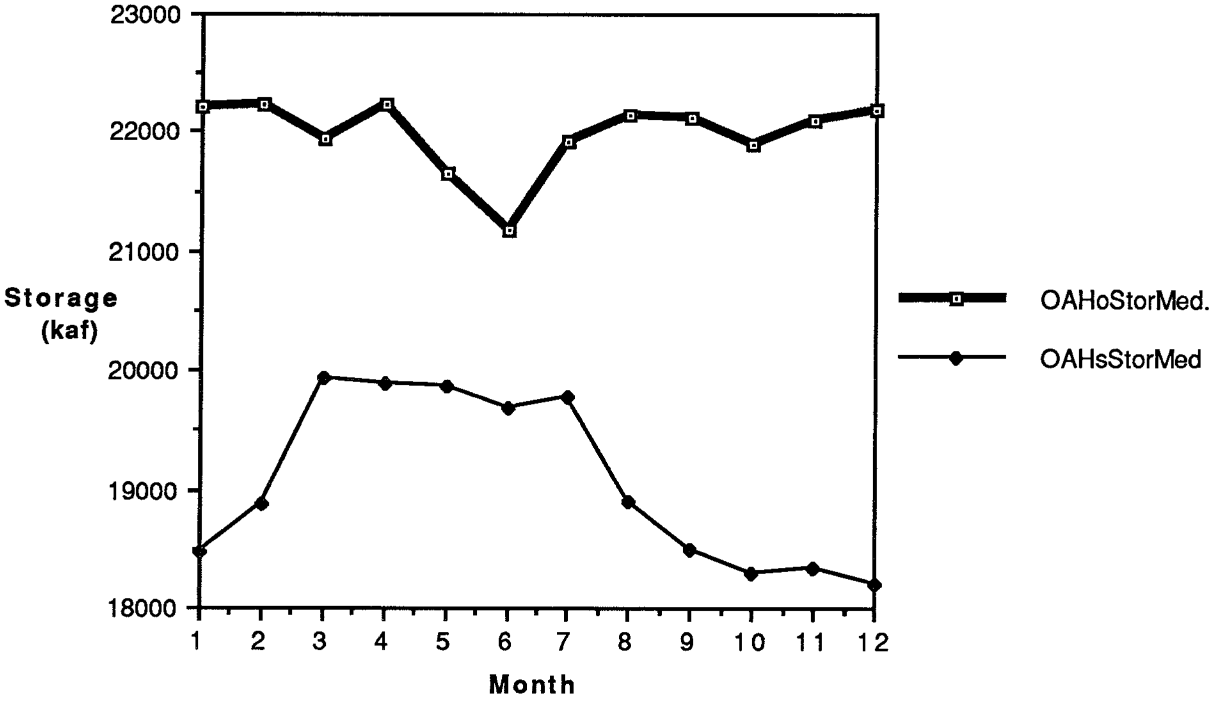

Figure 4-48

Oahe Median Optimal and Simulated Storage

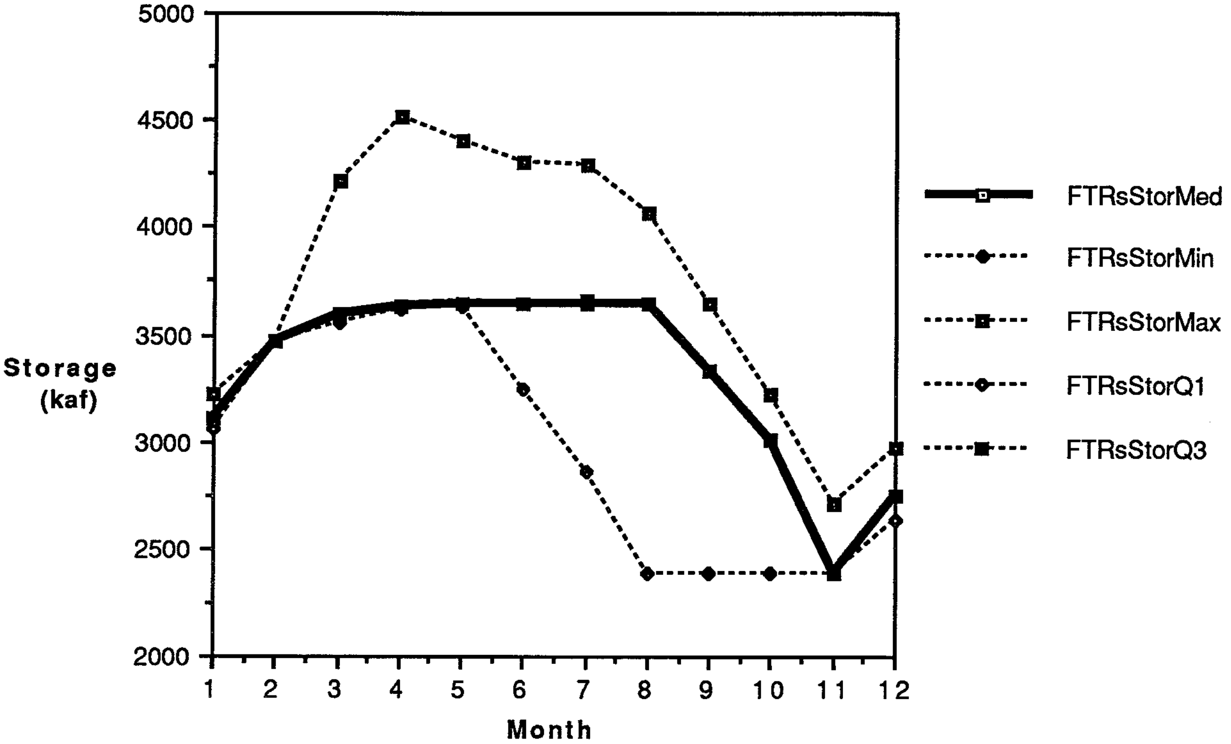

Figure 4-49

Fort Randall Simulated Storages By Month

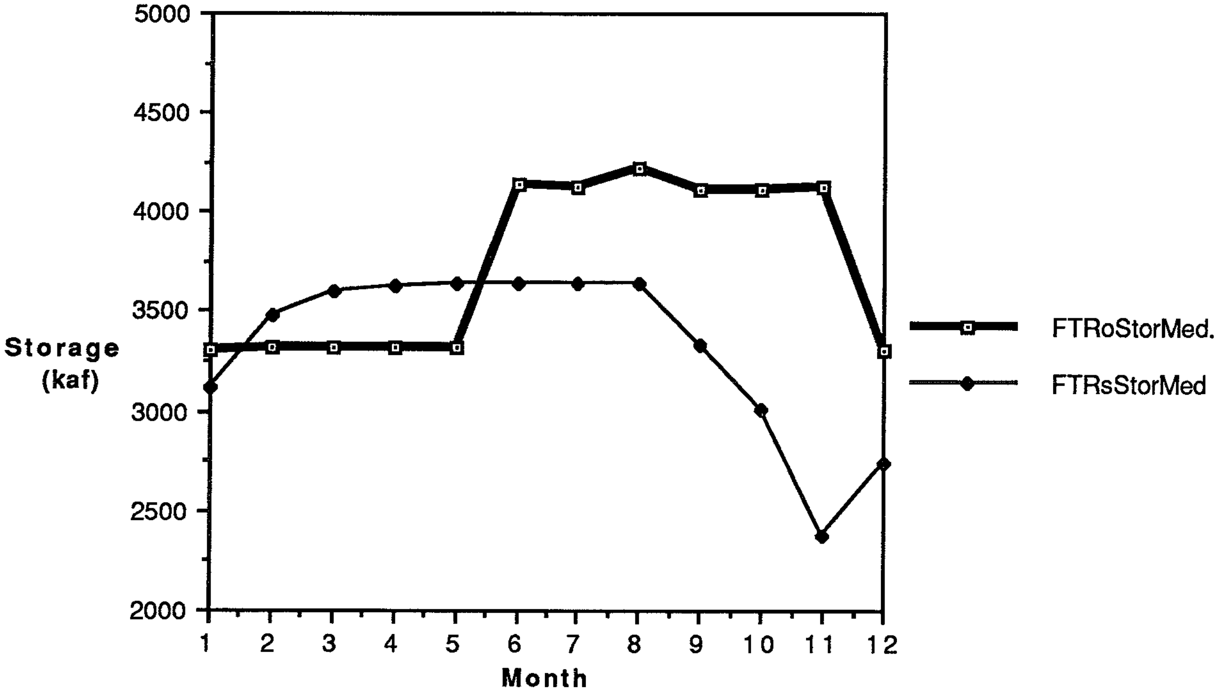

Figure 4-50

Fort Randall Median Optimal and Simulated Storages

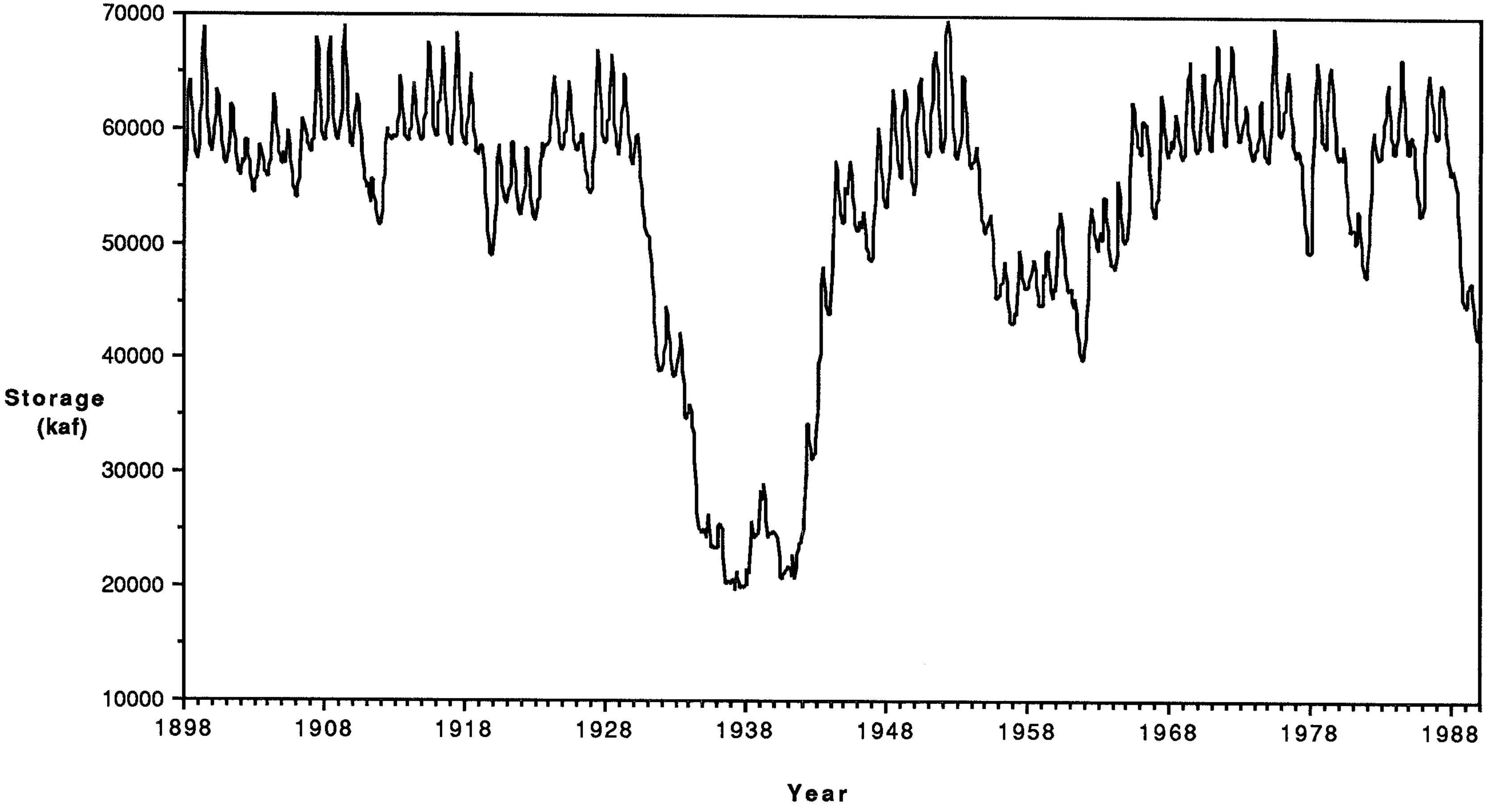

Figure 4-51

Time Series of Total Storage from MRD Simulation

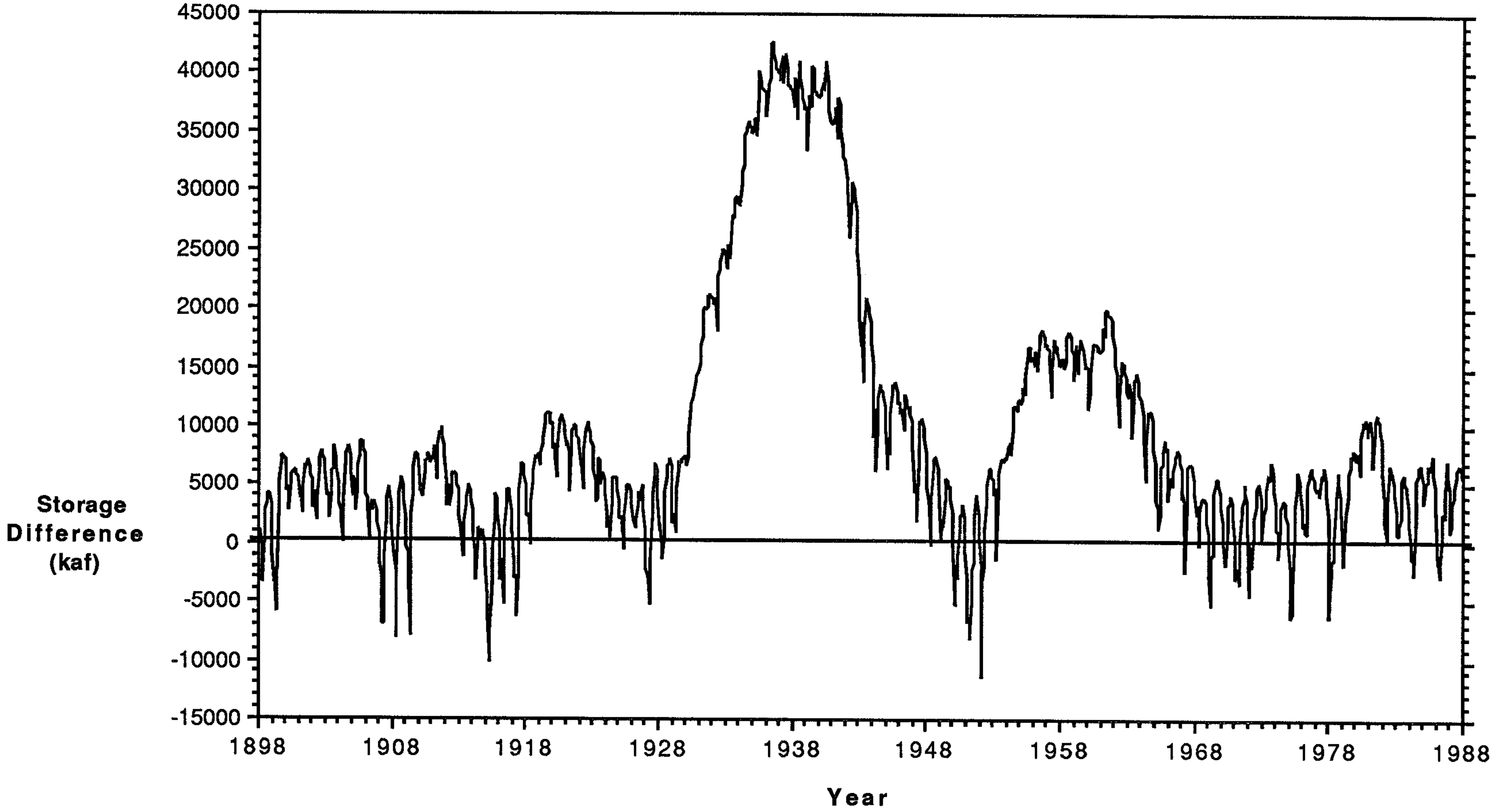

Figure 4-52

Optimal Minus Simulated Total Storage Over Time

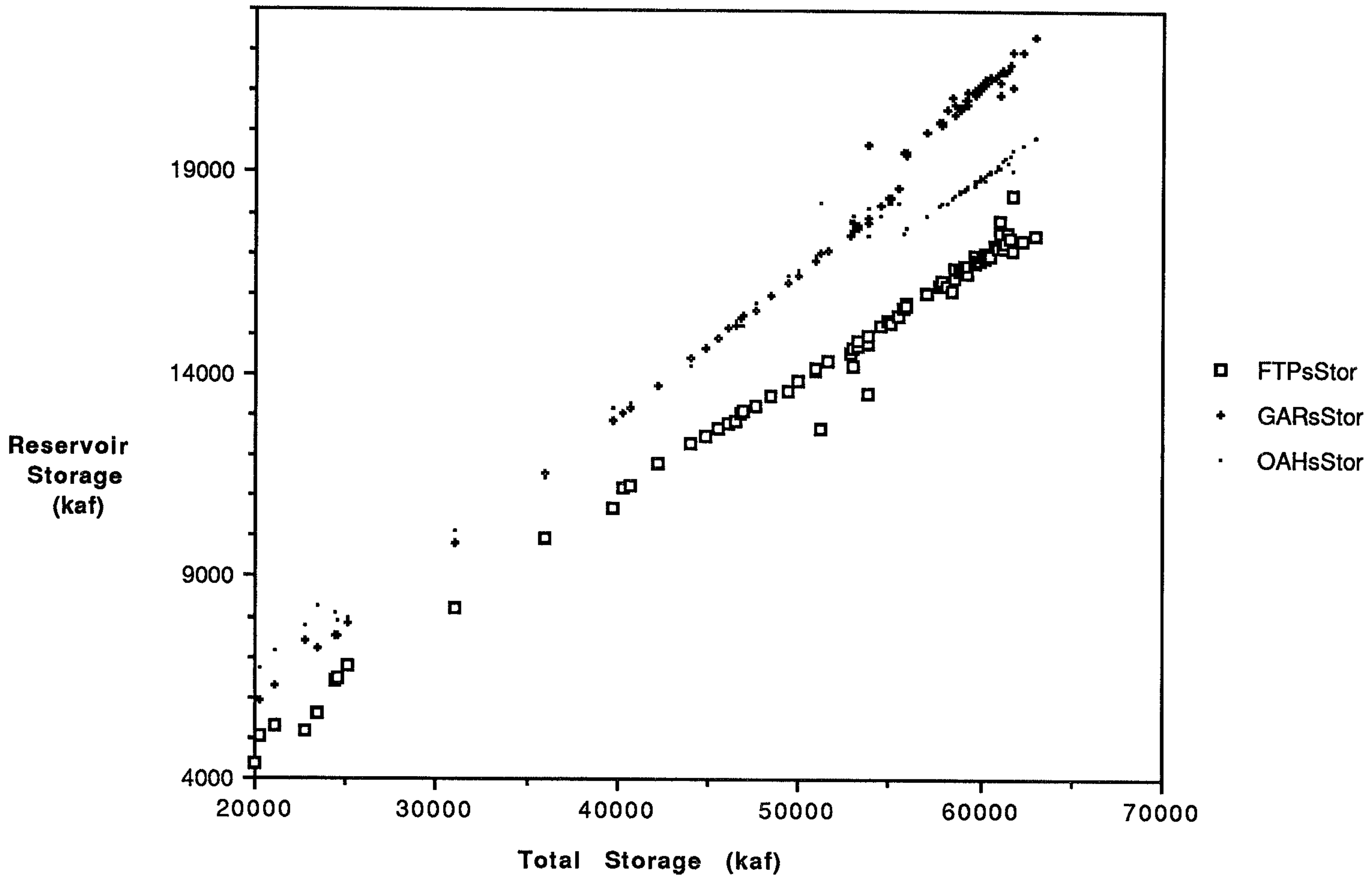

Figure 4-53

Simulated Current Allocation of Storage for October

Chapter 5

Operation Plan Development from HEC-PRM Results

This chapter presents two uses of HEC-PRM results for the development of operating rules for the Missouri River Main Stem system. The first use employs HEC-PRM results to "re-calibrate" the existing procedures for operating the main stem system. This approach represents an incremental effort to improve the system's operation. The second use employs HEC-PRM results to develop a set of operating rules which are independent of existing operating procedures. The intent here is to develop a set of operating rules, as if there were no prior experience or thought given to the operation of the system. It is, of course, possible and desirable for these two approaches to yield very similar rules. Where this occurs, it is evidence that current system operations are already optimal, in the sense that HEC-PRM results are optimal.

MODIFICATION OF EXISTING OPERATION RULES

A number of specific modifications to existing operating operation plans are suggested by the comparisons of HEC-PRM results with the simulation of current operation policies.

Navigation Service During Drought

As evident from Figures 4-32 and 4-52, HEC-PRM Phase I results curtail releases from Gavins Point greatly during drought compared to current operation policies. This is the primary cause of the much greater minimum pool storage for the Phase I HEC-PRM results. Essentially, the HEC-PRM operations imply the curtailment or elimination of navigation releases during major droughts. Shortening of the navigation season, a reduction of the navigation service levels, and elimination of navigation releases are suggested for dry years and particularly during long droughts.

Minimum Downstream Releases for Water Supply

Phase I HEC-PRM results also show the high value of downstream releases for water supply during the traditional navigation season, and indeed year-round. Figures 4-23 through 4-28 indicate that a combination of releases from Gavins Point and downstream inflows are always kept sufficient to maintain minimal downstream streamflows sufficient to maintain river stages needed for water supply withdrawals at all downstream reaches.

Reservoir Balancing Rules

Current operations attempts to balance the storage contained in the three largest reservoirs during the winter months. This current policy is shown well by Figure 4-53. Phase I HEC-PRM results suggest a somewhat different and more complex balancing rule, depicted in Figure 4-29 for the month of July. Here, the three largest reservoirs are not drawn down simultaneously. Rather, a definite optimal order of drawing down appears to exist over each range in total system storage.

A second difference in balancing rules is the lack of summer-winter shifting of storage between the four largest reservoirs that occurs in current operations.

Operation of the Three Smallest Reservoirs

Phase I HEC-PRM results suggest monthly storage targets for the three smallest reservoirs. This form of operation is fairly similar to current operation for Big Bend and Gavins Point, although the storage targets might be somewhat different. Current operation of Fort Randall is much more flexible than HEC-PRM operation. The monthly storage targets suggested by HEC-PRM results have a very different annual variation than current operation, as can be seen in Figures 4-49 and 4-50.

New Minimum Pool Levels

The comparisons presented in Tables 4-2 and 4-4 suggest that the minimum pool levels be greatly expanded in the four largest reservoirs. The total minimum pool storage suggested by the Phase I HEC-PRM results is 48.4 million acre-feet, the minimum storage seen over the 90-year optimization period.

New Annual Operating Pool Sizes

Tables 4-2 and 4-4 also attempt to compare the sizes of annual operating pools suggested by HEC-PRM with those resulting from current operations. The annual operating pool is the amount of storage used during a typical annual drawdown-refill cycle. This is a somewhat difficult concept to define precisely without defining what is meant by a "typical" year. (Usually, no year is ever completely "typical.") In this case, the annual range in median year storages was chosen to represent the annual operating pool. A pure comparison on this basis is made in Table 4-4. Table 4-2 compares HEC-PRM's median annual range of storages with currently designated "Flood Control and Multipurpose Use" storage, which is the range of storage over non-drought years, according to current operation plans.

Table 4-4 probably represents the best comparison. The total annual operating pool is almost the same between current and HEC-PRM operations. However, there is some difference in the allocation of this storage among the four largest reservoirs. More annual storage is kept in the two uppermost reservoirs (Fort Peck and Garrison) and less in Oahe and Fort Randall.

A STRATEGY USING HEC-PRM RESULTS TO DEVELOP OPERATION PLANS

The strategy employed here to infer new operating rules from HEC-PRM results is fairly informal, yet systematic. It begins with a fairly standard array of elementary data analysis tools to help detect consistent tendencies in the HEC-PRM results. As consistencies in the operation of individual reservoirs in individual months are discovered, this leads to more complex, but still elementary, exploration of potential inter-relationships which might reasonably be used as operating rules. Finally, as these more complex relationships are discovered, specific rules are sought which will logically complete the description of operating rules for the system.

The data files of HEC-PRM output employed in the quest for operating rules are: optimal releases for each reservoir, optimal storage levels for each reservoir, and optimal downstream flows. All of these are time series extending over the 90-year optimized operating period. The time series of tributary inflows both into the reservoir system and downstream was also employed. The statistical package MINITAB© and the graphics package CRICKET-GRAPH were employed to perform the manipulation of these data.

Consistent Seasonal Storage and/or Release Levels from HEC-PRM Results

The first "pass" through the HEC-PRM results was the calculation of descriptive statistics for each month for:

- each reservoir's optimal releases
- each reservoir's optimal storage
- the optimal downstream flows at each location downstream
- each tributary inflow.

These descriptive statistics for each month consisted of:

- the minimum value observed during the 90-year period
- the maximum value observed during the 90-year period
- the median value observed
- the upper (75th percentile) and lower (25th percentile) quartiles of values observed
- the mean value observed
- the standard deviation of the observations,

with each of these statistics representing some feature of the 90-year behavior of a particular release, storage, or flow variable.

From these statistics, a very quick overview of the system's behavior can be seen. Figures 4-1 through 4-6, 4-8 through 4-13, and 4-17 through 4-22 are drawn from these statistics.

For many of these monthly release, storage, and flow variables which have important operational implications histograms of the monthly behavior were also created. Histograms can be used to very quickly distinguish isolated outlying minima and maxima from a truly broad range of systematic behavior. Histograms also can be used to quickly distinguish multiple peaks in operations. For example, in several months Fort Peck releases tend to be at either zero or at maximum levels, with relatively rare releases made at intermediate levels.

For the lower three reservoirs, this simple approach revealed vary consistent operating procedures for each month over the 90-year period of HEC-PRM results. These simple statistics and presentations also revealed much about the limits of behavior of the upper reservoirs and their central tendencies.

Consistent Relationships Between Variables

It is unlikely that all aspects of a reservoir system's operations could be modelled as a series of simple monthly target storages or releases. Indeed, the operation of the three large upper reservoirs rarely showed a very narrow range of monthly release or storage levels.

Scattergrams were then used to seek bi-variate variations, particularly those that might exist between storage and release or release and inflow levels for each month. One such figure appears in Figure 5-1, which quickly demonstrated the difficulty of finding an optimal operating rule relating Gavins Point releases to total system storage.

One insightful set of scattergrams was that of storage in each of the uppermost reservoirs with total system storage. Sample plots for July and October appear in Figures 4-29 and 5-2. The scatter plot shows a fairly consistent balancing pattern of total reservoir storage between reservoirs, albeit a balance which changes with total storage level. This is similar to the operating rule form suggested by Loucks and Salewicz (1989). Other months have very similar patterns of balancing total storage among the three reservoirs. The consistency of these patterns of balancing storage appeared significant enough to form the basis for a set of monthly reservoir balancing-type operating rules.

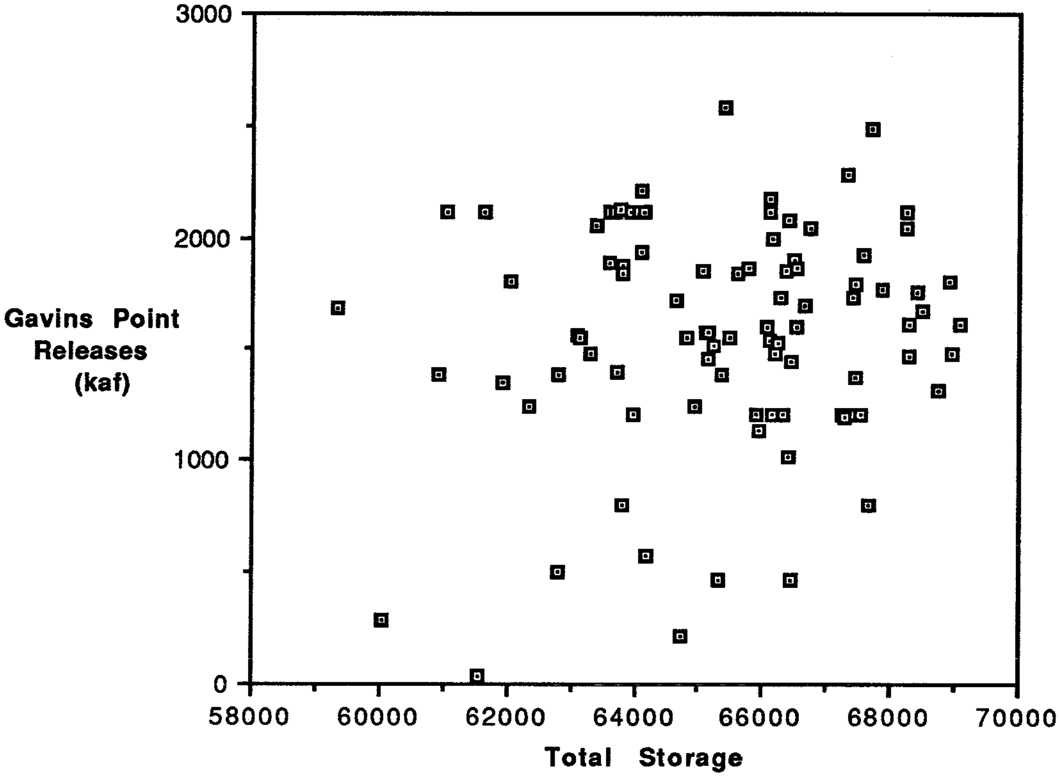

Figure 5-1

Optimal Gavins Point Releases Vs. Total Storage for July

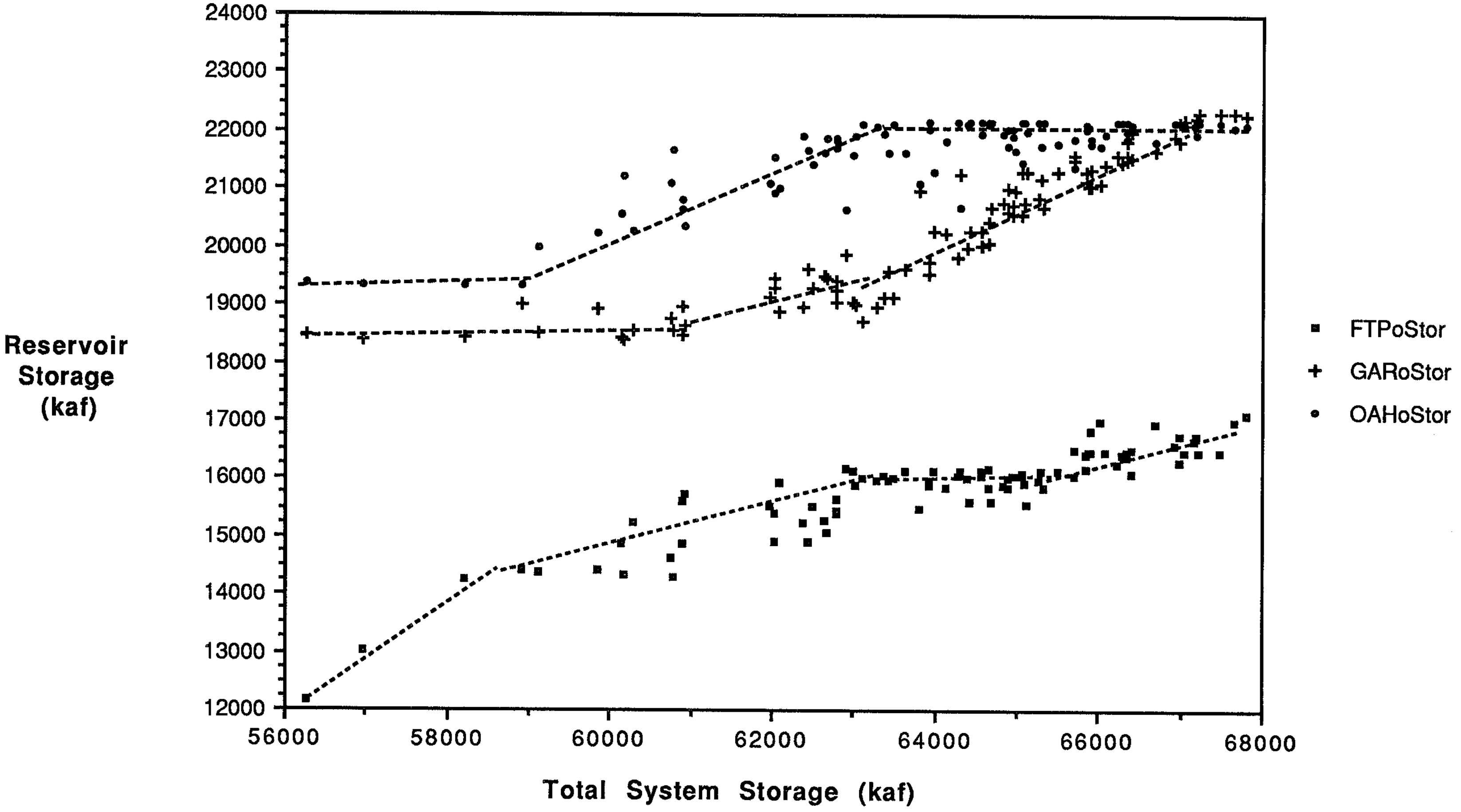

Figure 5-2

October Optimal Storage Relationships

These very simple analyses produced most of the "rules" for monthly storage levels for the lower three reservoirs and the balancing-type "rules" for the distribution of total system storage among the upper three reservoirs. Given these "rules," a complete specification of operation for the system requires only rules for determining releases from either Gavins Point or Oahe. With such release rules operating over time, total system storage is determined, which in turn, determines the operation of the remainder of the system.

Consistencies in Releases from Gavins Point

As the time series in Figure 4-7 and Figure 5-3 show, there is some pattern to releases from Gavins Point, but the pattern is not so clear as the patterns used to determine the other "rules" discussed above.

Multi-variate linear regression was also used to seek out trends between variables. In particular, multiple regression techniques were used to seek simple release rules from Gavins Point correlated with total storage, storage in individual reservoirs, inflows to the reservoirs and downstream and other variables which operators might conceivably know in an operational time-frame. For most months, several sets of independent variables were used in different attempts to find satisfactory regression equations to predict releases from Gavins Point. Stepwise multiple regression was used to select the most promising independent variables for these sets. These regressions were evaluated using standard r^2 estimates and from the size of residuals observed. None of these attempts at regression was very satisfactory. An example of the output of one linear regression, for October, appears in Figure 5-4. A plot of the HEC-PRM specified October release and the release predicted by the regression follows in Figure 5-5. The major contribution of the regression studies was to show the potential importance of downstream inflows for establishing releases from Gavins Point.

For October, the time-series plot (Figure 5-3) suggests some operating rules for Gavins Point releases:

- In typical years, releases of 2,000 KAF/month are made from Gavins Point in October.
- As with July, releases are sharply curtailed to counteract the effects of large flood inflows downstream. However, October floods are typically less frequent and severe, so this effect on releases is much less strong than in July.
- During major droughts, such as the 1930s drought, Gavins Point releases are reduced to the level needed to maintain minimum water supply levels downstream. These levels are about 500 KAF/month at Sioux City, Omaha, and Nebraska City and 750 KAF/month at Kansas City. Such flows would preclude navigation during October.
- As with July flows, restricting releases to reduce flooding downstream of Kansas City appears to be more important than maintaining navigation above Omaha.

From these results, it would appear possible to develop release rules for Gavins Point for each month. Such rules, when combined with the storage target and storage allocation rules outlined above, would completely specify the system's operations.

Figure 5-6 is another time-series plot of releases from Gavins Point and optimal downstream flows at four downstream locations for the month of July. This plot suggests several July release "rules" for Gavins Point.

- Releases in typical years for July tend to maintain flows of at least about 1,700 KAF/month downstream of Gavins Point.
- Releases from Gavins Point should be sharply curtailed to reduce flooding caused by high flows entering downstream of the main stem reservoirs. All of the major dips in releases shown in Figure 5-6 coincide with downstream flood inflows.

- Minimum downstream flows are always maintained. For July, these minimum flow levels downstream appear to be: 500 KAF/month at Sioux City, 1,000 KAF/month at Omaha and Nebraska City, and 2,000 KAF/month at Kansas City. Except for Kansas City, these are also the water supply flows specified by the Phase I penalty functions. These high minimum flows at Kansas City may result from the need to maintain the lower flows at upstream locations.
- Navigation flows at Sioux City and Omaha are less important than the reduction of flooding further downstream during major downstream flood events, as is evident for the years 1909, 1915, 1951, 1958, and 1969.
- For July, every case of reduced releases below the customary minimum navigation service releases was to counter the effects of downstream flooding inflows. This is true even for the 1930s drought.
- During extended droughts, such as the 1930s, reductions in releases in response to downstream flood inflows appears to occur more quickly.

The differences in minimum downstream flows for July and October during the 1930s drought are difficult to explain. There is no great difference between the downstream water supply penalties during these months. Perhaps the difference in releases during drought arises from differences in water availability during these months. An examination of the behavior of the system's penalty functions during these months might be instructive.

Rule Testing and Refinement by Simulation Studies

The preliminary nature of these "rules" cannot be over-stressed. They have in no way been tested, but are merely suggested from a preliminary analysis of the HEC-PRM Phase I results. Testing and refinement of these suggested "rules" by simulation studies is essential. More is said of rule refinement and testing in a later section.

SOME DISCARDED RULES

In the search for operation plans that would represent HEC-PRM results, a number of rules and rule forms were discarded. Some of these discarded rules are presented in this section to illustrate some of the difficulties in developing operating rules from optimization results.

Some Poor Fits

Early in the examination of the HEC-PRM results, simple monthly release targets were hoped for, of the form, "In July, release X thousand acre-ft of water from Fort Peck." Usually, these rules made for a poor fit. The histogram in Figure 5-7 illustrates one of the better fits of such a rule in the data set, for July releases from Garrison. Here, July releases in 75 of 91 years were at the maximum level permitted for Garrison. Figure 5-8 illustrates a more typical fit of such a rule, for July releases from Fort Peck.

An Oversimplified Rule

Early attempts were made to develop release rules from Gavins Point based solely on the month and total system storage. These rules were sought by plotting monthly scattergrams of Gavins Point releases, as in Figure 5-1. This scattergram reveals no such simple release rule.

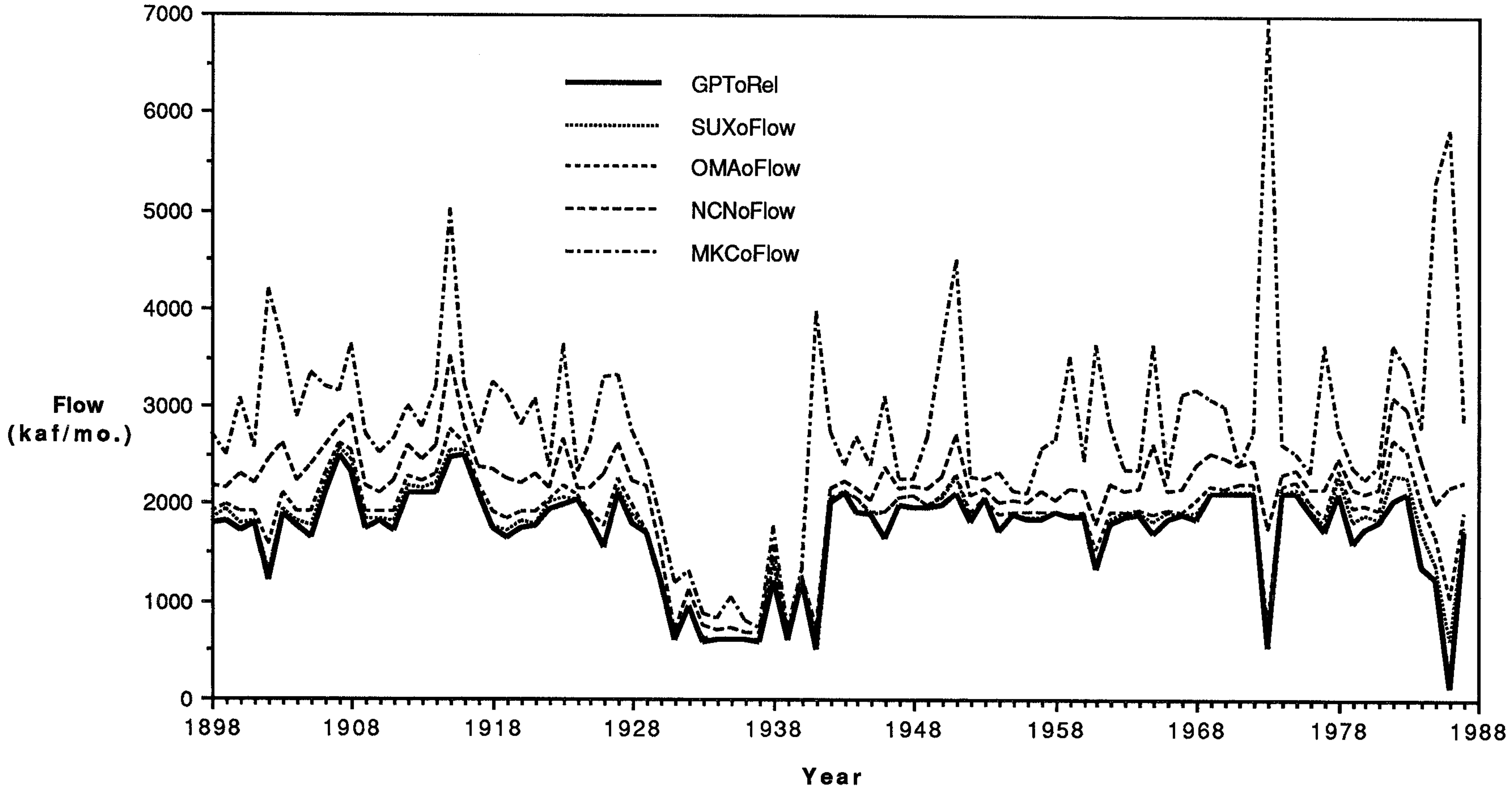

Figure 5-3

Time Series of Optimal October Releases and Flows Downstream

```
The regression equation is
GPToRel = - 3459 + 0.0756 TOToStor + 4.50 FTRinflo + 3.08 GPTinflo - 0.241 MKCinflo

Predictor    Coef      Stdev     t-ratio     p
Constant     -3459     1110       -3.12    0.003
TOToStor     0.07556   0.01697     4.45    0.000
FTRinflo     4.4986    0.9072      4.96    0.000
GPTinflo     3.085     1.021       3.02    0.003
MKCinflo    -0.24102   0.05453    -4.42    0.000

s = 384.4     R-sq = 43.8%     R-sq(adj) = 41.1%

Analysis of Variance

SOURCE       DF       SS        MS           F       p
Regression    4    9771598   2442899     16.53   0.000
Error        85   12559755    147762
Total        89   22331352

SOURCE       DF    SEQ SS
TOToStor      1    3654637
FTRinflo      1    2952477
GPTinflo      1     277817
MKCinflo      1    2886667

Unusual Observations
Obs.TOToStor  GPToRel        Fit     Stdev.Fit   Residual   St.Resid
 36   64298     592.0       1752.1     50.1       -1160.1    -3.04R
 37   60912     600.0       1402.2     82.4        -802.2    -2.14R
 38   62076     600.0       1409.6     69.9        -809.6    -2.14R
 39   60890     600.0       1396.2     82.4        -796.2    -2.12R
 42   62905     600.0       1604.7     63.7       -1004.7    -2.65R
 44   56254     516.0        656.4    187.7        -140.4    -0.42 X
 56   66284    2047.0       2353.3    164.7        -306.3    -0.88 X
 76   63969     543.0        886.7    243.1        -343.7    -1.15 X
 88   60178    1225.0       1164.0    179.7          61.0     0.18 X
 89   65685     127.0       1079.8    168.5        -952.8    -2.76RX

R denotes an obs. with a large st. resid.
X denotes an obs. whose X value gives it large influence.
```

Figure 5-4

Example Regression Results for October Gavins Point Releases

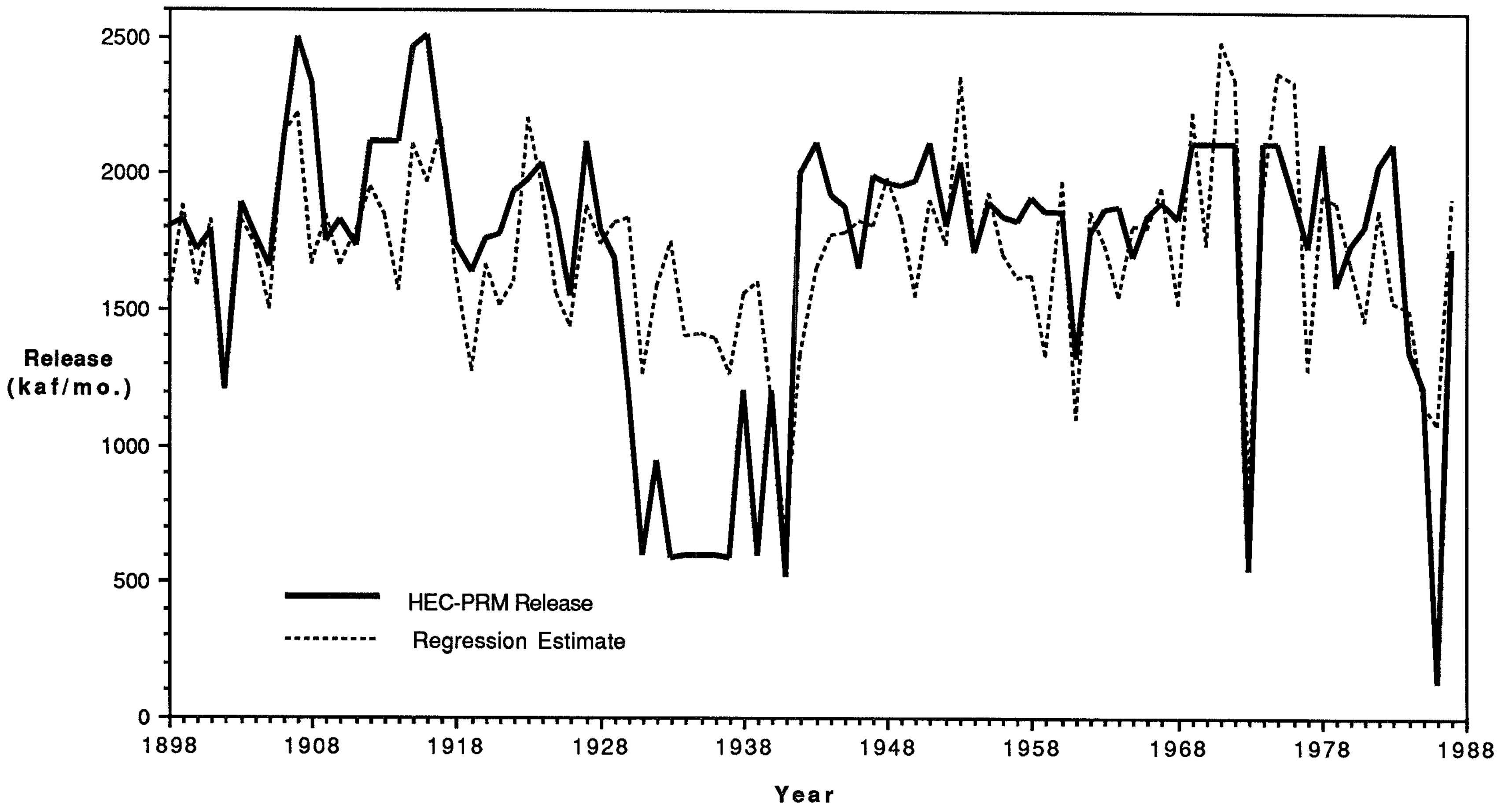

Figure 5-5

Times Series of Optimal Gavins Point Releases and Regression Estimates for October

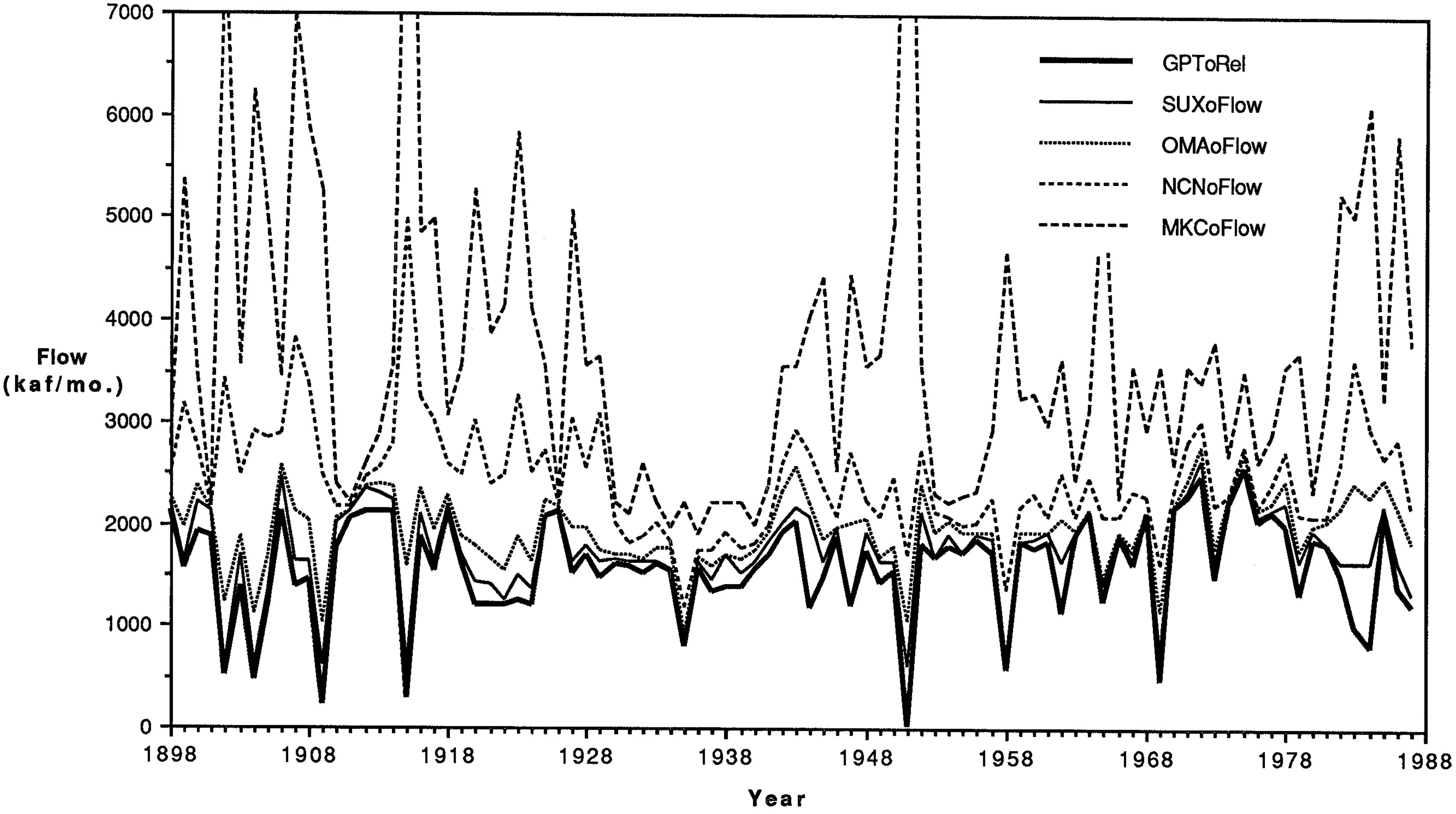

Figure 5-6

Time Series of Optimal July Flows Downstream

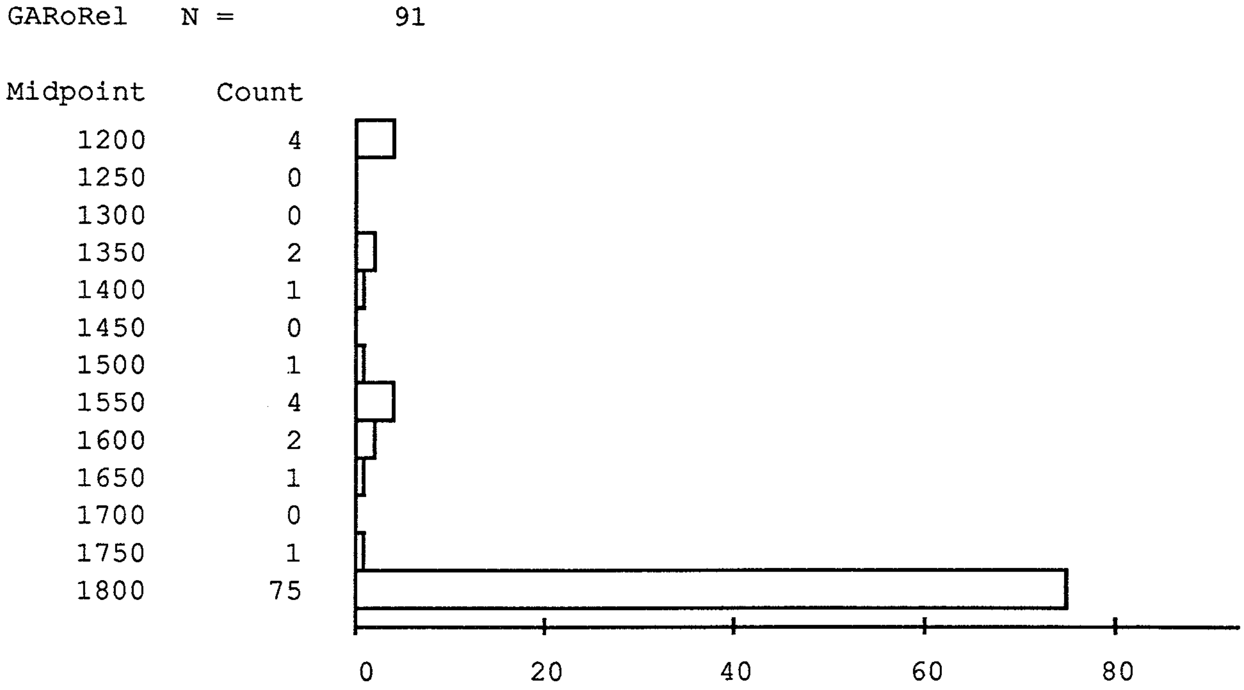

Figure 5-7

Histogram of Garrison Releases for July (kaf/mo.)

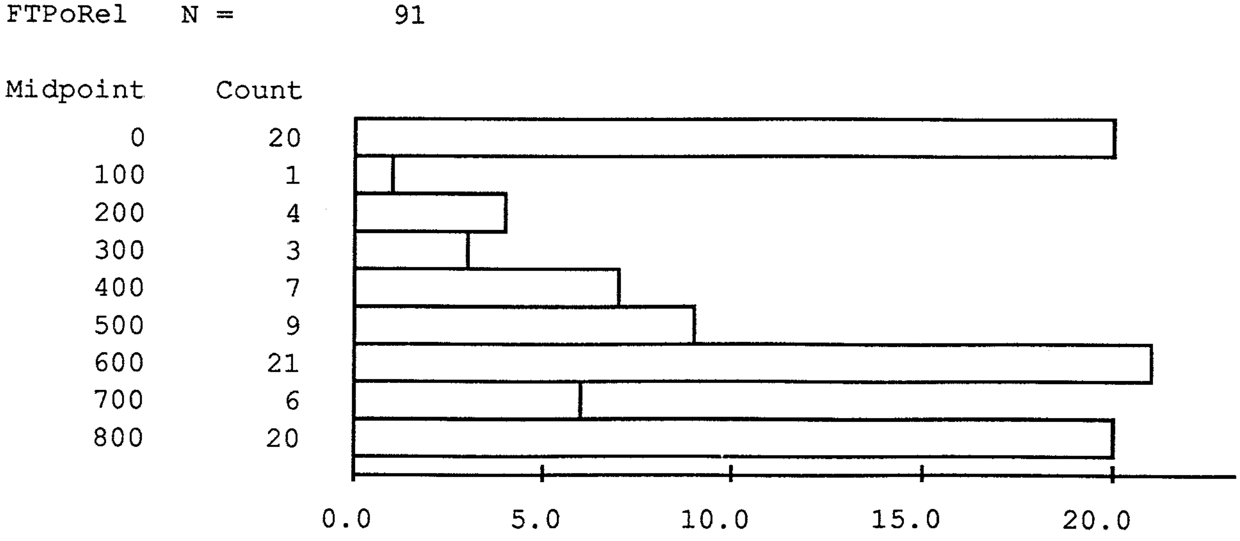

Figure 5-8

Histogram of Fort Peck Releases for July (kaf/mo.)

Regression-Based Rules

Following the success of Young (1966), attempts were made to estimate release rules from Gavins Point by multiple linear regression and stepwise linear regression. An example of one of the better regressions appears in Figures 5-4 and 5-5. While these regressions did not yield a release rule, they provided insight into which independent variables (inflows and storages) were important for developing the more complex rules eventually found for Gavins Point releases.

TESTING THE RULES

The testing and refinement of rules suggested by optimization results will be the most time-consuming and expensive part of any rule-making exercise. Much is likely to be learned about the meaning, if any, behind the optimization results through such intensive manipulation and examination of suggested "optimum" rules.

The testing of rules by simulation should have at least two objectives: 1) to see if the suggested rules do indeed lead to feasible operations and 2) to see if the releases, storages, and flows produced by implementing the suggested rules in a simulation model closely mimic those decisions and states in the original optimization model runs.

Since simplifications are typically required to make the description of the reservoir system and its penalty functions acceptable to HEC-PRM, it is desirable to use simulation modeling and engineering judgement to refine and improve the operating rules suggested by optimization results. Rules which appear feasible and provide a good fit with the optimal operations suggested by the optimization model may make their greatest contribution as a "point of departure" for more detailed simulation studies which can more realistically refine the operation of a complex reservoir system.

Some additional rationale and approaches for rule testing are discussed in Appendix A. The rules and rule changes suggested in this report are preliminary and untested. This is especially true given the potential deficiencies found in the Phase I HEC-PRM results.

CONCLUSIONS

It appears possible to develop a complete set of operation plans from HEC-PRM results for the main stem Missouri River system. HEC-PRM results also appear to be able to suggest improvements to existing operation plans. These suggestions for new or modified operations may aid in updating that system's Master Water Control Manual. However, any suggestions for new or modified operation plans should be thoroughly tested and refined by traditional simulation studies.

The greatest value of operation plans suggested by HEC-PRM results is likely to be as a point of departure for more traditional and intensive reservoir simulation studies. A major contribution of the HEC-PRM rule-making exercise is likely to be in the relatively rigorous establishment of approximately optimal operations.

Chapter 6

Lessons Suggested by the MRD Experience

The experiences presented in this report lead to a number of observations regarding the application of HEC-PRM to operation plan development for the Missouri River, potentially useful enhancements to HEC-PRM to facilitate the development of operation plans from HEC-PRM results, and suggestions for Phase II HEC-PRM runs for operation plan development.

APPLICABILITY OF HEC-PRM FOR OPERATION PLAN DEVELOPMENT

As discussed in detail in Chapters 4 and 5, it appears possible to use HEC-PRM results for the development of operation plans for the main stem reservoirs on the Missouri River. The approach taken was to use a commercial statistical package (MINITAB©) to manipulate and display HEC-PRM results to reveal apparent "rules" that could guide operation of the reservoir system.

These results, manipulations, and displays have been employed in two ways: (1) to suggest modifications in the existing operation plan for the reservoir system and (2) to suggest a somewhat different set of operating policies for the system.

SUGGESTED ENHANCEMENTS TO HEC-PRM POST-PROCESSING

The work presented in this report was done without the benefit of much of the post-processing capability now available for displaying HEC-PRM results. In particular, the inability to easily follow the behavior of different penalty functions over the course of HEC-PRM operations was a major impediment to the operation plan development presented here. This capability is currently available for HEC-PRM. Some features that would be useful for operation planning are listed in Table 6-1. Many of these features are available through the HEC's DSS package. It may not be worthwhile to implement all features into a HEC-PRM post-processor. Rather, for some features at least, the engineers performing the rule-making exercise might find the acquisition and use of statistical and graphics packages with these features desirable.

Ultimately, it may be desirable to create an elementary reservoir simulation package incorporating a flexible set of rule forms that could employ and display the HEC-PRM input and results and be used to test preliminary operation plans suggested by HEC-PRM results. Such a simulation package might be based on the reservoir network entered into HEC-PRM.

Table 6-1
Post-Processing Useful for Operation Plan Development from HEC-PRM Results

Ability to Store and Manipulate Many Types of HEC-PRM Data Together
  Hydrologic input for each location
  HEC-PRM storage output for each location
  HEC-PRM release output for each location
  HEC-PRM flow output for each location
  Penalty function values for each project purpose at each location

Ability to Perform Elementary Mathematics on Existing Variables to Create New Variables

Sorting and Separation of All HEC-PRM Data by Month

Deletion of Data for Specific Years

Descriptive Statistics for Results
  Minimum value
  Maximum value
  Upper and lower quartile values
  Median value
  Standard deviation of values

Time-Series Plots
  Time-series plots of single variables
  Time-series plots of multiple variables with multiple vertical scales
  Time-series plots for specific months

Histograms of variables

Scatter Plots
  Bi-variate scatter plots
  Multi-variate scatter plots

Regression (with elementary regression statistics)
  Step-wise linear regression
  Multiple linear regression

Hard Copy Output of Statistics and Graphics

User-Specified Output Formats for Interface with Local Simulation Software, Graphics Packages, or Spreadsheets

USES OF HEC-PRM BY MRD

At the time when this report is being written, MRD's experience with HEC-PRM is incomplete. Final production runs of HEC-PRM have not yet begun. Still, it appears that the process of developing the HEC-PRM application and preliminary results have had some effect on the course of MRD's Master Water Control Manual update study.

Explicit Presentations of Performance

Perhaps the greatest contribution of the HEC-PRM application to the MRD update study has been to further the idea of explicitly linking presentations of system performance for different reservoir purposes to simulation results. While this idea may not have originated with the HEC-PRM application, it seems to have been greatly supported by the development of the HEC-PRM application, and particularly the development of penalty functions. MRD has developed a set of "value functions" analogous to HEC-PRM's "penalty functions" for investigating the performance of different simulation runs for different project purposes.

This explicit linking of system performance measures with the simulation model is only a few conceptual steps short of an optimization model.

Employment of Optimization Results

It has only been in the last month that the HEC-PRM application has been transmitted to the MRD staff and their consultants. It is therefore too early to see if the optimization model will aid MRD in its update study. However, the complexity of MRD's task and the level of interest on the part of MRD personnel bodes well for the employment of HEC-PRM.

USE OF HEC-PRM FOR OPERATION PLANNING FOR OTHER BASINS

Some observations are offered for the application of HEC-PRM to the development of operation plans on other basins. First, all basins are somewhat unique. The hydrology, reservoir configuration, and purposes of each reservoir project will be substantially different from any other reservoir project. This implies that any application of HEC-PRM to other basins will require the same careful and complete effort at establishing penalty functions, system configuration, and inflow hydrology as was performed for the MRD study and will require simplifications of the original system to meet the computational and algorithmic requirements of HEC-PRM.

This uniqueness of each reservoir system implies that the development of operation plans from HEC-PRM results could be substantially different for different reservoir projects. The storage target, storage allocation, and release rule forms presented here which appear to work well for the Missouri River reservoirs may not work well for other systems. Indeed, the six main stem Missouri River reservoirs are probably simpler to study than many other systems because all six reservoirs are in series and there are only six reservoirs.

The Missouri River application is also facilitated by the presence of over 90 years of historical streamflow record. This record, which contains several sizable flood and drought events, gives some assurance that the HEC-PRM results will be somewhat representative of typical and somewhat extreme operations. Without this long streamflow record, a surrogate synthetic streamflow record might be appropriate. The development of such synthetic streamflows for such a large basin would be difficult, and perhaps provide only illusory benefits. Still, if one is interested in examining the optimal operation of the system under statistically very extreme conditions, synthetic hydrology, or perhaps scenario-based, approaches appear to be the only available options.

SUGGESTIONS FOR PRODUCTION RUN HEC-PRM APPLICATION FOR MRD

Two major suggestions are offered from this study for the production runs needed for actual application to the MRD update study:

1) Penalty functions need to be finalized. Existing penalty functions should be checked. Additional penalty functions for ice-related flooding are needed to make the HEC-PRM penalty functions more representative of the real reservoir system. It may also be desirable to add penalty functions for locations further downstream than Hermann.

2) The hydrologic inflows used by the HEC-PRM application need to be checked and corrected for the latest estimates of upstream depletions. As discussed in Chapter 4, this led to some curious divergences between HEC-PRM and the MRD monthly simulation model.

CONCLUSIONS

The preliminary development of operation plans for the main stem Missouri River system using HEC-PRM results has suggested some improvements for the post-processing of HEC-PRM output and the application of HEC-PRM for the Missouri River system. Some of these improvements have already been made. Others represent more long-term projects. For HEC-PRM to be useful for operation plan development on the Missouri River system, the development and incorporation of penalty functions for ice-related flooding is essential and it is desirable to check existing penalty functions and investigate the utility of adding further penalty functions for flows further downstream than Hermann.

Chapter 7

Conclusions

The development of operation plans for reservoir systems is a major objective behind the development of the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM). The work presented here investigated the ability to develop operation plans from HEC-PRM results for the main stem Missouri River system, one of the nation's largest reservoir systems. This preliminary effort was largely successful.

The development of operation plans from deterministic optimization results is a well-established concept (Young, 1966; Karamouz, et al., 1992). When long records of reservoir inflows are used for the optimization, the approach is often called *implicit stochastic optimization.* This term is used because the rules developed from a long record of deterministic optimal decisions should be quite similar to those developed from more rigorous, but computationally and practically less feasible explicitly stochastic methods. In many practical cases, only this implicit stochastic optimization approach is possible. The development of operation plans from HEC-PRM results rests on this premise and concept.

Many methods are available for developing operation plans from deterministic optimization results, such as those produced by HEC-PRM. As reviewed in Appendix A, these include: intuition and engineering judgement, regression, reservoir operation theory, and conjunctive use of simulation and optimization. For most real cases where the system modeled is both multi-purpose and has multiple reservoirs, a combination of these approaches is likely to yield the best results. This has been the case for the application of HEC-PRM to the Missouri River presented here.

It appears possible to develop preliminary operation plans for the main stem Missouri River system using HEC-PRM results. Such operating rules, based on Phase I HEC-PRM results, are presented in Chapters 4 and 5. However, because of the preliminary nature of the Phase I results, these rule suggestions should be viewed as preliminary. These rules have also not been fully developed for all months and remain unrefined and untested by simulation modeling. Still, these preliminary results bode well for the application of HEC-PRM to the Missouri River system.

Two rule-making approaches were taken for the development of operation plans. The first involved the use of HEC-PRM results to suggest modifications or "re-calibration" of existing reservoir operation plans. This involves using HEC-PRM results to suggest new pool levels or modifications to the rates and constants in the rule forms which govern the current system. This is an attractive approach since existing operation plans often embody a considerable amount of practical wisdom and experience. The second approach taken was to develop a qualitatively different set of operation plans, largely without regard for existing operation plans. This approach is more difficult and somewhat more subjective, but served to give a set of operation plans less bound by the practices of the past. There are advantages in pursuing both approaches.

The development of suggested operation plans from HEC-PRM results should be seen as part of a larger operation planning effort. Technically, the rules suggested by the optimization results should be refined and tested through more detailed and extensive simulation studies. Institutionally these simulation-optimization efforts are likely to be iterative and combined with some sort of formal and perhaps ultimately public review.

It is unthinkable to employ the operation plans suggested by HEC-PRM results without refinement and testing by simulation studies. The necessarily approximate nature of most optimization models implies a need for verification and probable refinement of suggested operation plans through simulation studies. All applications of implicit stochastic optimization to real reservoir systems have actively employed simulation as part of operation plan development. In some ways, the operation plans suggested by optimization results can be seen as points of departure for more detailed simulation studies.

For the application of HEC-PRM to the main stem Missouri River system and the development and updating of operation plans for this system, two improvements to the the Phase I HEC-PRM application are needed. 1) The penalty functions need to be finalized. Existing penalty functions should be checked; penalty functions for ice-related flooding should be added; and additional penalty functions downstream of Hermann may be desirable. 2) There appears to be some discrepancy in the application of upstream depletions to the inflows used for the Phase I HEC-PRM results. This discrepancy should be resolved.

Overall, HEC-PRM is a promising avenue for operation planning for reservoir systems. It offers a new, more rigorous, and potentially improved approach for the development, review, and updating of reservoir operations. HEC-PRM should provide a useful supplement to current practice in reservoir operation studies.

Appendix A

Methodologies for Developing Operation Rules from HEC-PRM Results

IMPLICIT STOCHASTIC OPTIMIZATION

The development of reservoir operation plans by abstracting operating rules from extensive deterministic optimization results is sometimes known as "implicit stochastic optimization" (Whitlatch and Bhaskar, 1978; Klemes, 1979; Karamouz, et al., 1992). The approach relies on using a long record of historical or synthetic hydrologic inflows to represent the uncertainty in inflows. The patterns seen in the deterministic optimization results, which have perfect knowledge of future inflows, should therefore represent optimal rules for operations even under uncertainty.

The major advantages of implicit stochastic optimization over explicit stochastic optimization, such as stochastic dynamic programming and stochastic linear programming, is the much greater computational feasibility of deterministic optimization (Young, 1966) and the relative ease of establishing input data sets needed for implementing deterministic optimization. Explicitly stochastic optimization methods, for example, typically require an explicit stochastic model of streamflows, which is typically elusive. There is even some work to suggest that the rules produced by implicit stochastic optimization are superior to those produced by explicit stochastic optimization under some circumstances (Karamouz and Houck, 1987).

Ideally, if a deterministic reservoir optimization is performed with a long enough hydrologic record, a contingency table could be developed to establish the mean optimal release from each reservoir given the current month, current storages, and current inflows throughout the system. This was originally done by Young (1966) for a single idealized reservoir using 5,000 periods of synthetic inflows with one season. It is unlikely that this ideal contingency table approach could be developed for most real reservoir systems that have significant monthly variation, multiple reservoirs, and less than a century of hydrologic record.

Nevertheless, implicit stochastic optimization approaches that have lesser requirements and produce more approximate rules have been common in the reservoir optimization literature (Young, 1966; Jettmar and Young, 1975; Whitlatch and Bhaskar, 1978; Bhaskar and Whitlatch, 1980; Trott, 1979; Karamouz and Houck, 1982; Karamouz, et al., 1992). Most applications of implicit stochastic optimization have been to cases with only a short streamflow record, typically less than 40 years. In these cases, use of the historic record would provide only a very limited and perhaps unrepresentative example of the range of streamflow experiences which are possible in the future. In these cases, synthetic streamflow generation has been employed to provide the statistical equivalent of a long streamflow record (Karamouz, et al., 1992). While synthetic streamflow generation may be unavoidable in the absence of a long streamflow record, there are important methodological difficulties with this approach (Klemes, 1974). Still, some have found that the use of even rather short (64-year) historic records can yield operating rules essentially the same as those found using longer synthetic streamflow records (Jettmar and Young, 1975).

DETERMINISTIC OPTIMIZATION FOR "TYPICAL" YEARS

Another common approach for developing optimization rules from deterministic optimization results is to specify a hydrology and water demands for a "typical" year or a set of typical years. Deterministic optimization is then used to find optimal operations for such years and these optimal results are then interpreted to find operating rules, often with the aid of simulation (King and Evenson, 1972). Rules developed by this approach may be informative, but will not be applicable to as wide a range of conditions as those developed by implicit stochastic optimization, using a much longer streamflow record.

RULES FROM RESULTS

A variety of general approaches are available for discerning reservoir operation rules from optimization results. Variants of these approaches have been employed in previous optimization studies.

Each of these approaches seeks to detect and substantiate a pattern in historical optimal operations that can be reduced to "rules" which are based on the reservoir operator's current state of knowledge. Thus, operation rules must be based on known states such as: the current month, current storage, and current or forecast inflows. For the Missouri River system, some typical examples of operation rules would be:

- A storage rule based solely on the month,
  "In February, keep Fort Randall storage at 3.5 MAF."
- A storage rule based on the current month and system storage,
  "In July, if total storage > 64 MAF, keep 22 MAF in Oahe."
- A release rule based on system storage,
  "In July, for total storage between 50.5 and 59.0 MAF maintain a flow of
  25,000 cfs + 706*(Storage - 50.5 MAF) at Sioux City."

The major difficulty in detecting these rule patterns in long-term optimization results is the amount of optimization result data available. For the case of the 90-year record used in the Missouri River exercise, a total of 13,248 optimal release and storage decisions were provided, in addition to input inflow data and data on consequent downstream flow consequences of release decisions. The four general approaches discussed below are, therefore, approaches employed to identify consistent trends in large amounts of data.

INTUITIVE APPROACHES

Intuitive approaches to discerning reservoir operation rules employ our innate and educated abilities as engineers to detect significant patterns in data. We all feel that we are able to "see" when plotted data seem to fit a linear trend.

The use of intuition in identifying and substantiating apparent "rules" in optimization results is greatly aided by the use of graphical and statistical tools. Descriptive statistics, histograms, scattergrams (data plots), and other techniques all present data in a form conducive to our "seeing" trends. Statistical and data analysis software packages can be very valuable in quickly providing a wide variety of such displays and descriptive statistics to the rule-maker. As described in the main body of this report, an educated intuition was the major approach used in developing the rules suggested in this report.

The utility of intuition in rule-making is limited by the intuitive abilities of the rule-maker and the complexity of the rule-making task. There may always exist a more perfect pattern that is too complex for a rule-maker to "see." Also, different rule-makers might "see" different patterns.

Finally, the complexity and quantity of the data may be difficult to present in a form conducive to intuitive rule-making. The limitations of intuition for rule-making are those of the individual, human rule-maker.

REGRESSION APPROACHES

Regression typically tries to develop equations which predict optimal decisions, such as releases, based on input data, such as current month, current storage, and forecast inflows. Regression techniques typically assume linear relationships between these variables and attempt to best "fit" the regression equation by finding parameters for the equations that satisfy some "fit" criterion, such as minimization of the sum of squared deviations between the optimal decisions and decisions predicted by the linear regression model.

Regression was first employed for developing reservoir operation rules from optimization results by Young (1966) and has been employed by others since (Jettmar and Young, 1975; Bhaskar and Whitlatch, 1980; Karamouz and Houck, 1982; Karamouz, et al., 1992). Before using regression to estimate an operating rule, specific dependent and independent variables must be defined. Independent variables would include those things known at the time of real operations, such as the current month, current storage, and current inflows. The dependent variable in the regression would be some operating decision which must be made, such as a release rate or a storage target. Given the relative ease of performing regression analysis with contemporary statistical packages, it is easy to explore a variety of dependent variables and several combinations of independent variables. The specification of independent and dependent variables is rather subjective, aided by intuition and judgement, reservoir operation theory, simulation results, and previous regression results.

Most use of regression for developing reservoir operation plans has been for single reservoirs (Young, 1966) or small multiple reservoir systems with a single operating purpose (Bhaskar and Whitlatch, 1980; Karamouz, et al., 1992). For larger reservoir systems, such as the Missouri River system, there are many possible sets of independent and dependent variables. The operation of multi-purpose reservoir systems, where the optimal operation is driven both by storage, release, and downstream flow values is also less likely to be revealed by simple linear relationships. In addition to the engineering judgement, intuition, theory and other aides to specifying independent variables, step-wise multiple regression can be of use in determining which of many possible independent variables tend to best explain variation in a particular release rate or storage level.

RESERVOIR OPERATION THEORY

Reservoir operation theory can be of great use in suggesting the form of operating rules that might be inferred from optimal operation results. Work on optimal rule forms and patterns can be particularly useful (Clark, 1956; Mass et al., 1966; Kelman, et al., 1989; Loucks and Salewicz, 1989; Johnson, et al., 1991). Some common examples of these optimal operating rule forms are:

- Space rules (Clark, 1956; Mass et al., 1966; Johnson, et al., 1991), which seeks to balance storage between reservoirs in parallel to minimize the likelihood of spills,
- Pack rules (Mass et al., 1966), which maintain storage at high levels as long as possible to increase hydropower heads and production, and
- Hedge Rules (Mass et al., 1966), which reduce reservoir releases early in a drought to reduce the risk of shorting more critical release uses later in a drought.

Other rules are suggested by work by other authors and the practice of reservoir operators. However, many of these additional rule forms have not been formally stated or examined.

MIXED SIMULATION-OPTIMIZATION APPROACHES

Simulation-optimization approaches to developing operation rules for reservoirs employ optimization models to suggest initial operating rules and simulation models to test and refine these rules. This process may involve several cycles of optimization and simulation runs, often conducted in a fairly adaptable and flexible, but systematic way. Almost every practical rule-making exercise undertaken using optimization has conjunctively employed simulation modeling (for example: Jacoby and Loucks, 1972; Evenson and Moseley, 1970; King and Evenson, 1972; Toebes and Rukvichai, 1978; Bhaskar and Whitlatch, 1980; Karamouz, et al., 1992). Some of the general rationale and uses for simulation are presented in Table A-1 and discussed below.

Rationale for Use of Simulation

There are several reasons to employ simulation in conjunction with optimization for reservoir rule-making. First, optimization models must typically be somewhat simpler than simulation models of a reservoir system. Optimization models typically require that definitions of the system and its objectives conform to specific mathematical conditions needed to implement a solution method. For HEC-PRM, an example is the requirement that all penalty functions be convex. Simulation models suffer much less from such constraints. This makes it possible to test rules developed from optimization results with more realistic simulation models. The greater realism of simulation models also provides opportunities to refine operation rules suggested by optimization results to make them more appropriate for the real reservoir system.

A second reason for employing simulation models in rule-making with optimization is the often greater ability of simulation modeling to perform "what if" studies. Specific flood control or drought scenarios can be studied easily using proposed operation rules in a simulation model. This would be awkward and often inappropriate for optimization models.

A third reason for employing simulation models is the greater speed of most simulation models. A larger number of specific cases can be studied by simulation modeling than would be possible by optimization. However, optimization results might suggest some of the more fruitful scenarios to be tested.

The final, and perhaps most important reason to employ simulation models is the greater acceptance enjoyed by simulation modeling and the frequent relative ease of explaining simulation results. Even where operating rules are unchanged by simulation modeling, simulation modeling is probably necessary to render the rules understandable and acceptable to concerned technicians and individuals.

Uses for Simulation

Rule Refinement

Since simulation models can both represent the reservoir system in greater detail and be executed more quickly than optimization models, simulation models are useful for refining the details of suggested operation plans suggested by optimization results. As such, the optimization-based suggested rules may serve mainly as a point of departure for more traditional simulation studies of operation plans.

Simulation modeling can also be used to refine the optimization model (Karamouz, et al., 1992). In this case, a cycle of optimization, rule-making, and simulation model proceeds iteratively until a satisfactory set of rules is developed.

Rule Testing

Again, since simulation models can represent the system in more detail and have already gained some acceptance, in most cases, simulation modeling is a rather inexpensive and effective approach to testing operation plans developed from optimization results. Such simulation tests have a number of objectives:

Do the suggested rules closely match the storage and release behavior from the optimization model? By implementing the suggested rules in a simulation model, rule-based storages and releases can be compared with those obtained directly from the optimization model (Bhaskar and Whitlatch, 1980). This comparison can be used to see if the suggested operation rules well represent the optimization results.

Are the suggested rules feasible? Unless the suggested rules are thoroughly thought out, it can be possible for rules to suggest impossible behavior. For instance a release rule based solely on the month can suggest release volumes in excess of available storage and inflows.

Are the suggested rules really optimal? Since a simulation model can usually represent the reservoir system in greater detail than an optimization model, implementing the suggested operation rules in a simulation model and performing sensitivity analysis on the parameters in the suggested rules can conceivably improve the optimality of the suggested rules. A similar test is to compare the detailed performance measurements from a simulation model employing existing operation plans with those from a simulation employing the suggested operation plan. If the optimization model represents too great a simplification of the real system, existing operations might in fact be superior to those suggested by the optimization model.

Do the suggested rules perform well under extreme detailed scenarios? It is often desirable to test a proposed operation plan under detailed flood control, drought, or emergency operation circumstances. If the suggested operations are not suitable for such emergency operations, the suggested operations, the importance of the chosen scenarios, and other responses to the proposed scenarios might be further examined. Often, further optimization and simulation studies would be useful for such questions. For instance, the introduction of further constraints to the optimization to facilitate emergency operation can give cost estimated of preparedness for such emergencies. In some cases, there might be less expensive approaches for emergency preparedness.

Implementation Issues

The use of simulation in conjunction with optimization is greatly facilitated by the prevalence of existing simulation models for reservoir planning and operation studies. Almost all large reservoir systems have one or more existing simulation models. Still, most existing reservoir simulation models are likely to require considerable modifications to accept the diverse forms of operating rules that are likely to be developed from deterministic optimization (HEC-PRM) results.

In many cases, the most difficult aspect of simulation studies of this nature is the incorporation of more explicit economic or environmental performance indices in an existing simulation model. While this may be a burdensome and time-consuming task, the presence of economic and environmental performance indices in a model can be of long-standing utility long after an operation plan study is completed.

Table A-1
Rationale and Uses for Simulation Modeling in Optimization Rule-Making

Rationale

Simulation models typically represent the system better than optimization models.

Simulation models perform some "what if" studies more easily than can optimization models.

Simulation models typically run faster than optimization models.

Simulation modeling is typically better understood and accepted than optimization modeling.

Uses of Simulation

Refinement of suggested optimization-based rules to increase realism in system operation.

Testing of suggested optimization-based rules for:
- feasibility
- detailed operational implications
- comparison with existing operation plans
- evaluation of desirability using more detailed operational performance measures

SOME POTENTIAL PITFALLS

There are several potential pitfalls in the development of operation plans from optimization results. Most of these can be detected by the use of simulation studies to test and refine suggested operation plans. Some of these pitfalls are probably mostly of academic importance, but may have practical importance in specific cases.

Infeasible Operations

It is possible for the set of rules suggested by optimization results to result in infeasible operations. Infeasible operations are those that would not be allowed by the constraints in the original optimization model or not physically possible in the real reservoir system. The likelihood of infeasible operations increases when the reservoir system faces more severe drought or flood events than those present in the hydrology entered in to the optimization model. Infeasible operations are also more likely to result from suggested rules which do not closely mimic the optimized operation of the reservoir system. An example of an infeasible operation is a release rule which specifies releases greater than the sum of the available storage and inflow.

Technical Suboptimality from Failure to Represent Uncertainty

The results of the deterministic optimization model represent an ideal operating policy, with perfect forecasting of future inflows and the perfect predictions of the value of different reservoir purposes. As such, it is unlikely that any set of rules triggered by current operator knowledge (such as current month, storage, and inflows) will be able to perfectly mimic the optimized results. This implies that the suggested rules will not produce as good an operation as that given directly by the optimization results.

The divergence between the rules suggested by the optimization results and the optimization results represents, in some sense, the cost of uncertainty in streamflow forecasts. It may be possible for a more rigorous stochastic optimization to provide rules for which this divergence would be less. However, such stochastic optimization is rather difficult or impossible for many real reservoir operation problems.

Technical Suboptimality from Optimization Model Simplification

As mentioned before, most optimization models require some simplification of the real reservoir operation problem. For HEC-PRM the need for the objective function to be convex is such a simplification. This implies that the optimal operations suggested by the optimization model may not be the real optimal operation. While some of this phenomena may be tested by simulation modeling, the exact optimal operation for the real system is in practice usually unknowable.

Oversimplification of Rule Forms

There is a great temptation to seek a few simple rule forms when developing operation plans from optimization results. This principle of parsimony is generally very useful and well accepted in professional and scientific fields. However, it may be possible for more complex rule forms to more closely mimic the optimization results and improve reservoir operations.

Overly Complex Rule Forms

Rule forms that are overly complex might more closely mimic the results of the optimization model. However, too complex a set of operating rules can result in a degree of spurious correlation between rule-based operation and optimization results. Complex operating rules also make simulation studies more difficult.

Replication of Existing Operation Through Rule Form Selection

If current operation plans are used as a guide for developing new operation plans from optimization results, it is likely that the "new" operation plans will be very similar to the existing operation plan. The use of the same form for new operating rules as existing rules will often result in a close replication of existing policies. Some attempt should always be made to see if rule forms different than existing forms can closely mimic optimization results. Despite such efforts, in many cases it is likely that "optimal" operating plans will be rather close to existing operating plans.

CONCLUSIONS

The development of operation plans from deterministic optimization results using long hydrologic records has advantages over traditional approaches employing simulation and engineering judgement or stochastic optimization. This approach to operation plan development has a long history in the engineering literature with a large number of plan development approaches being suggested.

In general, a combination of a variety of plan development approaches is likely to be preferred. In particular, the use of simulation modeling in conjunction with optimization results is almost essential to the technical and practical success of any rule-making exercise based on optimization results.

Appendix B

Potential Future Directions and Applications for HEC-PRM

This appendix outlines several applications that could be made of HEC-PRM to reservoir planning, operations, and management problems. The success of such applications is determined largely by the ability to formulate the problem in a form amenable to solution by HEC-PRM and an ability to usefully interpret the HEC-PRM results in the context of the problem. This will often involve employing HEC-PRM within a larger management and modeling context.

ESTIMATING THE OPTIMALITY OF OPERATION PLANS

One result produced by a HEC-PRM run is the value of the penalty function. The value of this penalty function is an indicates the overall desirability of the best possible operation plan, incorporating perfect knowledge of future streamflows. This index of the performance of the system under ideal conditions (when all future inflows are known) can be used comparatively to assess the optimality of existing and proposed reservoir operation plans, including operations plans which bear little resemblance to the operation plans that might be developed from optimization results.

Three approaches can be taken to find a value for the overall penalty function for an existing or proposed operation plan. First, the releases mandated by the proposed operation plan can be found by simulation. These releases could then be entered as constraints into the HEC-PRM application. The HEC-PRM run with these constraints would then have but one feasible solution, that particular set of releases, and HEC-PRM would also produce the consequent value of the overall penalty function.

A second approach to finding comparable penalty function values for a proposed alternative operation plan is to incorporate the penalty functions directly or indirectly into the simulation model.

The third approach is to use macros developed for HEC-PRM for use with HEC's MATHPK software to take the releases specified by a simulation model that employs the proposed operation plan and produce a penalty function value.

When overall penalty function values for both the HEC-PRM application and the proposed operation plan are available, operation planners can use the difference between these values to evaluate different operation plans. A table depicting such a comparison appears in Table B-1.

Such comparisons can indicate the proximity to ideal operations achieved by proposed and existing operation plans, given a consensus on the optimality of the HEC-PRM results, application, and penalty functions.

Table B-1
Sample Comparison of Alternative Operating Plans By Penalty Function Values

Operation Plan	Flood Control	Water Supply	Total
HEC-PRM results	900	800	1,700
Alternative A	1,000	950	1,950
Alternative B	2,000	700	2,700
Existing Plan	1,100	900	2,000

PLAN SCREENING STUDIES

Optimization models are frequently proposed to screen or preliminarily narrow the range of construction and operational alternatives examined in reservoir planning studies (Jacoby and Loucks, 1972). In this use of HEC-PRM, models could be formulated with various reservoir, hydropower plant, and channel capacity sizes. HEC-PRM runs for each of these alternatives would quickly indicate the rough relative desirability of each alternative, including optimal operation policies.

With this approach taken to quickly identify the most promising alternatives, more detailed simulation and optimization studies can be made to refine and improve the reduced number of alternatives. This should allow more effort to be devoted to the most desirable alternatives.

Another approach to screening studies is to develop an HEC-PRM model of the existing system. When this model is run, various constraints representing reservoir, plant, and channel capacities will "bind," indicating that there would be some value in expanding these facilities. Further simulation or optimization studies can then be conducted to estimate the value of improvements gained by expanding these facilities.

OPERATION PLAN DEVELOPMENT

The development of operation plans from HEC-PRM results is discussed at length in the main body of this report. To summarize, there are two fundamental ways that HEC-PRM results can be used. The first is to suggest modifications to existing operation plans, essentially "re-calibrating" existing operation procedures. The second approach is to use HEC-PRM results to develop entirely new forms of operation plans for a reservoir system.

SOME DESIRABLE TRAITS FOR HEC-PRM APPLICATIONS

Reservoir systems which are particularly amenable to application of HEC-PRM would include systems with the following traits.

Streamflow Records

The streamflow records used for HEC-PRM runs must be either long (typically > 50 years) or representative of particular scenarios of interest. Optimal operation to manage particular drought scenarios would require adequate representation of a "drought." Estimating optimal operation plans for typical years would require some hydrologic definition of a "typical" year (King and Evenson, 1972).

Convex Penalty Functions

Penalty functions for the reservoir system purposes are best when they are all convex. In some cases, very steep non-convex segments of penalties might be represented as constraints, however.

Constant-Lag or No Lag in Flows

HEC-PRM assumes that flow releases travel downstream during the same time-step (no lag in flows). Where constant lags in flows exist, this could be incorporated into HEC-PRM by routing flows into "future" arcs. However, this is not possible where the lag-time of flows varies significantly with storage levels downstream (backwater effects) or with the stage of the river corresponding to the volume of reservoir releases.

Independence of Penalty Functions and Streamflows

In some humid regions, irrigation demands (including lawn watering) increase dramatically during droughts, owing to the lack of rainfall. This same dearth of rainfall also reduces streamflows. This implies that the penalty functions for irrigation uses should be different for periods of low spring and summer streamflows. This is difficult to handle explicitly using HEC-PRM.

Appendix C

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Appendix D

Notation and Unit Conversions

Unit Conversions

1,000 cfs = 60,330 acre-ft/month

10,000 cfs = 0.6033 MAF/month

Notation

The manipulation of data for a large number of variables required the development of a notation scheme. This notation appears throughout this report on the figures. Use of full names would have been too cumbersome and awkward.

As an example, GPToRel, is the variable name for Gavins Point (GPT) optimal (o) Releases (Rel). This general system was applied throughout, using the following abbreviations.

BB - Big Bend
FTP - Fort Peck
FTR - Fort Randall
GAR - Garrison
GPT - Gavins Point
o - optimal (HEC-PRM result)
OAH - Oahe
Rel - Releases
s - simulated current operation plan
Stor - Storage
TOT - total system

Some other abbreviations and definitions are:
acre-foot - the volume that would cover an acre of land with one foot of water
kaf - thousands of acre-feet
MAF - million acre-feet