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Operating Rules from HEC-PRM Results for the Missouri River System: Development and Preliminary Testing

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The report describes the development and testing of preliminary 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 results are preliminary, with limitations noted in text. The reservoir operating rules presented are inferred directly from HEC-PRM and refined and tested using a coarse simulation model. Further detailed simulation modeling is required to more completely assess the value of suggestions for system operations presented.

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Table of Contents

Page Number

Chapter	Page Number

Chapter	Page Number

Appendices

Appendices	**Page Number**

List of Tables

List of Figures

Figure Number		Page Number

Preface

This report describes the development and testing of preliminary 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 practical importance than the actual coding and computational performance of the model.

The Missouri River System Analysis Phase I and Phase II reports (USACE, 1991, 1992a) present the formulation of HEC-PRM's application to the Missouri River system. A previous report (USACE, 1992b), interpreted HEC-PRM model results to identify a strategy for developing monthly reservoir operation plans being developed and tested with a simulation model. Since the HEC-PRM results for this work were preliminary, the operation plan suggestions uncovered by this work are also necessarily preliminary.

The research and report was prepared by Inês C.L. Ferreira and Jay R. Lund of the Department of Civil and Environmental Engineering, University of California, Davis under contract to the Hydrologic Engineering Center (HEC). Many others contributed to and commented on the work presented here and its predecessor (USACE, 1992b). Robert Carl, David Ford, Marilyn Hurst, Richard Hayes, David Moser, George Patenode, and Karen Wilson are all heartily thanked. Michael Burnham, Chief, Planning Analysis Division, HEC, provided general overview and coordination. Darryl Davis was director of HEC during the study.

Chapter 1

Introduction

This report reviews the use of the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) for developing operation plans for the Missouri River 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.

Simulation models, often very detailed, have long provided practicing engineers and operators with a useful tool in planning and operation studies. Reservoir system simulation models have system operating rules incorporated in the model. While the descriptive nature of simulation models allow for "what if" studies, their prescriptive capabilities are limited.

Optimization models are prescriptive in nature, and suggest promising decisions. Optimization models seek to optimize system performance as measured by a function representing system management objectives through numerical mathematical programming algorithms. In a prescriptive model such as HEC-PRM, the system analysis is based on a defined set of system's objectives and constraints. From the results of such a model, operation rules are inferred and then incorporated into a simulation model for testing and refinement.

HEC-PRM is a network flow model that seeks to minimize a complex linear objective function for multi-reservoir systems subject to flow and storage constraints (USACE, 1991, 1992a). HEC-PRM represents a reservoir system as a series of nodes connected by links. Associated with each link is an economic function for the flow in that link. Nodes representing reservoirs have an economic function representing storage. Economic functions and constraints represent the project purposes. For the main stem Missouri River system application the economic functions include hydropower, navigation, water-supply, flood control, and recreation (USACE, 1990).

HEC-PRM uses monthly time-steps, historical inflow as input data, and evaporation is described as a function of storage in each reservoir.

Following preliminary efforts (USACE, 1992b), reservoir operating rules were developed from HEC-PRM results using graphical display, simple descriptive statistics, and careful data interpretation. Trends and patterns in the data were found and simple storage target rules, storage allocation rules, and reservoir release rules were inferred. These rules were tested with a simple simulation model and the system's performance under these rules compared to optimized results and current operation simulation results.

Results indicate that these simple procedures can be useful in developing and/or updating reservoir operation plans even for large and complex systems such as the Missouri River system.

This report provides a sequel to previous studies on the applicability of HEC-PRM in the development of operating rules for the main stem Missouri River system (USACE, 1992b). The remainder of this report is organized as follows, Chapter 2 provides a brief description of the main stem Missouri River system and previous studies on HEC-PRM analysis of the Missouri River system. Chapter 3 describes the method of derivation of operating rules for the system. Chapter 4 presents the testing and refinement with simulation of the operating rules suggested in Chapter 3. Chapter 5 presents some conclusions from this study and suggestions for using HEC-PRM results in reservoir operating rule development. Appendix A presents a literature and theoretical discussion of operating rule development from prescriptive model results. Appendix B presents the simple simulation model used for operating rule refinement and testing. Appendix C contains a variety of comparative plots of results from HEC-PRM, simulated HEC-PRM derived operating rules, and results from a Missouri River Division (MRD) model of the system, reflecting current operations.

Chapter 2

The Missouri River System

2.1 The Main Stem Missouri River System

The main stem Missouri River system, spanning over seven mid-western states, is composed of six reservoirs followed by a long stretch of river between Sioux City, Iowa, and the confluence with the Mississippi River at St. Louis, Missouri. These reservoirs are constructed, operated, and maintained by the U.S. Army Corps of Engineers (USACE) for flood control, navigation, irrigation, hydropower, water supply, fish and wildlife, recreation, and water quality control. The six main stem reservoirs, with a total storage capacity of 73.9 million acre-feet (MAF), are located in Montana, North Dakota, South Dakota, and Nebraska (Figure 2.1). Reservoir capacities and mean annual inflows are shown in Table 2.1.

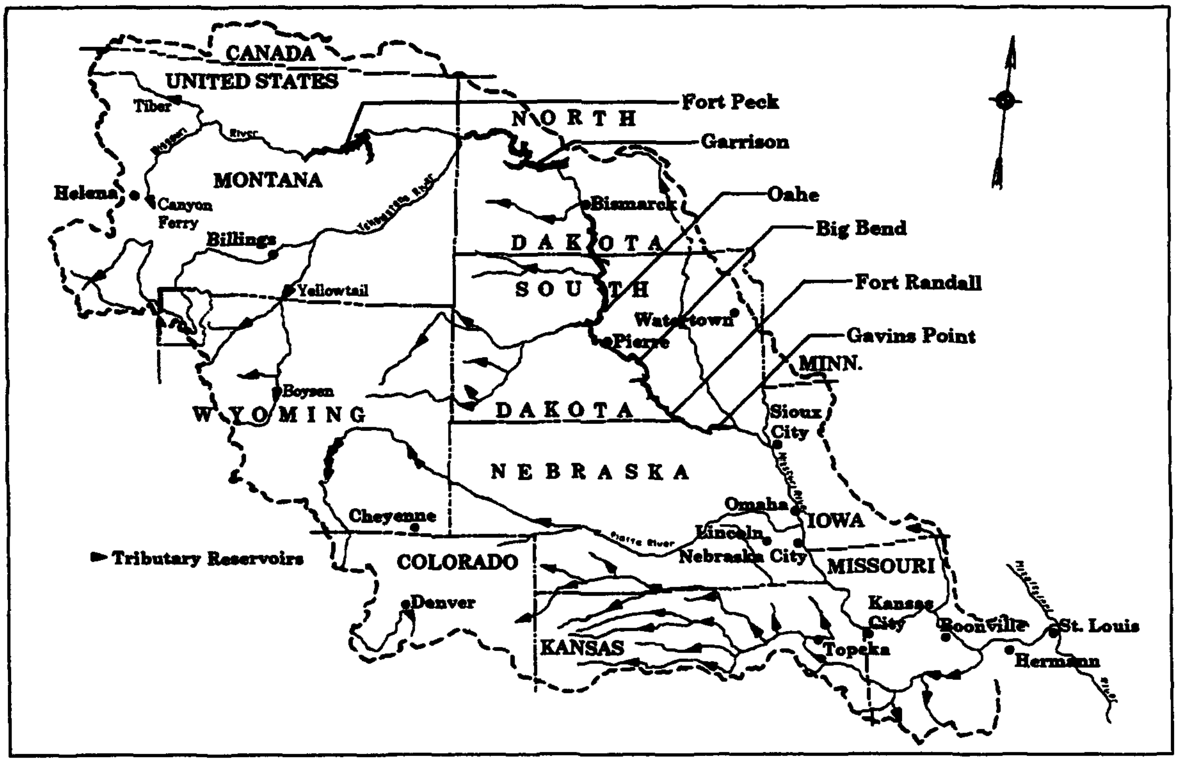


Figure 2.1 Missouri River Basin

Table 2.1
Capacities and Mean Annual Inflow of Main Stem Reservoirs

Reservoir	Capacity (MAF)	Tributary Inflow (MAF/year)	Cumulative Mean Annual Flow (MAF/year)
Fort Peck	18.7	7.0	7.0
Garrison	23.9	10.3	17.3
Oahe	23.3	2.2	19.5
Big Bend	1.9	0	19.5
Fort Randall	5.6	0.9	20.4
Gavins Point	0.5	1.5	21.9

A number of other projects have been constructed in the lower basin by USACE. These include the Missouri River Navigation and Bank Stabilization Project from Sioux City to St. Louis. Operation of this project is dependent on upper basin reservoir releases, requiring integrated management of the lower and upper basin projects (USACE, 1993).

While Fort Peck and Garrison receive eighty percent of the inflows in the upper basin, considerable tributary inflows also occur in the lower reaches of the Missouri River. These inflows are shown in Table 2.2. Large inflows in downstream reaches have a great effect on the operation of the main stem reservoirs.

Table 2.2
Mean Annual Inflow Downstream of Main Stem Reservoirs

Downstream Location	Tributary Inflow (MAF/year)	Cumulative Mean Annual Flow (MAF/year)
Sioux City	1.6	23.5
Omaha	1.6	25.1
Nebraska City	4.4	29.5
Kansas City	9.6	39.1
Boonville	6.4	45.5
Hermann	12.3	57.8

With an area of 529,350 square miles (one-sixth of the contiguous United States), the Missouri River basin envelops a wide range of latitude, longitude and elevation. Moreover, because of its central location in the North American Continent, the Missouri River basin experiences a wide range of climatic conditions. Mean annual precipitation varies from eight inches in the northern Great Plains to over forty inches at higher elevations in the Rocky Mountains and in the southeastern part of the basin. Temperatures are extreme with winter lows of -60^{o} F in Montana to summer highs of 120^{o} F in Nebraska, Kansas, and Missouri.

Total annual runoff varies considerably from year to year. The basin has experienced a number of devastating floods and three severe multiple year droughts in the last 100 years. Flooding usually occur in the late spring and early summer months as a result of snowmelt or frontal storms, and during summer and fall due to rain storms, usually in the lower basin.

Streamflow regulation provided by the main stem reservoirs has practically eliminated flooding between Fort Peck reservoir and the mouth of the Platte River below Omaha, Nebraska. However, large inflows common in the lower basin (Table 2.2), can still cause considerable flooding. This is a result of high local precipitation over tributary areas.

The Missouri basin has experienced three multiple-year droughts. The longest and most severe drought lasted twelve years, from 1929 to 1941. A less severe drought occurred in the 1950s and the most severe drought since the main stem reservoirs became operational took place from 1987 to 1992. Practically every system purpose was affected by the latest drought. Navigation season in the lower basin was shortened and service reduced. Lower reservoir levels have affected recreation, access to water supply intakes, and considerably reduced hydropower capacity. Lower water levels have also reduced wetlands along the river. Given the severity and length of drought events, drought operations are an important issue in the management of the main stem reservoirs (USACE, 1993).

2.2 Current Operations of the Main Stem Missouri River System

The main stem Missouri River system reservoirs began integrated operations in 1954. Early operations were developed after a series of extensive studies concerned with flood control, hydropower production, and water supply for downstream navigation (the authorized purposes of these reservoirs). These studies were among the first to use simulation modeling, a technique that has remained the primary method used in the planning of operations of the main stem system.

Specific guidelines for operations of the main stem reservoirs are published in the Master Water Control Manual for the Missouri River Main Stem Reservoir System (USACE, 1979) and summarized elsewhere (USACE, 1992b). The first master control manual was published in 1960. The manual was revised and updated twice, with updated versions published in 1975 and 1979.

Several simulation models are used in the main stem system operating studies. A monthly simulation model is used for long and medium term planning, while for streamflow routing and hydropower operations, a daily model is used.

The hydrologic records for the system start in 1898 and includes three multi-year droughts and several major flood events. Water supply and drought operations are tested for the longest and most severe drought in record, the 1930s drought, while flood operations are based on the reconstructed 1881 flood. This flood was used to establish reservoir size of flood control pools.

Current operation policies arise from the system's priorities, which are described in the present master manual as follows (USACE, 1979; USACE, 1992b):

1. flood control,
2. upstream Irrigation and other consumptive uses,
3. downstream municipal and industrial water supply and water quality,
4. releases from Gavins Point for hydropower and navigation,
5. hydropower, and
6. recreation, fish, and wildlife.

Current operating plans for the main stem system subdivides each of the six main stem reservoirs into four operational zones or pools.

2.2.1 Exclusive Flood Control

This top pool in each reservoir is reserved exclusively for flood control. This pool is kept empty and only used to store extreme or unpredictable flows. This pool must be vacated as quickly as downstream channels capacity allow. Six percent of the main stem storage is exclusive flood control.

2.2.2 Flood Control and Multiple Use

This second highest pool is the normal operating zone of each reservoir, within which the annual drawdown-refill cycle is to occur. Reservoir storage should fluctuate within this zone, with storage being made available to capture the high spring and summer inflows and then released to satisfy downstream purposes. This zone accounts for approximately sixteen percent of the total main stem storage.

2.2.3 Carryover and Multiple Use

Consisting of over fifty percent of the total main stem system storage, this pool provides storage that is "carried over" from wet to dry years. Storage within this zone is utilized when flows are insufficient to replenish the multiple-use pool. This pool essentially a drought reserve pool.

2.2.4 Permanent Pool

Storage within the lowest of the four pools is intended to remain inactive. This pool provides a minimum reservoir level for hydropower, sediment storage, recreation, fish and wildlife, and assures a minimum level for pump diversion. Approximately twenty-seven percent of the total main stem storage is contained in this pool.

Capacity within each pool for all reservoirs is presented in Table 2.3.

Table 2.3
Main Stem Reservoirs Pool Allocation (MAF)

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

2.3 Main Stem Releases to Lower Basin

2.3.1 Navigation Releases

The navigation season runs from April 1 through November, possibly extending to December 15 if system storage is sufficient and channel is free of ice. Reservoir system releases for navigation are based on total system storage and are determined twice a year, on March 15 and July 1. Depending on the total storage in the system on these two dates, the navigation season may be either shortened or lengthened, or the average release rate increased or decreased. Releases vary linearly from no navigation service releases when the total storage approaches the permanent pool to full service, when the total system storage is greater than 54.5 MAF in March and 59 MAF in July.

The length of the navigation season is determined on July 1. Assuming that the navigation season begins on April 1, the length of the navigation season varies from eight months if the system storage on July 1 is greater than 41 MAF to five and a quarter months if the storage is between 18.3 and 25 MAF. If the total system storage is less than 18.3 MAF, navigation releases are not made. It is generally thought, however, six months is the minimum navigation season length for economic viability of commercial shipping firms operating on the Missouri River.

2.3.2 Flood Control Operations

Flood control considerations in system releases vary seasonally. During winter months ice cover can substantially reduce channel capacities and thus reservoir releases. Releases downstream of Gavins Point vary from 15,000 cfs (0.9 MAF/month) under severe ice conditions to 23,000 cfs (1.4 MAF/month) during relatively ice-free winter periods.

Release restrictions during winter months imply that the flood control and multiple use pool must be vacated before the onset of severe winter conditions, generally by the beginning of December. During spring and summer periods, flooding can be caused by snow melt or large localized rain storms. Flood control pools are used to regulate flood flows in downstream channels.

2.3.3 Water Supply, Hydropower, and Water Quality

Water supply releases are such that river stages must be kept above water supply intake levels and also provide enough water for withdrawals. Year round minimum required releases range from 6,000 and 10,000 cfs (0.36 to 0.6 MAF/month). There are no specific hydropower releases. Releases for all other purposes are routed through turbines to generate power. Peak hydropower demand in summer is generally satisfied by navigation releases. Water quality control concerns, downstream of the reservoir system, are dissolved oxygen concentration and dilution of heat generated at downstream thermal power plants. Both concerns are adequately addressed by the minimum required release to maintain water levels above water supply intakes.

2.4 Operation Rules within the Reservoir System

Allocation of water among the main stem reservoirs results from a number of considerations. First, once water encroaches exclusive flood control pools it must be evacuated as quickly as possible. Flood control and multi-purpose pools must be vacated by March 1 to capture high spring and summer inflows. However, because of loss of channel capacity due to winter ice, this pool must be emptied before ice is formed on the channels.

Flood storage in the upper three reservoirs is generally used more than that in the lower three reservoirs. This allows not only for re-regulation of releases by lower reservoirs but also for greater hydropower head in lower reservoirs. There is a tendency to keep the upper three reservoirs "in balance".

Releases from the reservoirs are such that permanent pools remain full to provide recreation and minimum head for hydropower.

Navigation releases provide the system's hydropower during spring, summer, and fall. During winter months hydropower releases are made primarily from Fort Peck, Garrison, and to a lesser extent Oahe. These releases also serve the purpose of filling Oahe for use in the following navigation season.

During the fall navigation season, releases from Oahe and Big Bend are reduced so that Fort Randall is drawn down into the carryover storage zone. Upstream releases during the off-navigation season later replenish Fort Randall and as a result hydropower production is shifted from fall to winter.

From all main stem reservoirs there are minimum release requirements that ensure channel stages between reservoirs are kept above water supply intakes.

Spawning of fish and nesting of birds is encouraged by raising reservoir levels during specific seasons in different years for each reservoir.

2.5 Previous HEC-PRM Missouri River System Studies

Operation problems caused by the latest drought have prompted USACE, in conjunction with its Missouri River Division (CEMRD), to review and update the Master Water Control Manual, the basic document for operating the Missouri River System. The objective of this effort is to determine whether current operation plans can be improved to better meet the system's objectives. As part of this effort, HEC developed and applied a network flow model, HEC-PRM. Detailed description of HEC-PRM can be found in USACE publications (1991, 1992a, and 1992b).

In Phase I of the Missouri River study (USACE 1991), preliminary penalty functions were formulated and used in a minimum-cost network flow model (HEC-PRM) that was developed and applied to the Missouri River system on a trial basis. HEC concluded that a network flow model is an appropriate tool for the analysis of the Missouri River main stem reservoir system, because it satisfies institutional, economic, environmental, and engineering criteria (USACE, 1991).

In the Phase II of the Missouri River system study, the system was expanded to include the confluence of the Missouri and the Mississippi rivers at St. Louis and the hydrologic record was extended to 92 years (1898-1990) (USACE, 1992a). A penalty function representing Mississippi River navigation impacts was added in this study and it was found that the impact of this penalty function was minimal. The extended hydrologic record used in Phase II includes two major droughts and numerous flood events.

As part of the Phase II study, the penalty functions were to be refined to better reflect all the system's purposes. This updating of penalty functions was not accomplished. Most notable is the lack of penalty functions for ice-related flooding, a significant problem in the main stem Missouri River. Ice cover that often occurs during the winter months, considerably reduces channel capacity in the main stem Missouri River system and consequently allowable releases from reservoirs. Exclusion of ice-related penalty functions from the Phase I study resulted in HEC-PRM reservoir releases during winter months that are considerably greater than those allowed in practice.

An extension of the Phase II activities was the recommendation of procedures for developing operation plans for the Missouri River system from HEC-PRM results. This study was initiated by Lund (USACE, 1992b) and is concluded as documented in the present report. An "informal, yet systematic" procedure was used to infer operating rules from HEC-PRM results. Results were reviewed graphically with time series plots and histograms. With these basic graphing tools, patterns were identified in HEC-PRM results. Optimal monthly storage levels were identified for the lower three reservoirs and storage allocation rules for the upper three reservoirs.

Once storage target rules for the lower three reservoirs, and storage allocation rules for the upper three reservoirs are defined, system's operation rules are complete if releases rules from either Oahe or Gavins Point can be determined. The determination of Oahe releases and testing and refining of rules with a simulation model are the subject of this report.

Chapter 3

Monthly Operating Rules

3.1 Method of Derivation

The main difficulty in trying to infer operating rules from the results of HEC-PRM is that, being a deterministic optimization model, HEC-PRM solves for optimal reservoir releases with a perfect knowledge of all future flows into the system. This, of course, is not the case with actual real time operations. The challenge then is to try to develop near-optimal operating rules triggered only with knowledge of past and present system conditions.

Existing literature on development of reservoir operating rules from optimization models is limited to very simple systems, generally consisting of a single reservoir with not more than two types of demands or purposes. For such simple cases, a combination of optimization, regression and simulation has been a successful methodology. However, the main stem Missouri River System is comprised of six reservoirs serving multiple purposes, a feature which translates into a much more complex objective function for the optimization model and, consequently, optimal releases which are considerably more difficult to analyze.

Not unlike the procedure employed in the Preliminary Results study (HEC, 1982), the method employed in the derivation of operating rules for the Missouri River System is a systematic search of trends and patterns. Descriptive statistical measures are used as a first tool in detecting such trends in the data. In analyzing the data, potential relationships are explored by producing charts involving variables for which relationships are thought to exist. The search is for relationships between the many variables of the system and to what extent the HEC-PRM operations can be mimicked with only a knowledge of the past and the present without knowledge of future flows.

This search for relationships amongst the variables is greatly aided by a knowledge of the characteristics of the system. For instance, given that large flows due to snowmelt and precipitation are common occurrences in the spring and early summer months, it is reasonable to expect that reservoir releases will be reduced when flows in the downstream tributaries are excessive.

The data used in the search for operating rules include the system's inflows, optimal storages and releases for each reservoir and optimal flows at the downstream nodes. The time-series of inputs and outputs from HEC-PRM were sorted into monthly sets so that monthly operations could be investigated. These data sets were manipulated with the statistical package MINITAB© and the spreadsheet package EXCEL.

3.2 Storage Target Rules for the Lower Three Reservoirs

From the Phase I HEC-PRM results for the Missouri River System, the lower and smaller three reservoirs, Big Bend, Fort Randall and Gavins Point proved to be the most consistent and thus the easiest from which to develop operating rules. For each of the three reservoirs the storage remained practically constant within each month through the first ninety years for which the model was run. This can be observed in storage histograms for these reservoirs and typical histograms are shown in Figures 3.1, 3.2, and 3.3. The variability in storage was greatest for Fort Randall (the largest of the lower three reservoirs) for the month of August.

The rule suggested is, therefore, a monthly target storage for each reservoir, and is presented in Table 3.1.

Table 3.1
Target Monthly Storages for Big Bend, Fort Randall, and Gavins Point (KAF)

Month	Big Bend	Fort Randall	Gavins Point
January	1,693	3,310	431
February	1,696	3,313	432
March	1,696	3,313	432
April	1,696	3,313	430
May	1,725	3,313	432
June	1,720	4,133	372
July	1,721	4,126	372
August	1,712	4,115	429
September	1,711	4,114	429
October	1,712	4,115	430
November	1,718	4,150	430
December	1,717	3,305	430

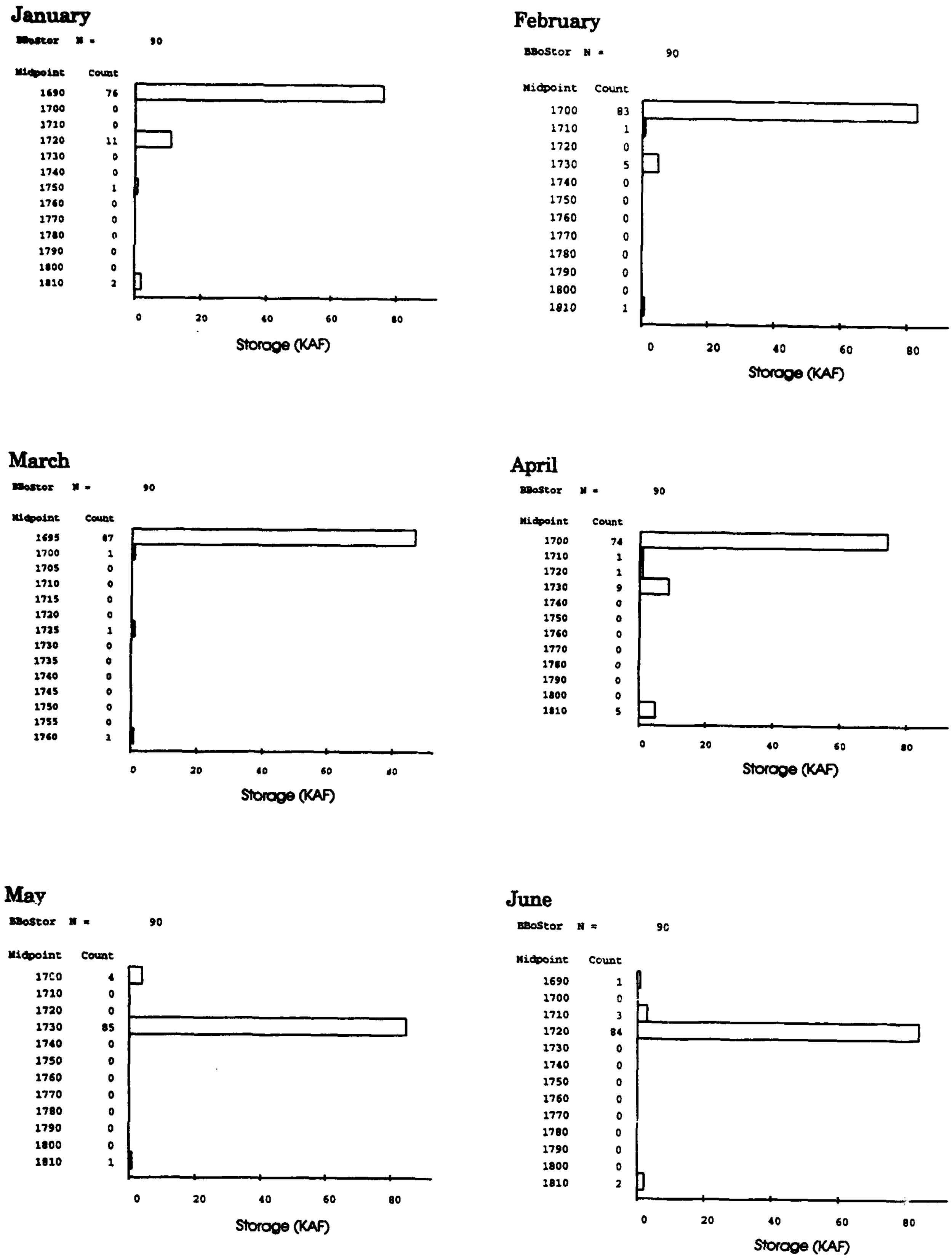


Figure 3.1 Monthly Storage Histograms for Big Bend Reservoir

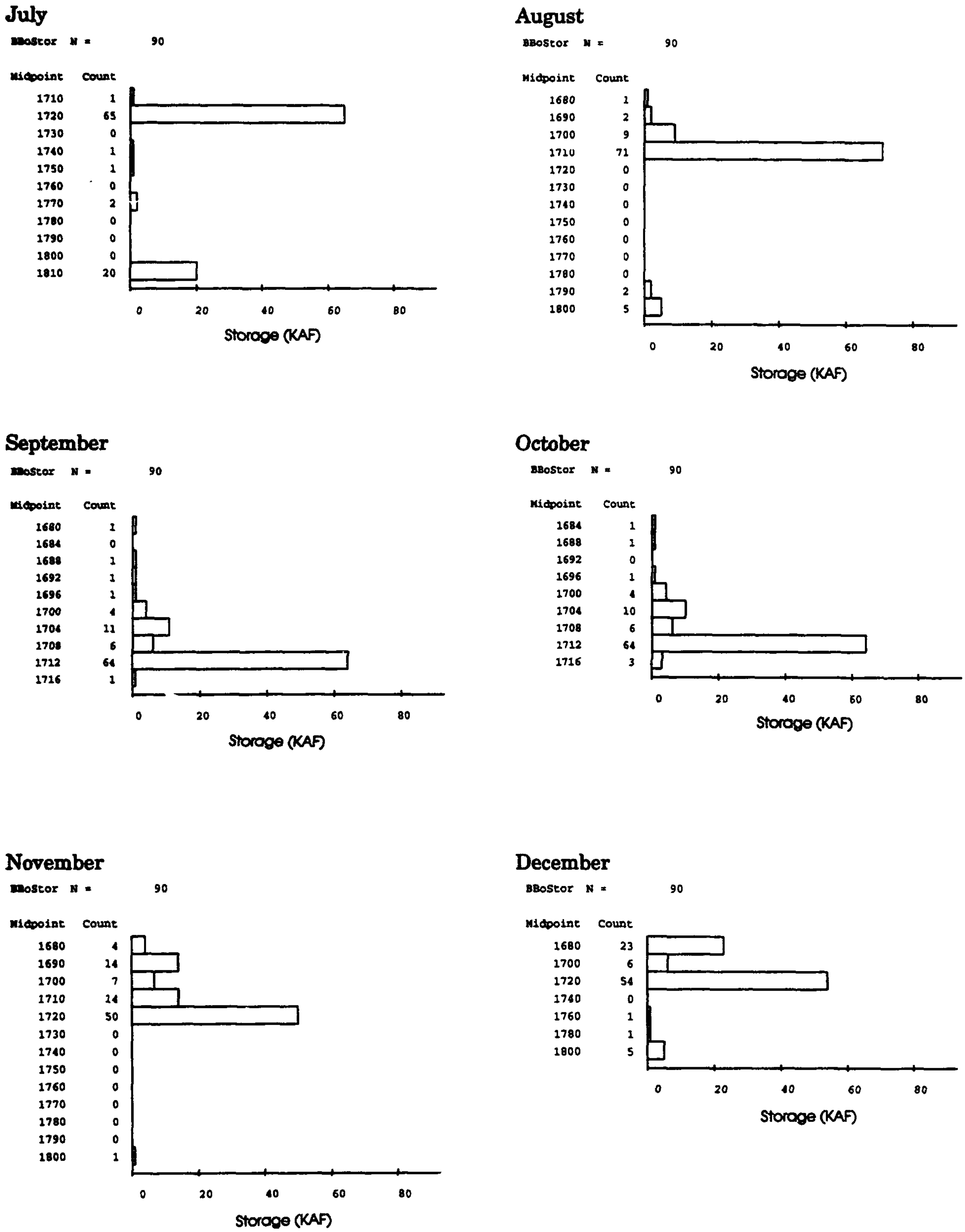


Figure 3.1 Monthly Storage Histograms for Big Bend Reservoir (continued)

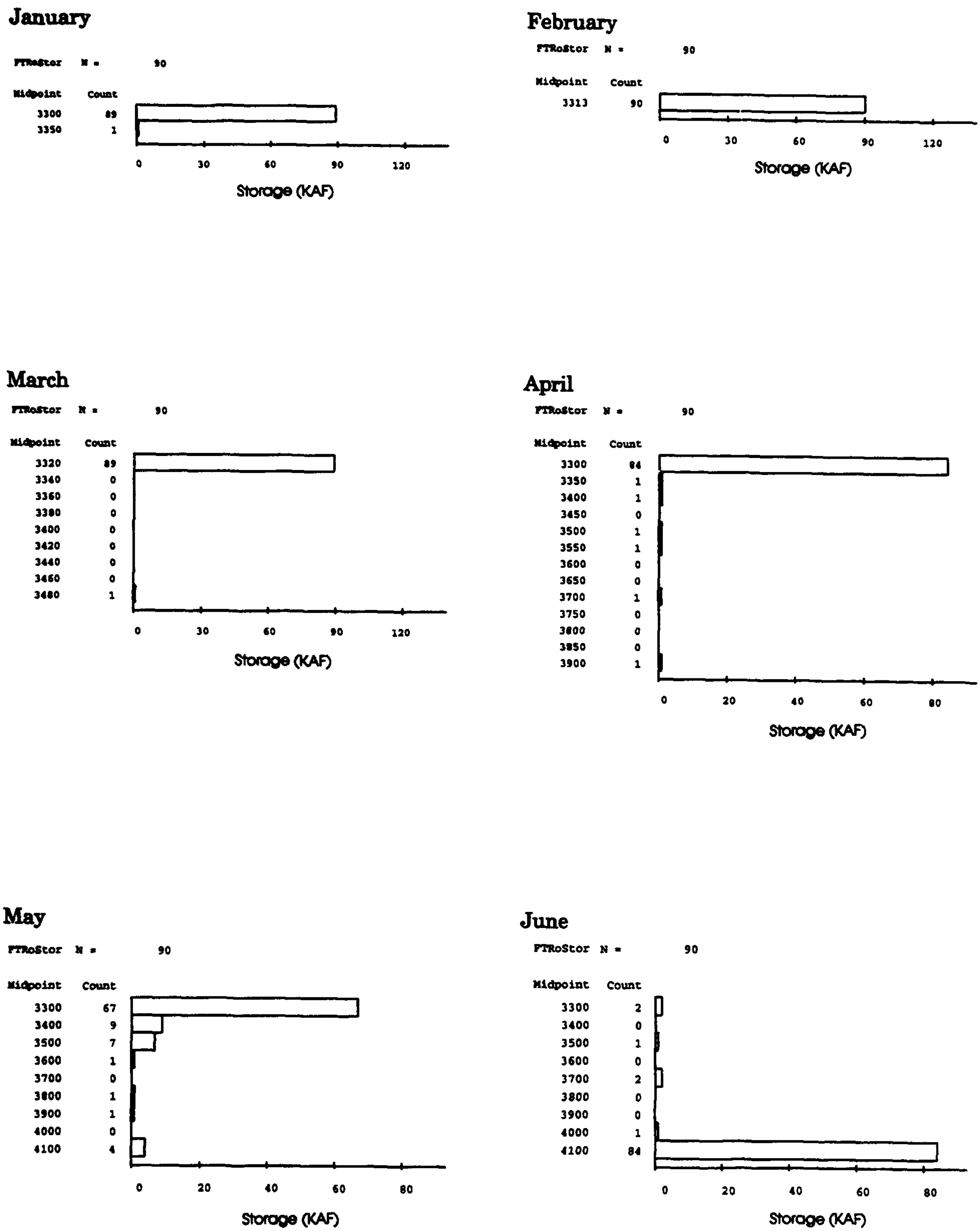


Figure 3.2 Monthly Storage Histograms for Fort Randall Reservoir

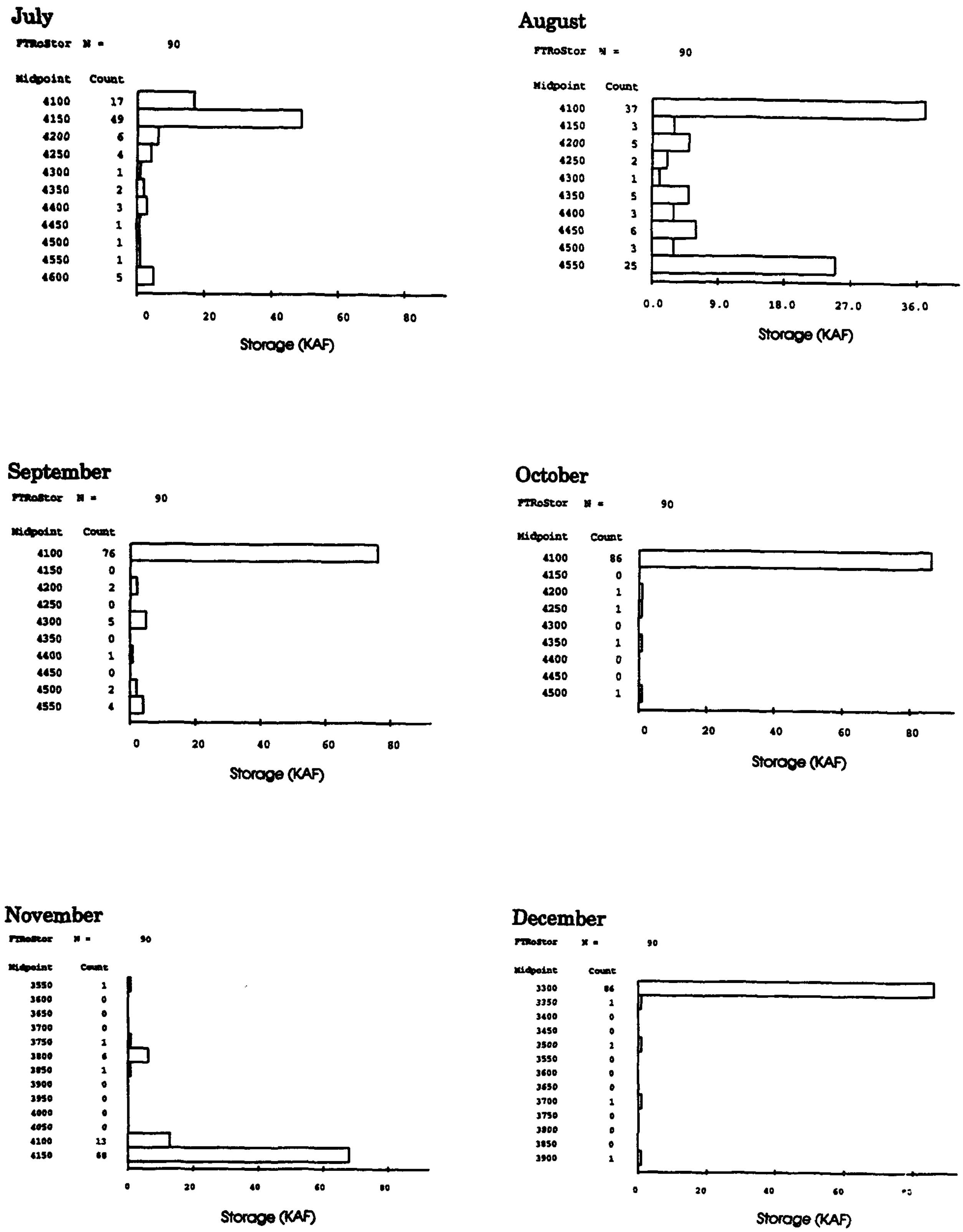


Figure 3.2 Monthly Storage Histograms for Fort Randall Reservoir (continued)

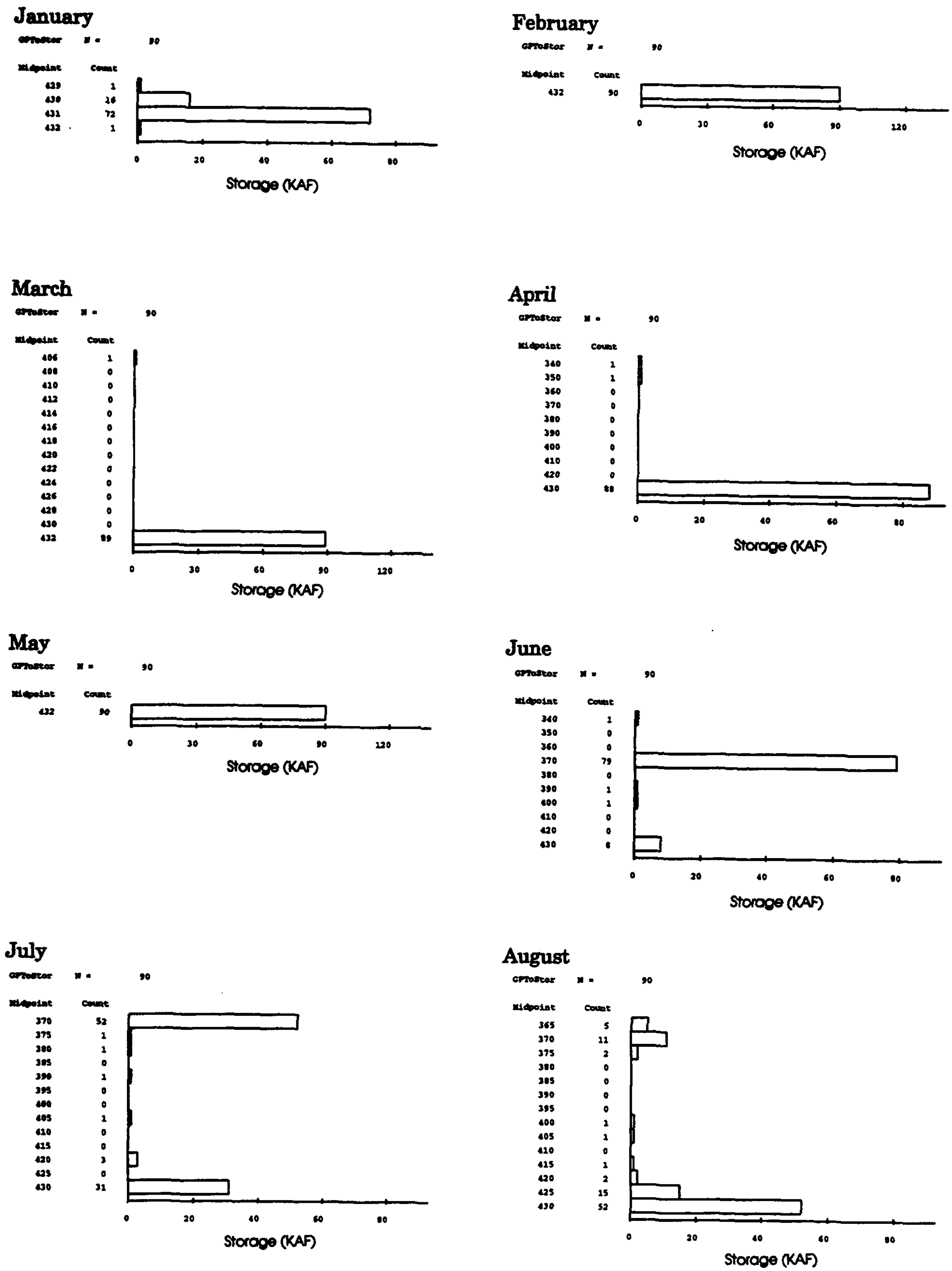


Figure 3.3 Monthly Storage Histograms for Gavins Point Reservoir

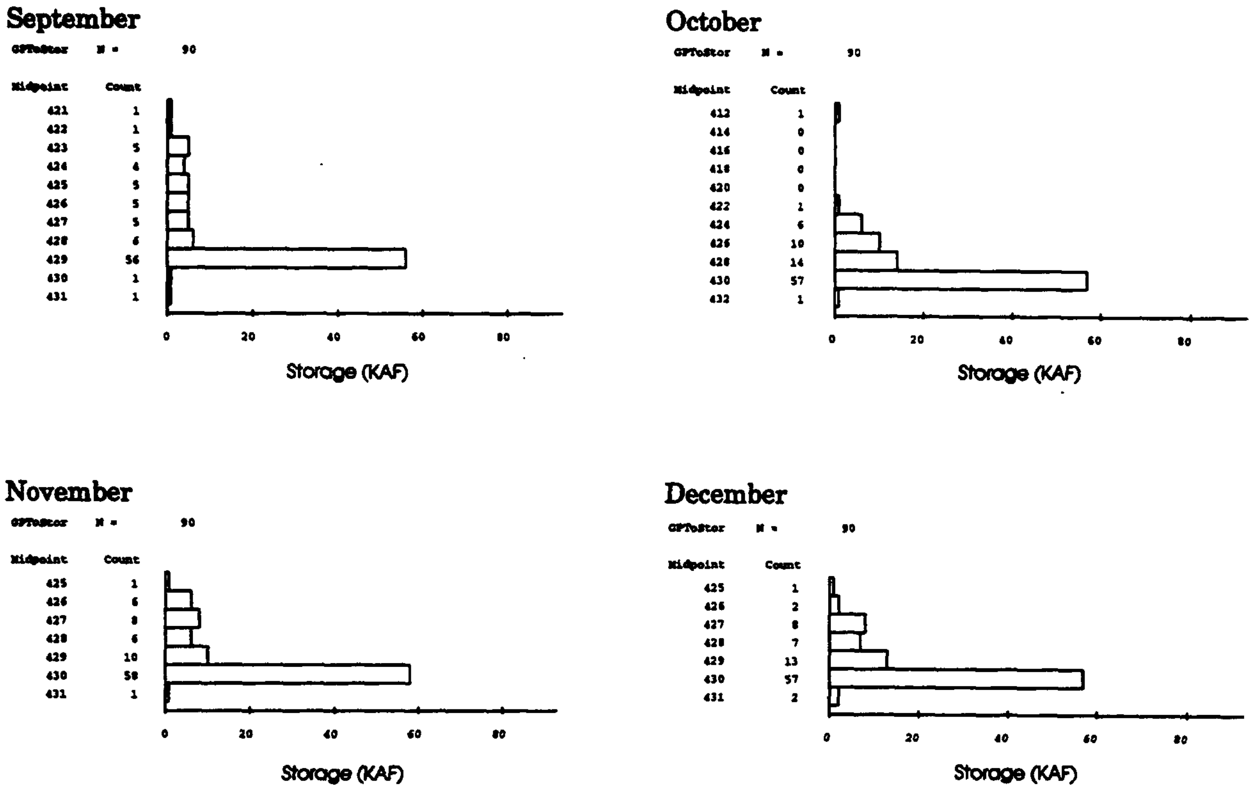


Figure 3.3 Monthly Storage Histograms for Gavins Point Reservoir (continued)

3.3 Storage Allocation Rule for the Upper Three Reservoirs

Unlike the lower three reservoirs, HEC-PRM monthly storages varied over a large range for Fort Peck, Garrison and Oahe reservoirs. Attempts at finding significant statistical correlation between monthly storages, inflows, and releases were unsuccessful.

The most interesting pattern observed for Fort Peck, Garrison and Oahe is the monthly storage allocation amongst these reservoirs. Figures 3.4 through 3.15, shows the storage of each of the three reservoirs against their combined storage, which clearly illustrate this pattern.

This conspicuous storage allocation pattern indicates a differentiation in drawdown rates for the upper three reservoirs. The drawdown rule which is suggested here differs greatly from present operations in which all three reservoirs are drawn at the same rate. HEC-PRM output suggests that Fort Peck and Garrison are drawn down before Oahe which, in all months except May through July, is kept practically full, with storages ranging from 21.5 to 22.2 MAF. This greater variability of Oahe storage in the spring and early summer months coincides with the time in which runoff resulting from rainstorms and/or rapid snownmelt is the greatest and flooding most likely to occur.

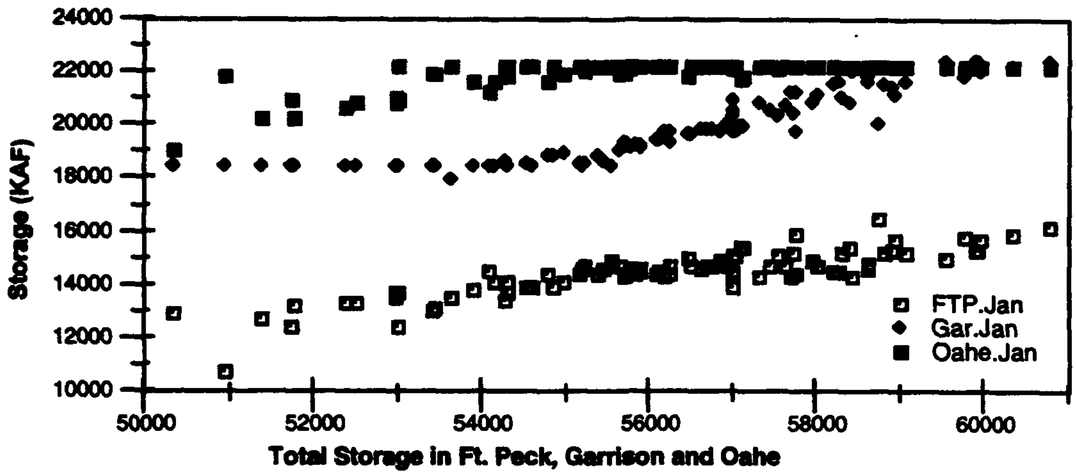
The storage allocation rules for the different months were derived by fitting straight lines to the data. This was achieved by simply drawing lines on the charts of Figures 3.4 through 3.15, estimating two points on this line and finding the equation of the line. All storage units in the allocation rule equations that follow are in MAF, and TS represents the total storage in Fort Peck, Garrison, and Oahe reservoirs.

Another release pattern observed was a maximum release for Fort Peck and Garrison reservoirs. In all twelve months the maximum HEC-PRM release from Fort Peck is 847 thousand acre-feet (KAF) per month and from Garrison 1,823 KAF/month. These maximum release values are included in the release rules and are exceeded only when necessary to ensure that storage does not exceed maximum storage.

3.4 Rules for Releases from the System

Given that monthly storages in the lower three reservoirs are fairly constant, the problem of deriving operating rules is reduced to the upper three reservoirs. Because there appears to be a very clear pattern of allocating storage amongst the upper three reservoirs, the problem is further reduced to that of establishing Oahe releases, thereby treating the upper three reservoirs as a control volume.

Attempts at using statistical methods to relate reservoir releases to any other characteristic of the system proved to be of limited use. This is not only because HEC-PRM takes into account future flows, but also because a certain range of releases

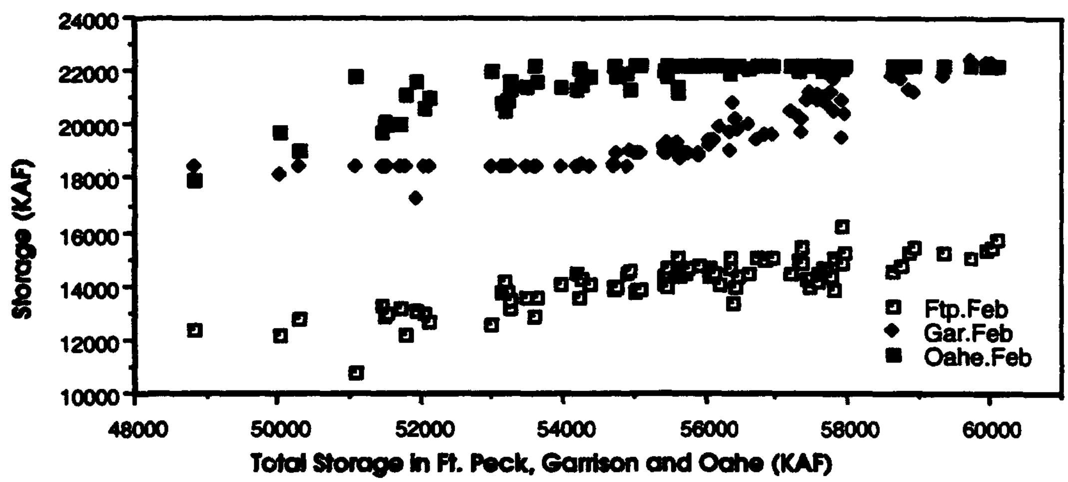


Oahe: If TS < 54.3 then Oahe Storage = 0.667 * TS -14.0 else Oahe Storage = 22.2.

Garrison: If TS < 55.0 then Garrison Storage = 18.5
else if TS < 59.6 then Garrison Storage = 0.841 * TS -27.8
else Garrison Storage = 22.2.

Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.4 January Storage Allocation Among Fort Peck, Garrison, and Oahe

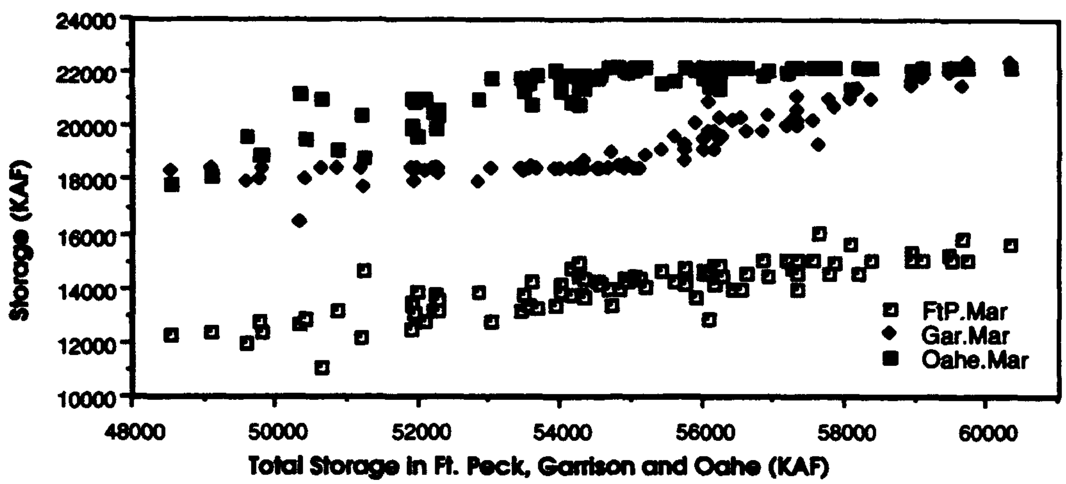


Oahe: If TS < 55.0 then Oahe Storage = 0.636 * TS -12.8 else Oahe Storage = 22.2.

Garrison: If TS < 55.0 then Garrison Storage = 18.5.
else if TS < 59.8 then Garrison Storage = 0.781 * TS - 24.5.
else Garrison Storage = 22.2.

Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.5 February Storage Allocation Among Fort Peck, Garrison, and Oahe

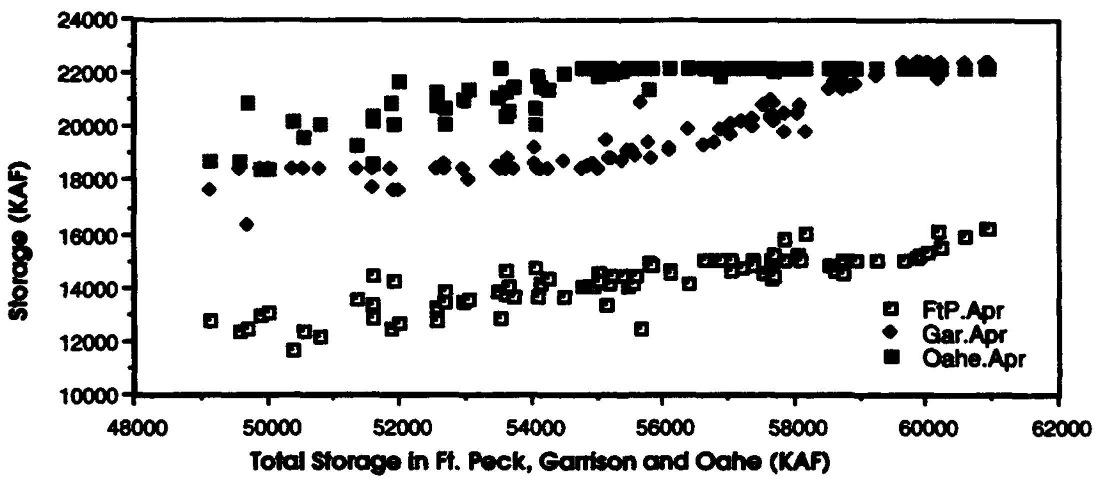


Oahe: If TS < 54.7 then Oahe Storage = 0.625 * TS -12.0 else Oahe Storage = 22.2

Garrison: If TS < 49.0 MAF then Garrison Storage = 0.136 * TS +11.8
else if TS < 54.9 then Garrison Storage = 18.5
else if TS < 59.8 then Garrison Storage = 0.779 * TS - 24.3
else 22.3

Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.6 March Storage Allocation Among Fort Peck, Garrison, and Oahe

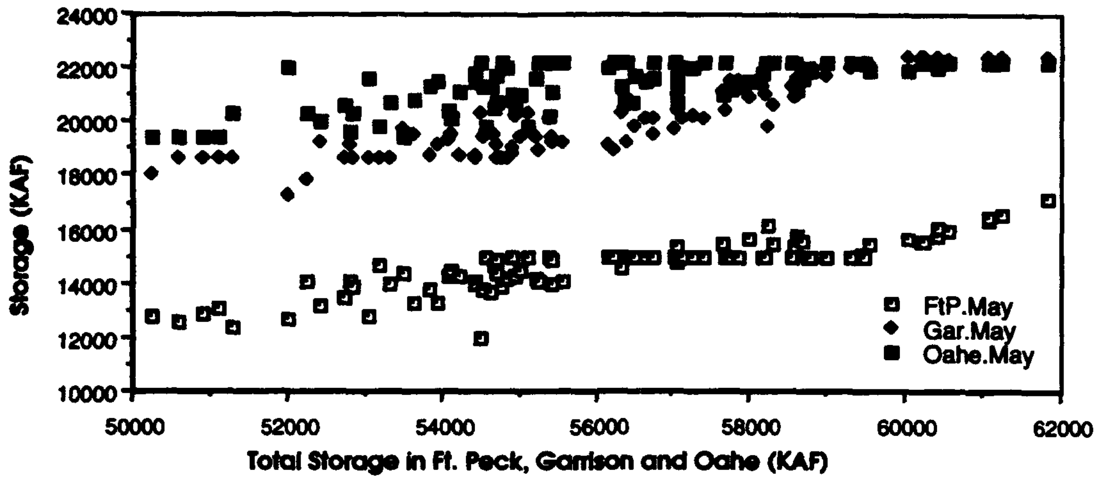


Oahe: If TS < 54.80 then Oahe Storage = 0.624 * TS - 11.9 else Oahe Storage = 22.2

Garrison: If TS < 59.9 then Garrison Storage = 18.5
else if TS < 59.8 then Garrison Storage = 0.806 * TS - 25.9
else Garrison Storage = 22.4

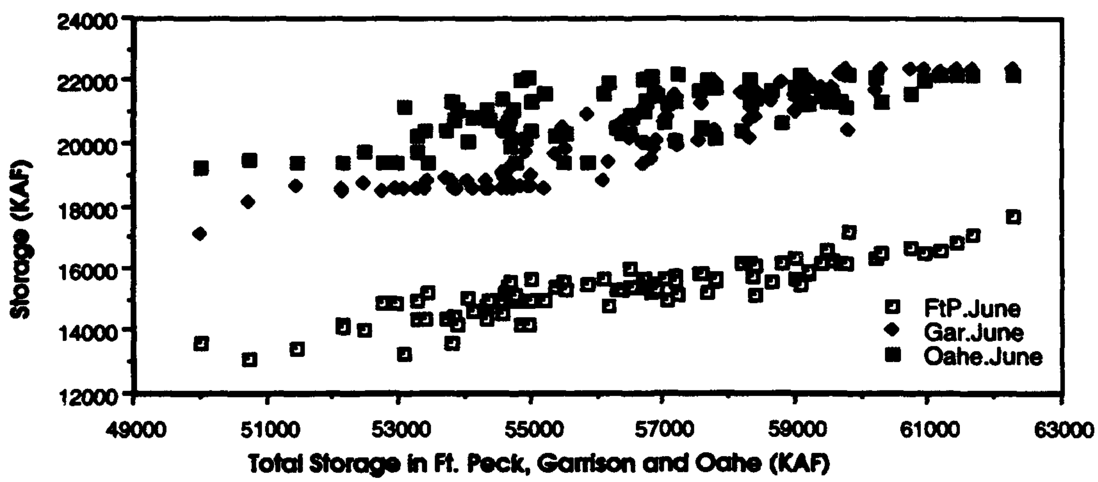
Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.7 April Storage Allocation Among Fort Peck, Garrison, and Oahe



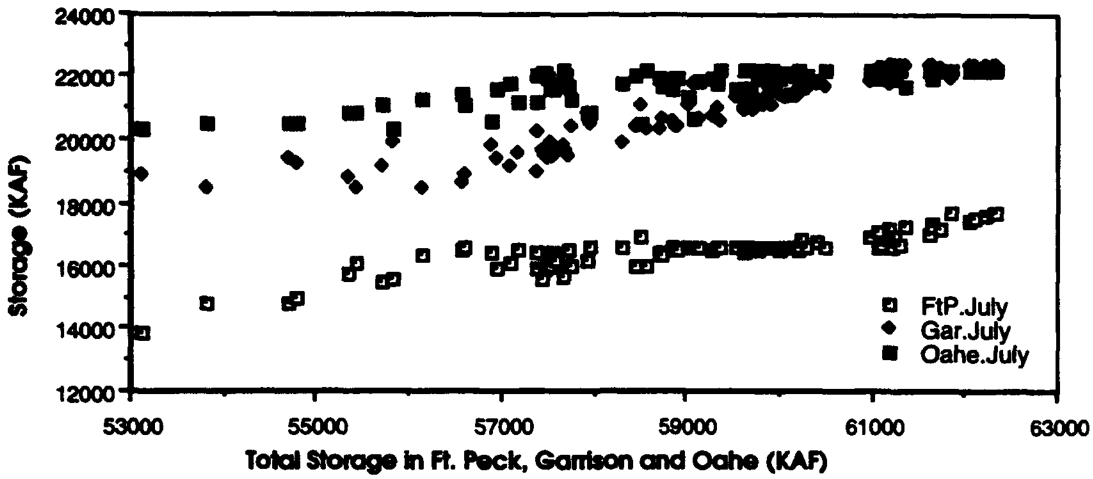
Oahe: TS - (Oahe Storage + Garrison Storage)
Garrisonn: If TS < 54.80 then Garrison Storage = 18.6
else if TS < 60.0 then Garrison Storage = 0.731 * TS - 21.5
else Garrison Storage = 22.4.
Fort Peck: If TS < 56.2 then Fort Peck Storage = 0.403 * TS - 7.8
else if TS < 59.5 then Fort Peck Storage = 14.9
else Fort Peck Storage = 0.938 * TS - 40.8

Figure 3.8 May Storage Allocation Among Fort Peck, Garrison, and Oahe



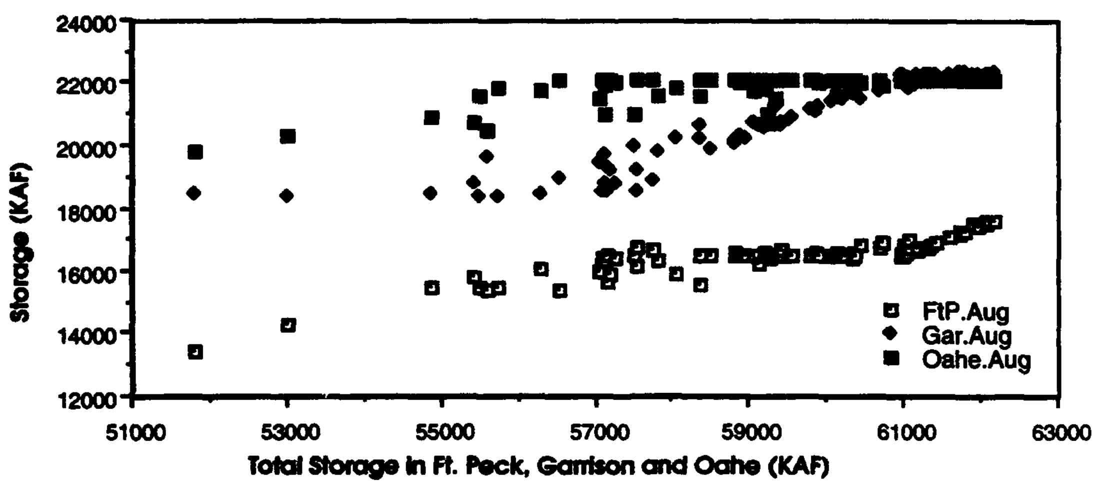
Oahe: TS - (Oahe Storage + Garrison Storage)
Garrison: If TS < 51.2 then Garrison Storage = 0.977 * TS - 31.4
else if TS < 55.0 then Garrison Storage = 18.6
else if TS < 59.4 then Garrison Storage = 0.864 * TS -28.9
else Garrison Storage = 22.4.
Fort Peck: If TS < 61.0 then Fort Peck Storage = 0.254 * TS + 0.95
else Fort Peck Storage = 0.875 * TS - 36.9

Figure 3.9 June Storage Allocation Among Fort Peck, Garrison, and Oahe



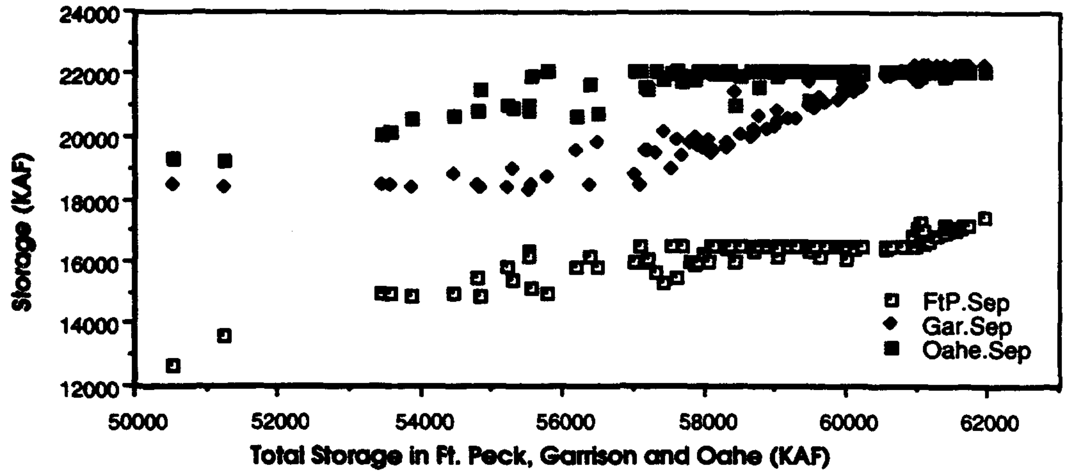
Oahe: TS - (Oahe Storage + Garrison Storage)
Garrison: If TS < 56.2 then Garrison Storage = 18.5
else if TS < 61.3 then Garrison Storage = 0.765 * TS - 24.5
else Garrison Storage = 22.4
Fort Peck: If TS < 56.5 then Fort Peck Storage = 0.714 * TS - 23.9
else if TS < 60.5 then Fort Peck Storage = 16.5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

Figure 3.10 July Storage Allocation Among Fort Peck, Garrison, and Oahe



Oahe: TS - (Oahe Storage + Garrison Storage)
Garrison: If TS < 56.8 then Garrison Storage = 18.4
else if TS < 61.0 then Garrison Storage = 0.929 * TS - 34.3
else Garrison Storage = 22.3
Fort Peck: If TS < 56.50 then Fort Peck Storage = 0.55 * TS - 15.0
else if TS < 61.0 then Fort Peck Storage = 16.5
else Fort Peck Sotrage = TS - 44.6

Figure 3.11 August Storage Allocation Among Fort Peck, Garrison, and Oahe

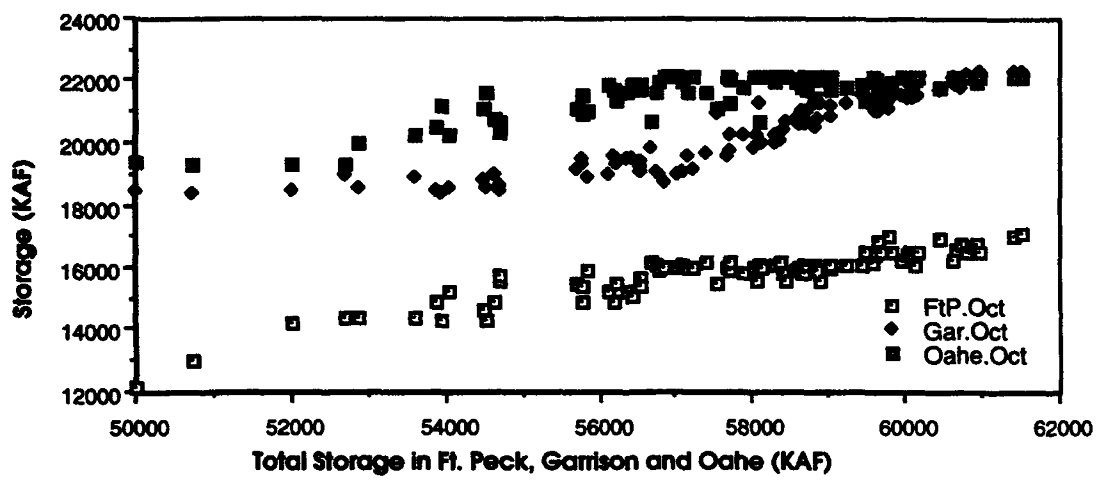


Oahe: If TS < 51.20 then Oahe Storage = 19.6
else if TS < 57.6 then Oahe Storage = 0.445 * TS - 3.6
else Oahe Storage = 22.2

Garrison: If TS < 57.0 then Garrison Storage = 18.3
else if TS < 61.0 then Garrison Storage = TS - 38.7
else Garrison Storage = 22.3

Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.12 September Storage Allocation Among Fort Peck, Garrison, and Oahe

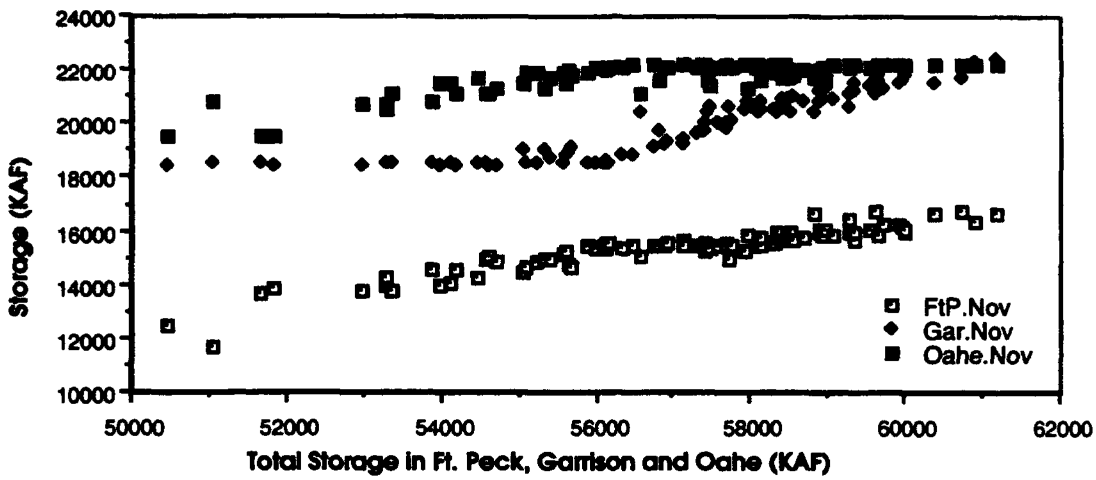


Oahe: If TS < 52.4 then Oahe Storage = 19.4
else if TS < 57.0 then Oahe Storage = 0.585 * TS - 11.3
else Oahe Storage = 22.2

Garrison: If TS < 57.0 then Garrison Storage = 0.103 * TS - 13.2
else if TS < 60.8 then Garrison Storage = 0.84 * TS - 28.9
else Garrison Storage = 22.3

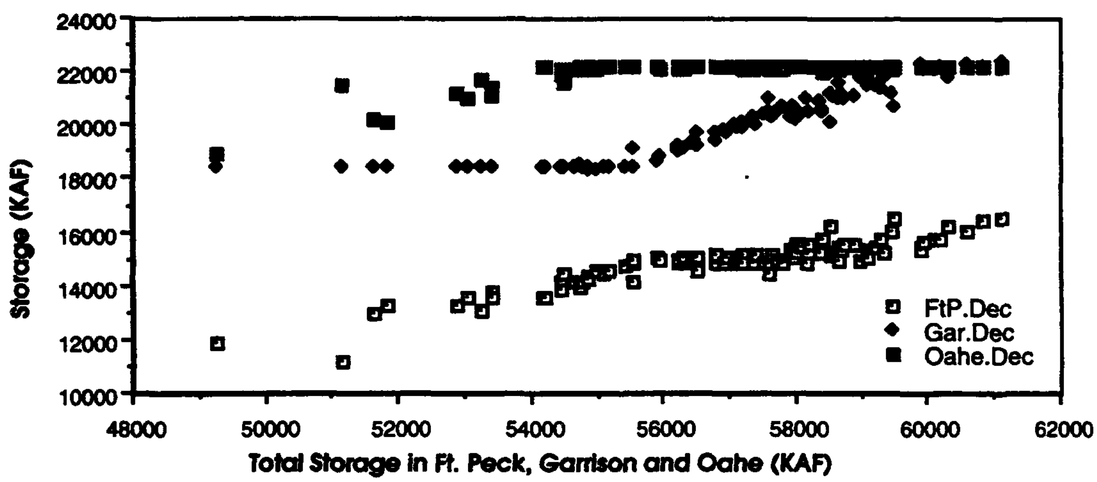
Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.13 October Storage Allocation Among Fort Peck, Garrison, and Oahe



Oahe: If TS < 56.0then Oahe Storage = 0.492 * TS - 5.4 else Oahe Storage = 22.2
Garrison: If TS < 56.1 then Garrison Storage = 18.4
else if TS < 57.9 then Garrison Storage = TS - 37.7
else if TS < 60.9 then Garrison Storage = 0.72 * TS - 21.5
else Garrison Storage = 22.4
Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.14 November Storage Allocation Among Fort Peck, Garrison, and Oahe



Oahe: If TS < 54.5 then Oahe Storage = 0.59 * TS - 10.0 else Oahe Storage = 22.2.
Garrison: If TS < 55.6 then Garrison Storage = 18.2
else if TS < 60.0 then Garrison Storage = 0.948 * TS - 34.5
else Garrison Storage = 22.4
Fort Peck: TS - (Oahe Storage + Garrison Storage)

Figure 3.15 December Storage Allocation Among Fort Peck, Garrison, and Oahe

from Oahe can be due to distinct factors. For instance, depending on the month, low releases can be due to either low inflows due to drought or as a flood control measure against high inflows downstream. On the other hand, however, high inflows into the upper three reservoirs or low downstream inflows do not necessarily result in higher releases.

Because Oahe is kept full most of the time, a large number of releases from it are spills. The highest number of spills occur in November, when spills occur in sixty-four percent of the periods. Attempts at linking Oahe releases to storage of any of the upper three reservoirs were largely unsuccessful.

Of the full set of ninety years of model output, releases from Oahe were the simplest to analyze in years of drought or floods. During fall and winter months, low releases from Oahe generally occur when inflow into the upper three reservoirs is low. This pattern can be seen in the time-series plots of Figures 3.17, 3.19, 3.35, 3.36, and 3.38 representing the months of January, February, October, November, and December, respectively. For these five months, the response of HEC-PRM to low upper basin inflows was consistently one of reducing Oahe release. The model response to the 1930's drought is apparent in these five figures, where both inflow and releases are low. The 1950's drought, a less severe one, is only clearly discernible in the months of January and February.

There were exceptions to this response to low inflows into the upper three reservoirs during the fall and winter months. A stark example is the basinwide flood of 1967. During June and July the inflows into the whole system were so high (upper basin inflow 6,848 and 4,098 KAF/month and lower basin 13,172 and 5,630 KAF/month for June and July respectively), that a high release from Oahe would result in even more severe floods downstream. For this reason, HEC-PRM starts emptying Oahe as early as December, despite the fact that the inflows into the upper three reservoirs are below average. By doing so, storage in Oahe is reduced to 19.5 MAF in the beginning of June and an extremely low release of seven KAF/month is possible that month. Similar patterns can be observed in 1949, 1950 and 1982.

Another consistent pattern in the HEC-PRM results is the response to downstream floods when releases from Oahe are reduced to mitigate flood damages downstream. Although more pronounced in the spring and early summer months, when flows into the downstream nodes are higher due to snowmelt and rainstorms, this pattern can also be observed in the late summer and fall.

Spring and early summer inflows are considerably higher than those of winter and fall months. Consequently, drought releases are not clearly discernible from normal year releases. In fact, the months of March, April, and May proved to be the most difficult to derive any type of Oahe release rule.

The rule derivation method for Oahe releases was somewhat empirical. The patterns described above were noticed in time-series plots of HEC-PRM's Oahe releases and upstream and downstream inflows. As mentioned previously, because correlation and other statistical methods proved fruitless, a spreadsheet listing of data and HEC-PRM output were produced for each month.

Some conspicuous relationships were noticed from these data listings. For instance, when low inflows occur during the fall and winter months, releases from Oahe are set so as to guarantee a minimum flow at Sioux City of 543 KAF/month in January, February and March, 600 KAF/month in September and October, and 574 KAF/month in November and December. These low flows are a reflection of levels below which the penalty function associated with the streamflow at that reach becomes extremely high. During the twelve year long drought of the 1930's, the minimum low flows at Sioux City were met exactly in all twelve years in January and February, in eleven years in March and December, eight years in October and November and, three years in September.

The use of an inexpensive high-lighting pen, greatly aided the identification of tendencies and relationships in HEC-PRM of Oahe release data. Variables that seemed to relate to Oahe releases were sorted in ascending order. For instance, the January spreadsheet was sorted in ascending order of inflows into the upper three reservoirs. All data of a year of low release were then highlighted and other common features then searched.

The development details of specific Oahe release rules for each month follows. Table 3.2 contains notation used in Oahe release rule description.

Table 3.2
Notation

Symbol	Description
(FtP→OAH) Inflow	Combined tributary inflow at all nodes between Fort Peck and Oahe
(FtP→OAH) Inf Dec	Combined tributary inflow at all nodes between Fort Peck and Oahe in previous December
(FtR→SUX) Inflow	Combined tributary inflow at all nodes between Fort Randall and Soux City
(FtR→NEB) Inflow	Combined tributary inflow at all nodes between Fort Randall and Nebraska City
(FtR→KAN) Inflow	Combined tributary inflow at all nodes between Fort Randall and Kansas City
(FtR→HER) Inflow	Combined tributary inflow at all nodes between Fort Randall and Hermann

3.5 January Release Rule for Oahe

3.5.1 Rule Summary

if ((FtP→OAH) Inf Dec<550) and (60<(FtR→SUX) Inf Dec<109)
or ((FtR→HER) Inf Dec<870) and (100<(FtR→SUX) Inf Dec<160)
then Oahe Release = 553 - (FtR→SUX) inf KAF
else if ((FtR→HER) inf<1900) and (800<(FtR→KAN) inf<1100)
then Oahe Release = 1100 KAF
else if ((FtP→OAH) inf<630) then Oahe Release = 553-(FtR→SUX) inf KAF
else 2000

3.5.2 Rule Development

The histogram and time-series plot for HEC-PRM Oahe releases for January (Figures 3.16 and 3.17) indicate five release categories:

1) Drought releases: In the range of 400 to 600 KAF/month.
2) Below normal releases: Between 600 to 1,000 KAF/month.
3) Normal year releases: Approximately ranging from 1,000 to 1,500 KAF/month.

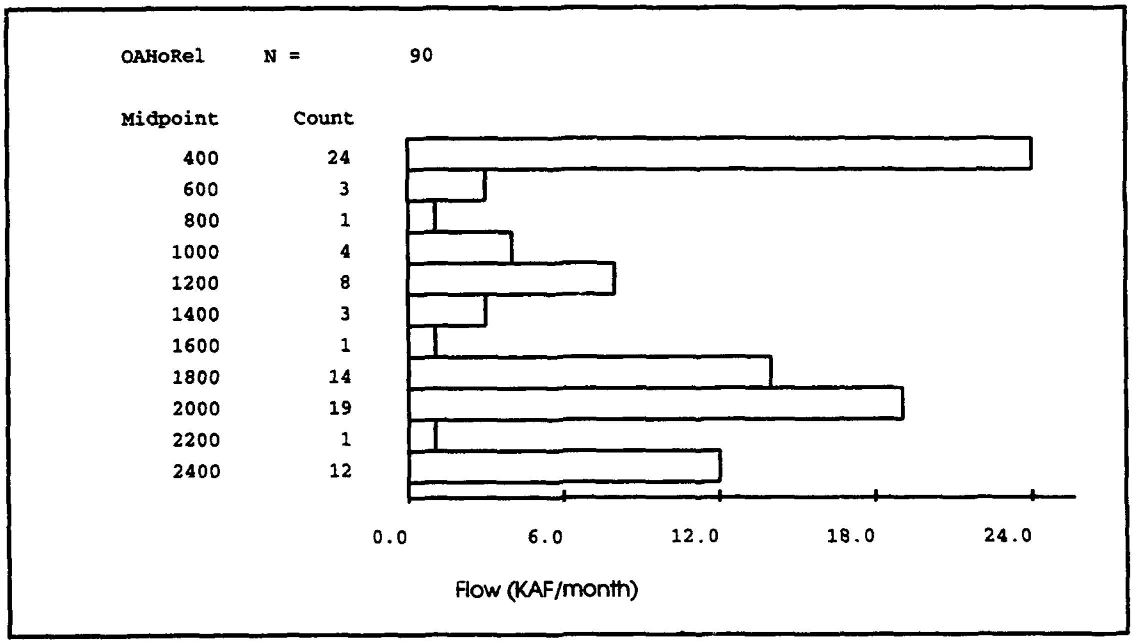


Figure 3.16 Histogram of Oahe Releases for January

4) Above normal future inflows: In the region of 1,600 to 1,900 KAF/month.

5) Great future inflows: Releases generally greater than 1,900 KAF/month.

3.5.3 Drought Releases

Time-series plots of Oahe releases and total inflow into the upper three reservoirs for the month of January (Figure 3.17) depict the two major multiple-year droughts that occurred in the historical period used in this study: the 1930's and the 1950's droughts. Releases during these droughts are clearly lower than in non-drought years. Also noticeable in this figure is that low drought releases generally correspond to low inflows into the upper three reservoirs. This fact is more marked during the 1930's drought which was the most severe of the two droughts.

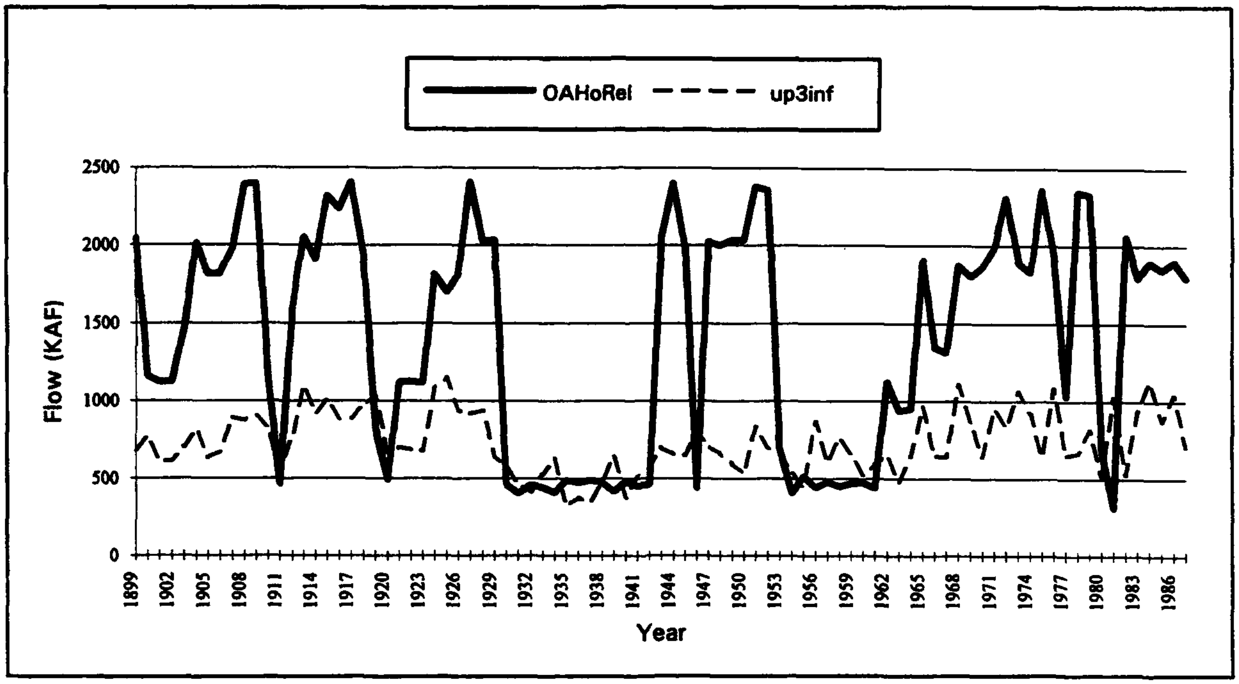


Figure 3.17 Time-Series of Optimal January Releases and Total Inflow Into the Upper Three Reservoirs

Inspection of the numerical data (Table 3.3) confirms this and also shows that optimized releases from Oahe are such that a minimum streamflow of 543 KAF/month is met at Sioux City during droughts. These observations evolved into the following Oahe drought release rule for January:

if (FtP+GAR+OAH) inf < 630 then Oahe Release = (553 - (FtR→SUX) inf) KAF

Unfortunately, not all periods in which the total flow into the upper three reservoirs was less than 630 KAF/month resulted in HEC-PRM drought releases. Likewise, not all drought releases for January are selected with this rule. From Table 3.3, drought releases in 1939, 1956, 1958, 1959, and 1981 are not picked by this rule. Although drought releases in the winter months can usually be related to low

Table 3.3
Numerical Data for January Drought Releases (KAF/month)

Year	OAH opt Release	GPt opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1911	464	537	543	87	546	466	2
1930	462	529	543	89	577	464	2
1931	404	531	543	121	461	432	28
1932	459	523	543	99	415	454	-5
1933	444	533	543	113	527	440	-4
1934	408	531	543	154	627	399	-9
1935	491	537	543	75	326	478	-13
1936	473	543	543	84	376	469	-4
1937	490	543	543	77	352	476	-14
1938	477	541	543	83	476	470	-7
1939	417	525	543	141	645	412	-5
1940	480	543	543	79	380	474	-6
1941	454	513	543	105	508	448	-6
1942	462	537	543	91	573	462	0
1954	405	522	543	146	535	407	2
1955	514	543	543	37	445	516	2
1956	444	512	543	107	869	446	2
1957	480	543	543	71	606	482	2
1958	448	525	543	103	763	450	2
1959	471	538	543	80	660	473	2
1960	477	538	543	74	526	479	2
1961	438	543	543	113	591	440	2
1981	311	438	543	247	1024	306	-5

flows into the upper three reservoirs, there are periods in the beginning or within a drought event when the inflows are not so low and thus escape a low inflow rule. HEC-PRM, on the other hand, evaluates releases with perfect knowledge of all future inflows, and so is able to establish drought releases despite the temporary higher inflow.

In fact, the best indicators of drought conditions were inflow volumes in December. For this reason, December through April release rules use December conditions as an additional indicator of when Oahe release should be reduced to drought levels.

The years 1949, 1950, and 1982 were incorrectly chosen with the January drought rule. Here, HEC-PRM was able to look into the future and spot large inflows into the upper three reservoirs. Despite very low inflows during January in 1949, 1950 and 1982, HEC-PRM released large volumes of water from Oahe to make extra storage available to capture high flows during the upcoming spring months. All optimized January releases above 1,800 KAF/month, totaling forty-six years, are for flood control later in the year.

3.5.4 Normal Releases

Since the majority of the releases fall in a high release bracket, an attempt was made to determine a release rule for the 'normal' year release. It was noticed that the majority of releases in the 'normal' range had a corresponding total inflow into the upper three reservoirs in the range 600 to 700 KAF/month; a range which includes the median of the combined inflow into the upper three reservoirs which is 680 KAF/month. There were, however, many flood control releases with total upstream inflow in this range. Upon close observation of the numerical data, a rule which correctly selects nine of the sixteen releases in this range and does not include any incorrect selections was:

if ((FtR→HER) inf<1900) and (800<(FtR→KAN) inf<1100) then Oahe Release = 1100 KAF

These releases seem to be made so as to guarantee a flow of approximately 1,230 KAF/month at Sioux City. Data from which this rule was derived is included in Table 3.4.

Table 3.4
Numerical Data for January Normal Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1900	1,160	1,234	978	1,351	769	1,100	-60
1901	1,124	1,230	982	1,655	610	1,100	-24
1902	1,124	1,216	1,055	1,294	614	1,100	-24
1921	1,124	1,226	978	1,351	703	1,100	-24
1922	1,126	1,208	58	1,531	686	1,100	-26
1923	1,120	1,230	886	1,659	679	1,100	-20
1964	950	1,272	816	970	642	1,100	150
1966	1,347	1,641	895	1,881	648	1,100	-247

Because all remaining releases are dependent on future flows, and thus cannot be triggered by either present or past conditions, the rule for the remaining years is simply:

else Oahe Release = 2000 KAF

3.6 February Release Rule for Oahe

3.6.1 Rule Summary

If ((FtP→OAH) Inf Dec<550) and (50<(FtR→SUX) Inf Dec<109) or
((FtR→HER) Inf Dec<870) and (100<(FtR→SUX) Dec<160)
then Oahe Release = 543-(FtR...SUX) inf KAF
else if (FtP→OAH) inf<565) or ((FtP→OAH) inf<730) and
(160<(FtR→SUX) inf<190)) then Oahe Release = 543-(FtR→SUX) inf
else if (1500<(FtR→HER) inf<2050) and (180<(FtR→SUX) inf<280)
then Oahe Release = 1055 KAF
else if ((FtR→HER) inf<1230) and ((FtR→NEB) inf>400) then Oahe Release = 1000 KAF
else Oahe Release = 2000 KAF

3.6.2 Rule Development

The pattern of Oahe releases in February nearly mimics that of January. Both the histogram (Figure 3.18) and the time-series plot of Oahe releases (Figure 3.19) are very similar to the corresponding figures for January.

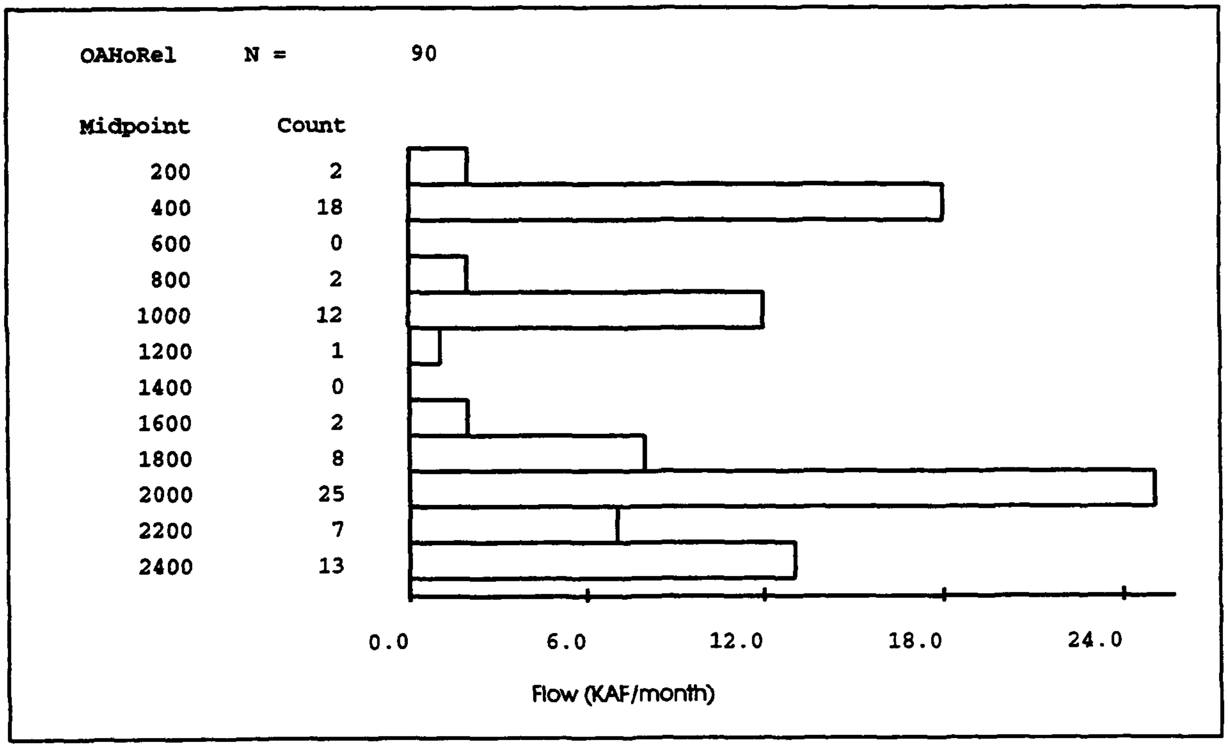


Figure 3.18 Histogram of Oahe Releases for February

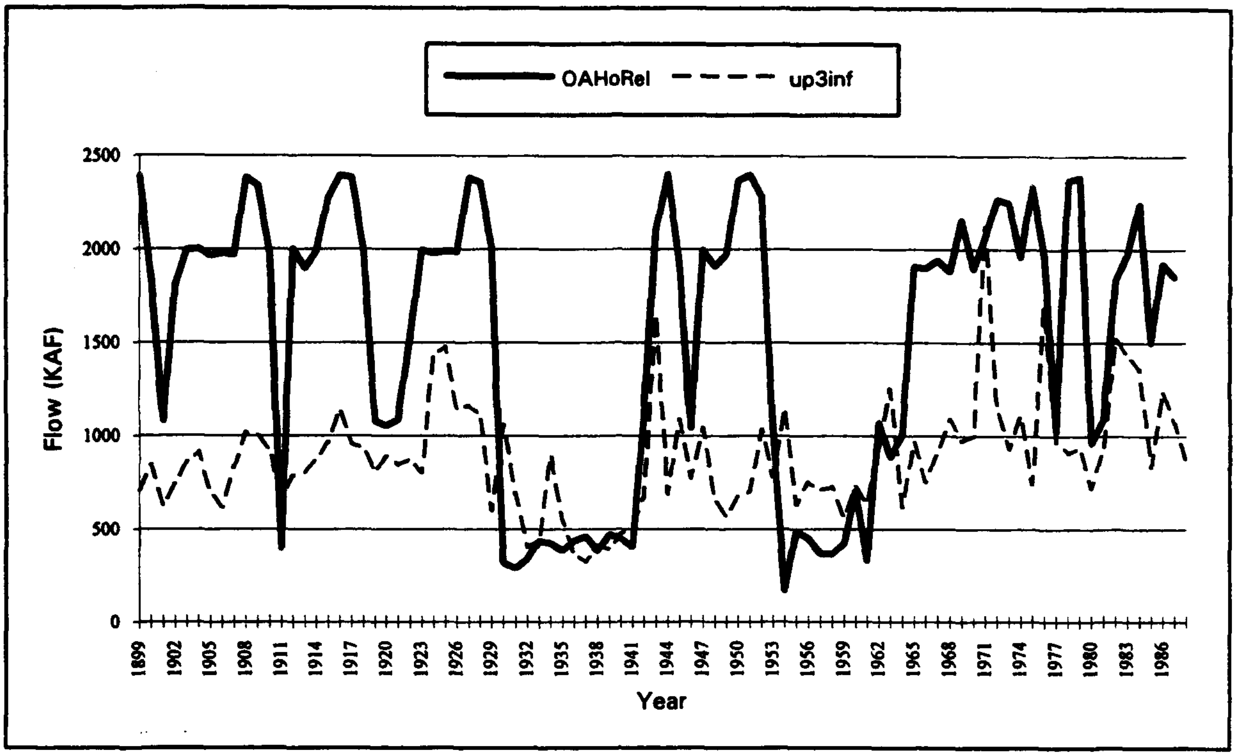


Figure 3.19 Time-Series of Optimal February Releases and Total Inflow Into the Upper Three Reservoirs

Like January, the range of February HEC-PRM releases from Oahe can be classified in four categories, which are distinct in the histogram (Figure 3.18); drought releases (less than 500 KAF/month), normal releases (700 KAF/month to 1,300 KAF/month) and two levels of flood control releases.

The range of flows into the upper three reservoirs is, however, more varied in February than in January. Although flows into the upper three reservoirs during drought periods are generally lower than non-drought inflows (Figure 3.19), these are not as consistently low as the December and January inflows.

3.6.3 Drought Releases

February drought rule developed from the numerical data is

else if ((FtP→OAH) inf<565) or ((FtP→OAH) inf<730) and (160<(FtR→SUX) inf<190))
then Oahe Release = (543-(FtR.→SUX) inf) KAF

which, combined with the December drought indicator rule, makes up the February drought rule.

The first part of this rule reflects the most indicative factor of drought conditions: low inflow into the upper three reservoirs. The second part of this rule is also dependent on low inflows into the upper three reservoirs and correctly picks up three years of the 1950's drought: 1957, 1958 and 1960. The restriction of total inflows into Fort Randall, Gavins Point, and Sioux City is such that HEC-PRM higher release years which have low inflow into the upper three reservoirs are not incorrectly selected with this rule. This downstream restriction does not seem to be related to any demands or constraints on the system, it simply worked in this case. The numerical data from which this rule was selected is presented in Table 3.5

Table 3.5
Numerical Data for February Drought Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1932	337	543	206	403	337	0
1933	437	543	106	438	437	0
1935	385	543	158	543	385	0
1936	438	543	79	370	464	26
1937	460	543	83	323	460	0
1938	383	543	160	413	383	0
1939	472	543	71	392	472	0
1940	450	543	93	471	450	0
1941	404	543	139	520	404	0
1957	369	543	174	712	369	0
1958	367	543	176	728	367	0
1959	422	543	121	562	422	0

This drought rule for February correctly selects only twelve of a total of twenty drought releases. Together with the December rule as a predictor, however, twenty drought periods are selected, with two years incorrectly chosen. The only optimized drought release not selected by the combined drought rule for February is in 1911. Table 3.6 presents the numerical data for the years selected with December drought indicator, together with the release determined by (543 - (FtR→SUX) inf) KAF/month and the error in this rule.

Like January, drought releases are done so as to guarantee a minimum streamflow at Sioux City of 543 KAF/month. As can be seen from Tables 3.5 and 3.6, a drought release of (543-(FtR→SUX) inf) KAF/month is extremely accurate in February. This implies that the three reservoirs downstream from Oahe did not re-regulate releases form Oahe during these drought periods.

Table 3.6
Numerical Data for February Drought Rule with December as Drought Indicator (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1929	2,016	2175	159	602	384	-1,632
1930	321	543	222	1,060	321	0
1931	289	543	321	687	222	-67
1934	424	543	119	895	424	0
1953	1,036	1,248	212	783	331	-705
1954	169	543	379	1,146	164	-5
1955	488	543	55	635	488	0
1956	451	543	92	753	451	0
1960	706	864	158	728	385	-321
1961	329	543	214	636	329	0

3.6.4 Normal Releases

For releases in the middle range, the rule found by examining the numerical data was:

If (1500<(FtR→HER) inf<2050) and (180<(FtR→SUX) inf<280) then Oahe Release = 1055 KAF
if ((FtR→HER) inf<1230) and ((FtR→NEB) inf>400) then Oahe Release = 1000 KAF

This rule correctly estimates nine of the fifteen releases in this range. As in January, these releases are such that the flow at Sioux City is between 1,200 and 1,340 KAF/month. The data pertinent to this rule is contained in Table 3.7.

Table 3.7
Numerical Data for February Normal Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1901	1,079	1,336	423	1,224	625	1,000	-79
1904	2,002	2,187	185	1,651	912	1,055	-947
1919	1,079	1,260	181	2,025	808	1,055	-24
1920	1,053	1,328	275	1,741	889	1,055	2
1921	1,088	1,314	226	1,692	846	1,055	-33
1922	1,525	1,702	422	1,062	875	1,000	-525
1944	2,404	2,597	449	1,122	691	1,000	-1,404
1947	1,996	2,173	540	994	1,041	1,000	-996
1953	1,036	1,248	212	1,566	783	1,055	19
1964	1,012	1,245	604	866	620	1,000	-12
1965	1,910	2,159	249	1,862	966	1,055	-855
1977	1,022	1,290	268	1,735	970	1,055	33
1981	1,092	1,277	465	1,002	939	1,000	-92

The majority of the remainder releases are high releases for future flood control and cannot, therefore, be predicted by present or past conditions. The rule for the remaining years is:

else Oahe Release = 2000 KAF

3.7 March Release Rule for Oahe

3.7.1 Rule Summary

if (FtR→HER) inf>9800 then 0
else if (FtR→OAH) Inf Jan<630 then 200
else if (FtP→OAH) Inf Dec<550 and 50<(FtR→SUX) Inf Dec<109) or
(FtR→HER) Inf Dec<870 and 100<(FtR→SUX) Inf Dec<160 then 200
else if (FtP→OAH) inf>3480 and (FtR→KAN) inf<3600 then 2200
else if 3000<(FtP→OAH) inf<3480 then 1300
else if 4870<(FtR→HER) inf<5800 and 350<(FtR→SUX) inf<1020 then 2300
else if 2000<(FtR→HER) inf<2600 and (FtR→KAN) inf<1900 then 2200
else 1800

3.7.2 Rule Development

Oahe release histogram for March (Figure 3.20) indicates a range of optimized releases as wide as January and February. Reasons for these releases, however, are slightly different from the two previous months. Unlike January and February, March high releases can be explained not only as a flood control measure for future high inflows, but also as a response to present high inflows into the upper three reservoirs. These patterns can be observed in the time-series plot of March inflows and optimized releases presented in Figure 3.21.

As can be seen from the rule summary for March, Oahe optimized releases are almost exclusively dependent on the inflow volumes downstream from Oahe. Unlike January and February, March experiences much greater inflows throughout the system, implying the need to operate the system to avoid floods rather than for low flow conditions. As suggested in the time-series plot of Figure 3.21, low releases occur not only during droughts but also as a means of minimizing flood damages downstream. This pattern continues until August, when a transition into lower fall and winter inflows occur.

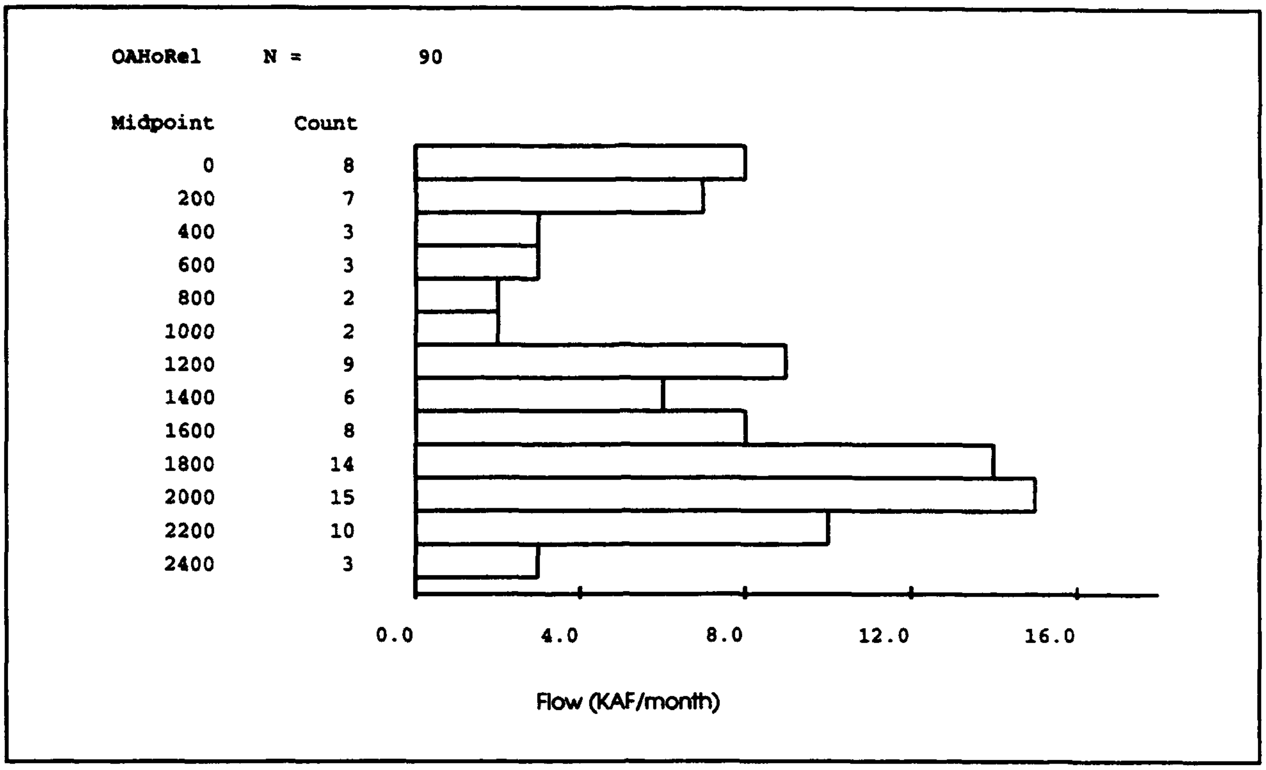


Figure 3.20 Histogram of Oahe Releases for March

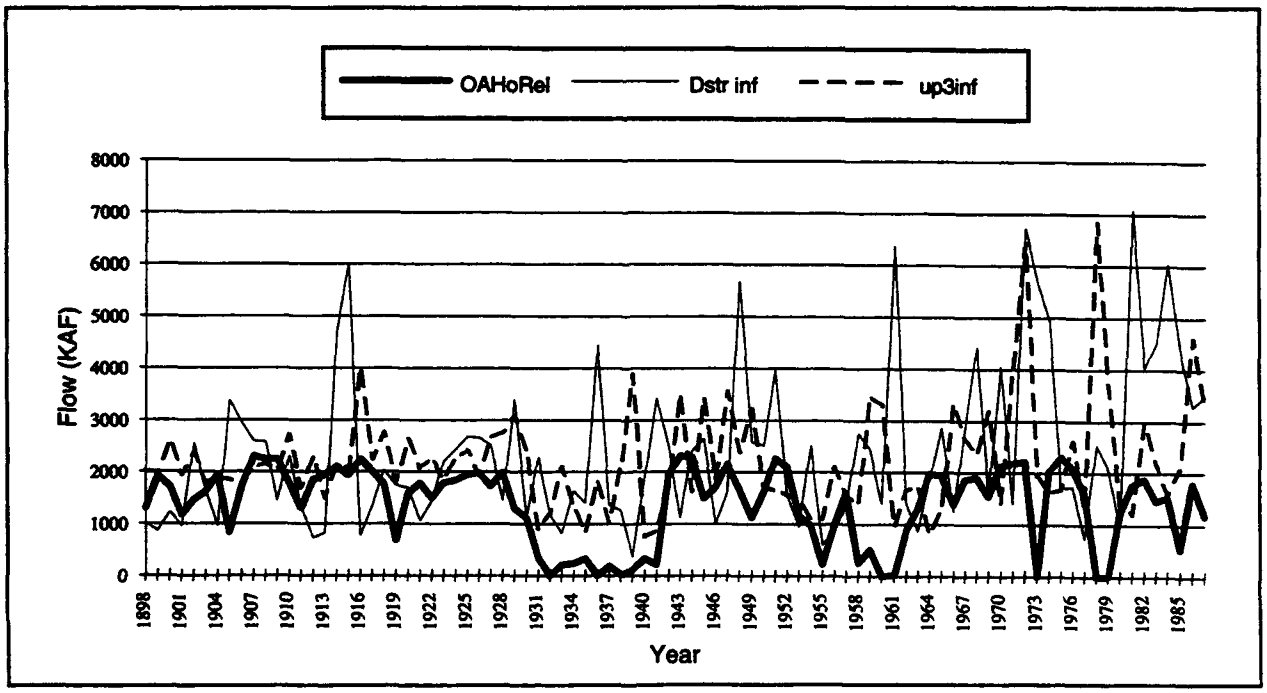


Figure 3.21 Time-Series of Optimal March Releases, Total Inflow Into the Upper Three Reservoirs, and Total Inflow Downstream of Oahe

3.7.3 Drought Releases

March optimized releases from Oahe during the 1930s and 1950s droughts are distinct from those of other months, in so far as they do not occur as a response to low inflows into the upper three reservoirs. Low optimized drought releases take place in March despite inflows being high. This is so not only because HEC-PRM "knows" there is a drought but also because the navigation season has not yet started.

Given that optimized drought releases cannot be predicted by March conditions, the drought rules for December and January were included here. The combined drought rules for these two months serve as triggers of March drought releases resulting in the following drought rule for March:

else if (FtR→OAH) Inf Jan<630 then Oahe Release = 200 KAF
else if ((FtP→OAH) Inf Dec<550) and (50<(FtR→SUX) Inf Dec<109)
or ((FtR→HER) Inf Dec<870) and (100<(FtR→SUX) Inf Dec<160) then Oahe Release = 200 KAF

Table 3.8 contains data of years selected by the drought rule for March. Optimized Oahe releases during the 1930s drought, like those of January and February, are reduced so that a minimum streamflow of 543 KAF/month is met at Sioux City. Data in Table 3.9 indicate how, by reducing releases in March, the system is able to store the extra flow for future use.

3.7.4 Flood Control Releases

Another characteristic of March optimized releases that can be noticed in Figure 3.21 is the reduction of releases when the total inflow downstream is large. This observation and careful consideration of the numerical data resulted in the rule:

if ((FtR→HER) inf>9800) then Oahe Release = 0

This reduction of releases is clearly carried out to avoid or minimize downstream floods. In 1973, 1978 and 1979, the three years with the highest total downstream inflow volumes, Oahe releases were exactly zero KAF/month, and urban flooding occurred only in 1973 and 1979 in the Boonville to Hermann reach. For this reach, zero flooding penalty occurs at a flow level of 7,543 KAF/month. In 1985, another year selected by this rule, optimized Oahe release was 512 KAF/month and floods were avoided on all reaches. Table 3.9 presents the data for years selected by this rule.

Table 3.8
Numerical Data for March Drought Rule with December and January as Drought Indicators (KAF/month)

Year	OAHE opt Release	SUX opt Flow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Total System Inflow	(FtP→OAH) Beginning Storage	(FtP→OAH) Ending Storage
1901	1,167	2,026	4,183	1,939	6,122	56,022	56,794
1902	1,455	2,113	2,770	2,360	5,130	54,657	55,562
1911	1,281	1,546	2,508	1,690	4,198	56,613	57,021
1929	1,299	3,010	7,551	3,080	10,631	56,253	58,033
1930	1,110	1,612	1,948	2,398	4,346	59,669	60,957
1931	342	543	1,226	900	2,126	60,342	60,900
1932	0	543	2,665	1,189	3,854	54,292	55,481
1933	208	543	1,558	2,093	3,651	57,794	59,678
1934	236	543	1,152	1,349	2,501	59,108	60,221
1935	334	543	3,120	826	3,946	54,533	55,025
1936	0	543	3,739	1,829	5,568	56,008	57,837
1937	192	543	3,617	1,017	4,634	54,572	55,397
1938	19	543	1,655	2,121	3,776	53,027	55,129
1939	117	543	3,419	3,883	7,302	56,259	60,025
1940	332	543	1,467	752	2,219	57,241	57,660
1941	209	543	1,107	869	1,976	51,906	52,565
1942	1,942	2,173	3,571	1,711	5,282	50,615	50,384
1949	1,124	2,467	7,778	3,218	10,996	54,001	56,094
1950	1,609	2,684	3,263	1,721	4,984	49,796	49,908
1952	2,092	3,496	7,537	1,568	9,105	51,884	51,360
1953	1,168	2,434	3,112	1,474	4,586	57,336	57,641
1954	971	1,448	1,201	1,116	2,317	59,742	59,887
1955	221	1,153	4,225	1,101	5,326	57,854	58,734
1956	974	1,248	660	2,091	2,751	56,424	57,541
1957	1,595	1,929	1,456	1,578	3,034	55,049	55,032
1958	249	616	5,942	1,381	7,323	56,557	57,689
1959	512	834	3,866	3,465	7,331	55,773	58,725
1960	0	1,468	4,719	3,301	8,020	55,613	58,914
1961	27	553	6,187	973	7,160	57,160	58,106
1963	1,300	1,703	3,861	1,727	5,588	58,190	58,617
1980	1,222	1,665	3,504	1,386	4,890	59,505	59,669
1982	1,894	2,389	6,048	2,979	9,027	48,509	49,593

Table 3.9
Numerical Data for March Flood Control Releases (KAF/month)

Year	OAH opt Release	BNV opt Flow	HEM opt Flow	FtR Inflow	(FtR→HER) Inflow	Release Rule	Error
1973	0	10,421	15,561	184	15,745	0	0
1978	0	7,573	10,439	940	10,806	0	0
1979	0	10,075	11,286	219	11,505	0	0
1985	527	5,317	10,306	215	9,808	0	-527

3.7.5 Normal Releases

For releases which are neither drought nor flood control releases, the following rule was developed. The numerical data from which this rule was derived is presented in Table 3.10.

else if 3000<(FtP→OAH) inf<3480 and (FtR→SUX) inf<1800
then Oahe Release = 1300 KAF

This rule allows for an increase in Oahe release if the total inflow into the upper three reservoirs is large and the inflows downstream are small enough so that the increased releases do not cause floods downstream.

Table 3.10
Numerical Data for March Normal Releases (KAF/month)

Year	OAHE opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1929	1,299	3,010	1,711	7,551	3,080	1300	1
1945	1,483	2,494	1,011	8,117	3,416	1300	-183
1949	1,124	2,467	1,343	7,778	3,218	1300	176
1966	1,376	2,394	1,135	3,217	3,325	1300	-76
1969	1,532	2,236	704	6,166	3,176	1300	-232
1987	1,169	2,518	1,349	8,556	3,301	1300	131

3.7.6 High Releases

Similar to January and February, high optimized releases in March can be explained as flood control later in the year. This is not so, however, for all high releases from Oahe in March. Because March inflows into the upper three reservoirs can be quite considerable, some of the high releases can be explained by these high inflows. The Oahe release rule that captures most of these high releases is

else if (FtP→OAH) inf>3480 and (FtR→KAN) inf<3600 then Oahe Release = 2200 KAF
else if 4870<(FtR→HER) inf<5800 and 350<(FtR→SUX) inf<1020 then Oahe Release = 2300 KAF
else if 2000<(FtR→HER) inf<2600 and (FtR→KAN) inf<1900 then Oahe Release = 2200 KAF

Numerical data from which this data was derived is presented in Table 3.11.

The remaining releases are estimated with the rule:

else Oahe Release = 1800 KAF

Table 3.11
Numerical Data for March High Releases (KAF/month)

Year	OAHE opt Release	(FtR→SUX) Inflow	(FtR→NEB) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1905	827	607	3,245	5,204	1,858	2,300	1,473
1907	2,304	714	1,841	2,408	2,083	2,200	-104
1909	2,239	1,017	3,811	4,874	2,025	2,300	61
1911	1,281	265	1,045	2,508	1,690	2,200	919
1914	2,101	446	1,486	2,053	2,125	2,200	99
1916	2,241	781	3,122	4,285	3,994	2,200	-41
1925	1,939	206	639	2,302	2,416	2,200	261
1926	1,983	201	808	2,371	1,936	2,200	217
1943	2,312	229	639	1,552	3,500	2,200	-112
1944	2,288	455	2,158	5,421	1,622	2,300	12
1947	2,148	407	1,439	3,413	3,544	2,200	52
1951	2,259	620	2,431	5,051	1,643	2,300	41
1970	2,133	581	1,454	2,202	1,405	2,200	67
1971	2,187	884	3,323	5,686	4,036	2,300	113
1972	2,220	776	1,664	2,529	6,431	2,200	-20
1975	2,306	355	1,832	5,782	1,675	2,300	-6

3.8 April Release Rule for Oahe

3.8.1 Rule Summary

if ((FtP→OAH) Inf Dec<550) and (50<(FtR→SUX) Inf Dec<112)
or ((FtR→HER)Inf Dec<870) and (100<(FtP→OAH) Inf Dec<160) then 1100
else if ((FtR→HER) inf>13000) then 30
else if ((FtR→HER) inf>8050) then 300
else if ((FtR→NEB) inf>3220) then 1000
else if ((FtR→HER) inf<2900) and ((FtP→OAH) inf>3300) then 2400
else if (3000<(FtR→HER) inf<4000) and ((FtP→OAH) inf>1670) then 2100
else if ((FtR→HER) inf>4950) and ((FtP→OAH) inf<1700) then 1300
else if (1600<(FtP→OAH) inf<1700) then 1000
else 1750

3.8.2 Rule Development

The pattern of inflows into the system in April, both upstream and downstream of Oahe, is akin to that of March and, with the exception of navigation, demands on the system are also similar. For these reasons, HEC-PRM releases for Oahe in April (Figures 3.22 and 3.23) and the justification for the release rules selected are very similar with those for March.

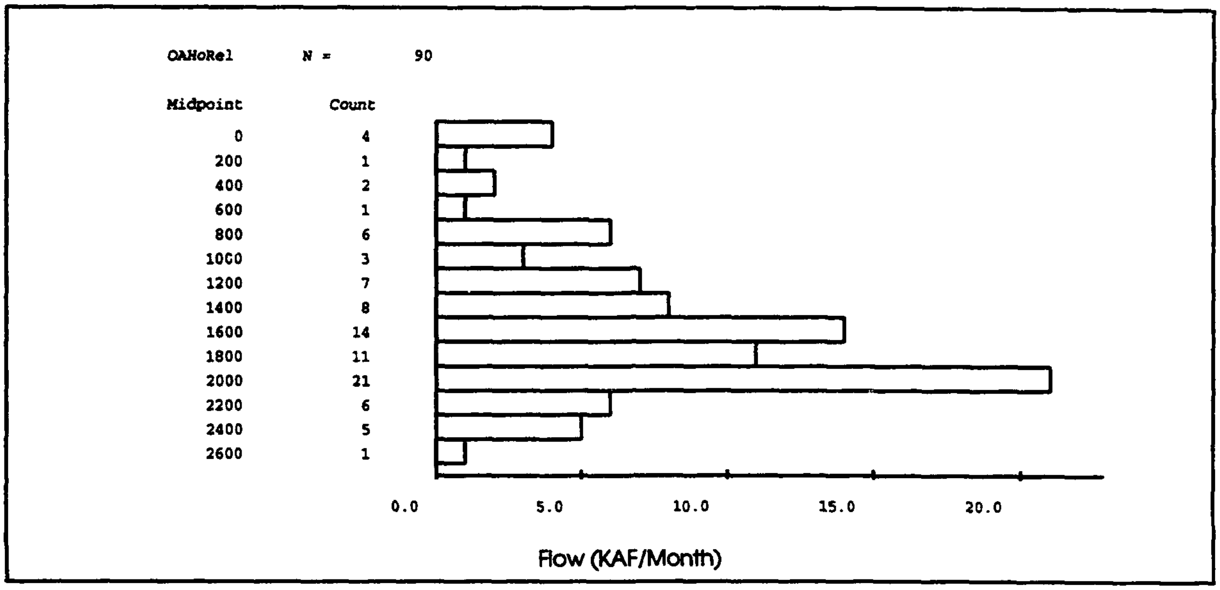


Figure 3.22 Histogram of Oahe Releases for April

3.8.3 Drought Releases

April, the first month of the navigation season, induces greater releases from Oahe than during the off-navigation season. Therefore, HEC-PRM drought releases are not as low as winter drought releases. This can be observed in the time-series plots of Figure 3.23, in which Oahe releases, although reduced, are not as drastically reduced as during the winter months.

During the 1930s drought, HEC-PRM releases are decreased to between 776 KAF/month and 1,452 KAF/month. These releases are such that a streamflow of 1,565 KAF/month is guaranteed at Sioux City. From 1931 through 1937, these were the lowest optimized flow volumes at Sioux City during any drought period. Such streamflows do incur a penalty since they are lower than the minimum flow of 1,870 KAF/month that is required for zero value penalty function value. The streamflow associated with a maximum penalty value in the reach Sioux City to Omaha is 1,448 KAF/month.

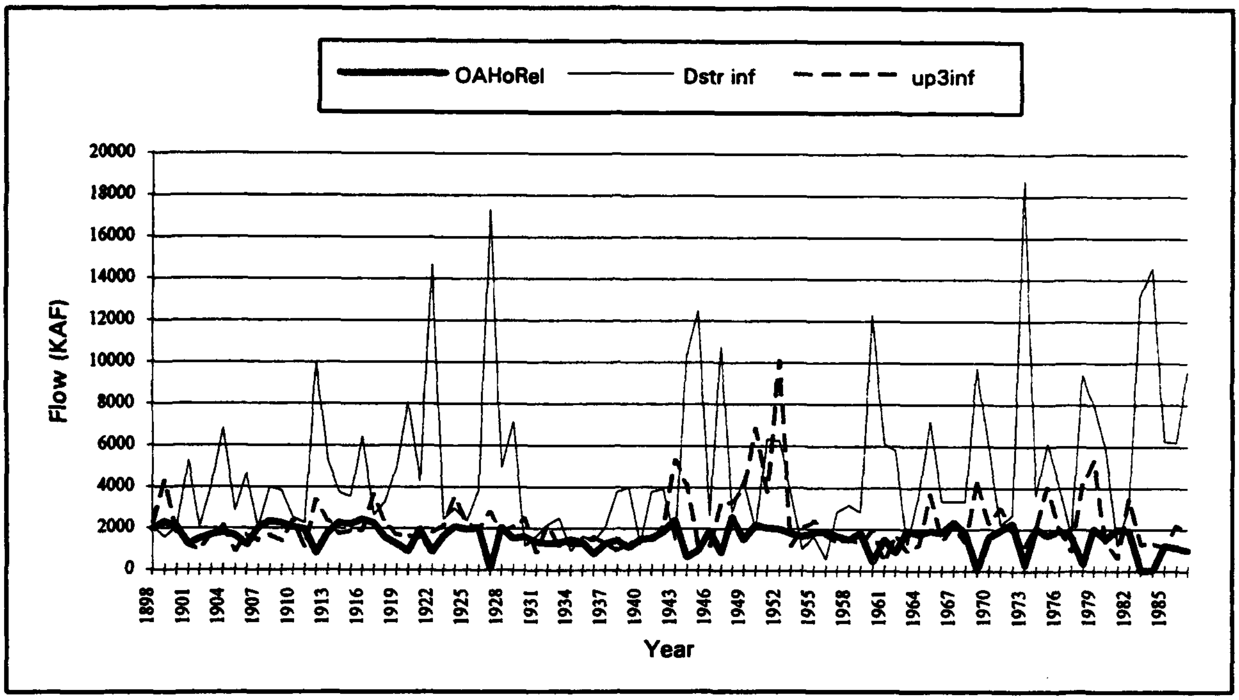


Figure 3.23 Time Series of Optimal April Releases, Total Inflow Into the Upper Three Reservoirs, and Total Inflow Downstream of Oahe

As in other months of high inflows (March through July), the inflows into the system are, with the exception of very severe droughts, high enough to allow for higher releases from Oahe, thus avoiding the cancellation of navigation.

Like March, inflows into the system in April are not an accurate predictor of HEC-PRM Oahe drought releases. Therefore, inflows in the preceding December are used as an indicator of drought conditions and thus as the drought release rule for April:

if ((FtP→OAH) Inf Dec<550) and (50<(FtR→SUX) Inf Dec<112) or ((FtR→HER)Inf Dec<870) and (100<(FtP→OAH) Inf Dec<160) then Oahe Release = 1100 KAF

The years selected with this rule are presented in Table 3.12.

3.8.4 Flood Control Releases

The lowest optimized releases from Oahe were those associated with high downstream inflows. This pattern can be observed in Figure 3.23. The rule obtained for these flood control releases is:

• *else if ((FtR→HER) inf>13000) then Oahe Release = 30 KAF*
else if ((FtR→HER) inf>8050) then Oahe Release = 300 KAF
else if ((FtR→NEB) inf>3220) then Oahe Release = 1000 KAF

Table 3.12
Numerical Data for April Drought Releases with December as Drought Indicator (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtP→OAH) Inflow	Release Rule	Error
1929	1,519	2,399	2,086	1,100	-419
1930	1,615	1,877	2,474	1,100	-515
1931	1,346	1,565	869	1,100	-246
1933	1,322	1,565	1,183	1,100	-222
1934	1,452	1,565	1,266	1,100	-352
1935	1,344	1,565	1,213	1,100	-244
1936	776	1,565	1,620	1,100	324
1937	1,268	1,565	1,289	1,100	-168
1938	1,445	1,766	46	1,100	-345
1939	1,093	1,687	1,260	1,100	7
1940	1,462	1,797	1,430	1,100	-362
1949	1,471	2,100	3,924	1,100	-371
1953	1,795	2,315	1,196	1,100	-695
1955	1,820	1,736	2,395	1,100	-720
1956	1,904	2,053	1,769	1,100	-804
1960	437	1,957	1,927	1,100	663
1962	872	2,881	1686	1,100	228

Releases are clearly graded with the inflow volume downstream of Oahe; the higher the downstream inflows the lower the release. The numerical data from which this rule was derived is presented in Table 3.13.

3.8.5 High Releases

With fewer exceptions than in previous months, high optimized releases in April can be predicted from present flow conditions. Most high April HEC-PRM release years can be triggered by rules which combine high inflow into the upper three reservoirs and low inflow (at least not high) downstream from Oahe.

Table 3.13
Numerical Data for April Flood Control Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1912	808	1,312	598	9,968	3,368	300	-508
1920	882	1,589	736	8,081	1,639	300	-582
1922	854	1,097	271	14,684	1,785	30	-824
1927	61	587	555	17,300	2,770	30	-31
1944	624	1,188	593	10,313	4,151	300	-324
1945	958	1,416	486	12,494	1,262	300	-658
1947	837	1,565	757	10,750	3,203	300	-537
1960	437	1,957	2,415	12,312	1,927	300	-137
1962	872	2,881	2,038	5,814	1,686	1,000	128
1969	29	2,102	2,308	9,735	4,243	300	271
1973	263	974	556	18,757	1,212	30	-233
1978	317	1,709	1,118	9,430	4,141	300	-17
1983	29	1,161	1,265	13,268	1,288	30	1
1984	29	2,092	2,419	14,577	1,344	30	1
1986	1,122	3,183	2,089	6,196	2,168	1,000	-122
1987	992	1,466	1,328	9,610	2,039	300	-692

There are a few exceptions, however, in years in which optimized releases are high so as to make storage for high inflows in June or July. As before, these releases cannot be selected by rules derived from existing conditions. Years which fall in this category are only 1907 and 1909. The rule for high release is:

else if ((FtR→HER) inf<2900) and ((FtP→OAH) inf>3300) then 2400
else if (3000<(FtR→HER) inf<4000) and ((FtP→OAH) inf>1670) then 2100

This rule correctly estimates eleven of the twenty-two periods of optimized releases greater than 2,000 KAF/month. Data for the years selected by this rule is contained in Table 3.14.

3.8.6 Low Releases

Low releases which are neither drought nor flood control releases were found to be a response to low inflow into the upper three reservoirs. The rule derived from the numerical data (Table 3.15) is:

else if ((FtR→HER) inf>4950) and ((FtP→OAH) inf<1700) then Oahe Release = 1300 KAF
else if (1600<(FtP→OAH) inf<1700) then Oahe Release = 1000 KAF

Table 3.14
Numerical Data for April High Releases (KAF/month)

Year	OAH opt Release	(FtP→OAH) Inflow	SUX opt Flow	(FtR→HER) Inflow	Release Rule	Error
1899	2,319	4,246	2,649	1,562	2,400	81
1917	2,248	3,614	2,718	2,659	2,400	152
1943	2,433	5,297	2,521	1,457	2,400	-33
1948	2,594	3,301	2,764	2,797	2400	-194
1950	2,200	6,824	2,849	2,009	2,400	200
1908	2,339	1,672	2,764	3,988	2,100	-239
1914	2,279	1,753	2,606	3,,751	2,100	-179
1915	2,193	1,888	2,970	3,561	2,100	-93
1918	1,561	2,288	1,957	3,281	2,100	539
1926	2,032	1,951	2,159	3,824	2,100	68
1942	1,840	2,035	2,184	3,928	2,100	260
1967	2,343	2,157	2,582	3,363	2,100	-243
1974	2,058	2,056	2,142	3,640	2,100	42
1982	1,924	3,453	2,373	3,147	2,100	176

This rule indicates reduction of releases from Oahe when inflow into the upper three reservoirs is low, in fact, within the lower quartile. The first part of the rule also ensures that the inflow into the lower basin is low thus avoiding floods in the downstream reaches.

Table 3.15
Numerical Data for April Low Releases (KAF/month)

Year	OAH opt Release	(FtP→OAH) Inflow	SUX opt Flow	(FtR→HER) Inflow	Release Rule	Error
1901	1,233	1,197	1,670	5,269	1,300	67
1962	872	1,686	2,881	5,814	1,300	428
1980	1,548	1,363	1,740	5,887	1,300	-248
1985	1,220	1,131	2,098	6,245	1,300	80
1903	1,682	1,660	2,334	4,008	1,000	-682
1962	872	1,686	2,881	5,814	1,000	128

The remaining releases from Oahe are accounted for with the rule

else Oahe Release = 1750 KAF

3.9 May Release Rule for Oahe

3.9.1 Rule Summary

if ((FtP→OAH) inf>4100) and (FtR→HER)<7000 KAF then Oahe Release = 2550 KAF
else if ((FtR→HER) inf>7000) and ((FtR→SUX) inf>1100) then Oahe Release = 550 KAF
else if (710<(FtR→SUX) inf<950) and (2200<(FtP→OAH) inf<2700)
then Oahe Release = 3000 KAF
else if ((FtP→OAH) inf>3000) and ((FtR→KAN) inf<1000) then Oahe Release = 3026 KAF
else if ((FtP→OAH) inf<2200) and ((FtR→HER) inf>6000) and ((FtR→SUX) inf>300)
then Oahe Release = 1100 KAF
else if ((FtP→OAH) inf>2400) and ((FtP→OAH) inf<2900) and ((FtR→NEB) inf>1500)
t hen Oahe Release = 1700 KAF
else if ((FtP→OAH) inf>2500) then Oahe Release = 2500 KAF
else Oahe Release = 2300 KAF

3.9.2 Rule Development

Inflows into the system in May are large enough that releases do not have to be greatly reduced during droughts. All optimized Oahe releases less than 1,000 KAF/month in May are due to high inflows downstream of Oahe.

3.9.3 Flood Control Releases

Like other spring and summer months, Oahe releases in May are reduced either to avoid or to decrease flood damages in the lower basin. This pattern can be seen in Figure 3.24, representing the time-series of Oahe releases, total downstream inflows and total inflow into the upper three reservoirs. Clear reduction of optimized releases occur when flows in the lower basin are high.

The release rule for reduced release due to high downstream flows deduced from the numerical data is

if (FtR→HER) inf > 7000 and (FtR→SUX) inf > 1100 the Oahe Release = 550 KAF
else if (FtR→HER) inf > 6000 and (FtP→OAH) inf <2300 and (FtR→SUX) inf>300
then Oahe Release = 1100 KAF

By reducing releases from Oahe, flood damages are minimized. Data and error associated with this rule are contained in Table 3.16.

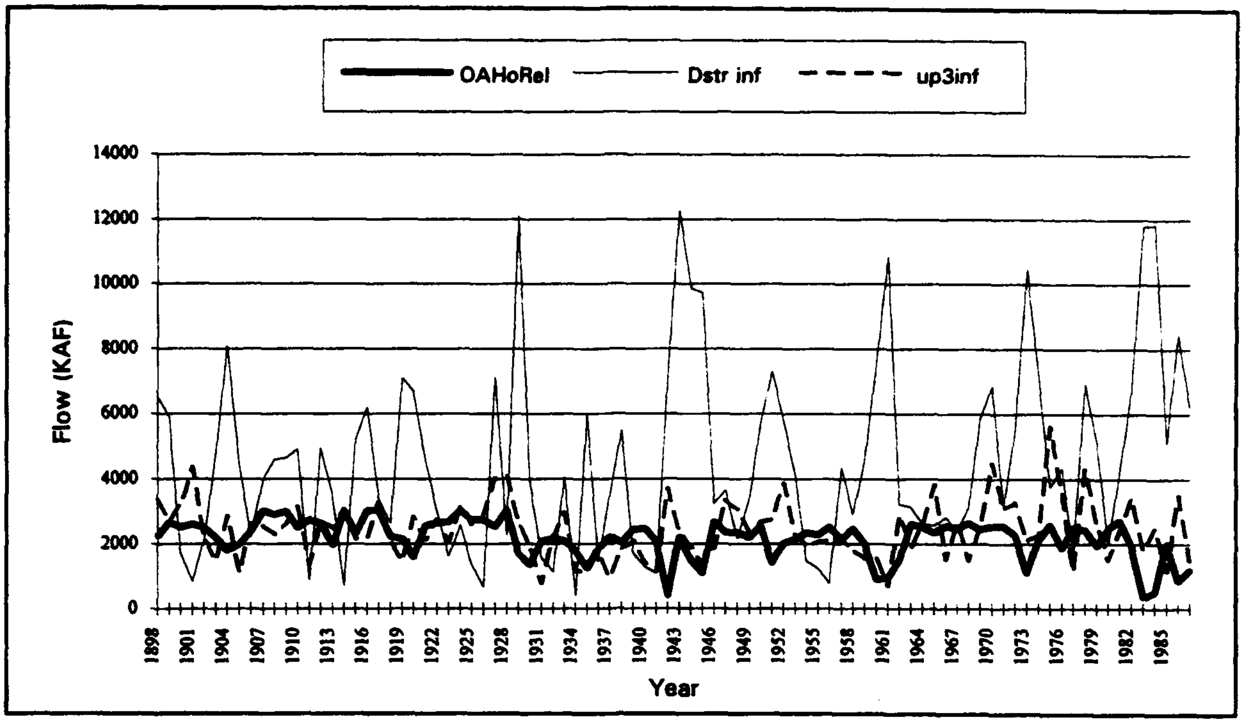


Figure 3.24 Time-series of Optimal May Releases, Total Inflow Into the Upper Three Reservoirs, and Total Inflow Downstream of Oahe

Table 3.16
Numerical Data for May Flood Control Releases (KAF/month)

Year	OAH opt Release	HEM opt Flow	(FtR→SUX) Inflow	(FtR→HER)II nflow	(FtP→OAH) Inflow	Release Rule	Error
1935	1255	6,490	341	6,003	1,143	1,100	-155
1942	396	6,700	2,200	7,100	3,689	550	154
1944	1519	10,617	963	9,865	1,891	1,100	-419
1945	1084	10,050	309	9,733	1,383	1,100	16
1960	906	8,416	704	7,553	1,555	1,100	194
1961	963	11,054	430	10,858	720	1,100	137
1973	1,110	10,729	497	10,445	2,114	1,100	-10
1983	358	11,436	1,168	11,800	1,814	550	192
1984	515	11,854	1,346	11,838	2,470	550	35
1986	868	8,557	1,743	8,457	3,489	550	-318
1987	1,203	7,426	597	6,223	1,509	1,100	-103

3.9.4 Normal Releases

If the inflow into the upper three reservoirs is higher, then Oahe releases can be increased, resulting in the rule *else if (FtP→OAH) inf > 2400 and (FtR→NEB) inf > 1500 then Oahe Release = 1700 KAF*

The numerical data related to this rule is contained in Table 3.17.

Table 3.17
Numerical Data for May Normal Releases (KAF/month)

Year	OAHE opt Release	SUX opt Flow	NEB opt Flow	(FtR→NEB) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1899	2,676	2,480	3,704	1,796	2,704	1,700	-976
1904	1,807	1,413	2,825	1,718	2,854	1,700	-107
1913	1,963	1,800	2,812	1,616	2,479	1,700	-263
1920	1,588	1,800	3,412	2,591	2,810	1,700	112
1929	1,721	1,583	2,772	1,818	2,688	1,700	-21
1951	1,417	2,161	3,591	2,144	2,746	1,700	283
1962	1,502	1,800	2,675	1,940	2,872	1,700	198
1979	1,954	2,641	3,506	1,589	2,632	1,700	-254

As can be seen from the histogram of Oahe releases (Figure 3.25), the bulk of Oahe releases are in the range 1,900 KAF/month to 2,700 KAF/mo. These releases are considerably higher than in any other month, with the median value of Oahe release being 2,328 KAF/month, a lower quartile of 1,963 KAF/month and an upper quartile of 2,559 KAF/month.

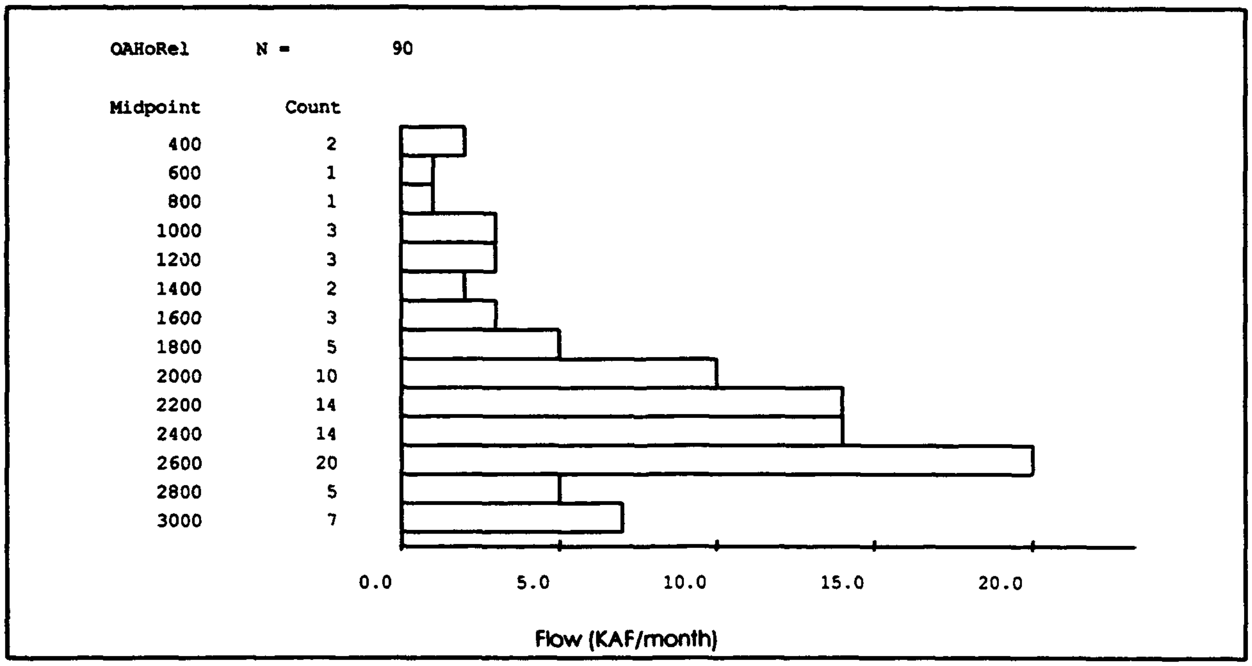


Figure 3.25 Histogram of Oahe Releases for May

Given also that the inflows into the upper three reservoirs are generally high, May is the month with the highest optimized Oahe releases during drought years. The only drought releases below 1,800 KAF/month occurred in 1930 and 1935, and these were at 1,359 KAF/month and 1,255 KAF/month respectively. These releases were further reduced at Gavins Point. However, neither of these drought releases could be captured by a rule since they did not reflect either low inflow into the upper three reservoir or any other drought condition.

3.9.5 High Releases

Like April, high optimized releases from Oahe in May can be explained either as a combination of high inflow into the upper three reservoirs and low to average downstream inflows or, as flood control in June or July. The rule developed for this range of releases is:

else if 2200<(FtP→OAH) inf<2700 and 710<(FtR→SUX) inf<950 then Oahe Release = 3000 KAF
else if (FtP→OAH) inf>3000 and (FtR→KAN) inf<1000 then Oahe Release = 3026 KAF

Once again these releases are such that, by restricting the range of inflows downstream, flooding is avoided in the lower basin. Another condition is that there be enough inflow into the upper three reservoirs to allow for such high releases. Numerical data from which this rule was developed is contained in Table 3.18.

Table 3.18
Numerical Data for May High Releases (KAF/month)

Year	OAHE opt Release	SUX opt Flow	KAN opt Flow	(FtR→SUX) Inflow	(FtR→KAN) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1898	2,241	2,248	3,551	774	2,077	3,346	3,000	759
1906	2,402	2,397	3,551	762	1,916	2,597	3,000	598
1907	3,026	3,232	3,482	893	1,143	2,553	3,000	-26
1908	2,898	2,900	4,029	714	1,843	2,303	3,000	102
1909	2,999	3,174	4,428	942	2,196	2,650	3,000	1
1914	3,026	2,807	2,958	404	555	3,047	3,026	0
1916	3,026	3,057	5,798	715	3,456	2,230	3,000	-26
1924	3,026	2,473	2,996	214	737	3,139	3,026	0
1927	2,532	2,585	3,839	821	2,075	4,012	3,000	468
1928	3,026	2,624	3,001	259	636	4,073	3,026	0
1951	1,417	2,161	6,710	714	5,263	2,746	3,000	1,583
1978	2,437	2,398	4,943	722	3,267	4,309	3,000	563
1979	1,954	2,641	4,664	724	2,747	2,632	3,000	1,056

3.9.6 Moderately High Releases

For the modal range of releases the rule is:

else if ((FtP→OAH) inf>4100) and (FtR→HER)<7000 KAF then Oahe Release = 2550 KAF
else if 2500<(FtP→OAH) inf<2950 and then Oahe Release = 2600 KAF

Table 3.19
Numerical Data for May Moderately High Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	HER opt Flow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1899	2,676	2,480	7,794	5,886	2,704	2,500	-176
1906	2,402	2,397	3,870	2,235	2,597	2,500	98
1907	3,026	3,232	6,358	4,019	2,553	2,500	-526
1909	2,999	3,174	6,877	4,645	2,650	2,500	-499
1912	2,648	2,297	6,900	4,953	2,709	2,500	-148
1922	2,645	2,198	4,901	3,024	2,735	2,500	-145
1925	2,741	2,149	3,348	1,375	2,617	2,500	-241
1926	2,744	2,239	2,648	672	2,921	2,500	-244
1950	2,559	2,353	7,529	5,738	2,666	2,500	-59
1964	2,521	2,204	4,376	2,623	2,617	2,500	-21
1967	2,465	2,647	4,693	2,389	2,697	2,500	35
1969	2,450	2,544	7,765	5,877	2,512	2,500	50
1901	2,615	2,367	2,799	849	4,350	2,550	-65
1970	2,541	2,245	8,639	6,865	4,488	2,550	9
1975	2,598	2,216	5,590	3,760	5,622	2,550	-48
1978	2,437	2,398	8,621	6,945	4,309	2,550	113

For the remaining years the rule is:

else Oahe Release = 2300 KAF

3.10 June Release Rule for Oahe

3.10.1 Rule Summary

if ((FtR→HER) Inflow>11000) and ((FtP→OAH) Inf>900)
or (FtP→OAH) Inf>1500 then 10
else if ((FtR→HER) Inflow>10200) and ((FtP→OAH) inf<5000) then 200
else if ((FtR→HER) Inflow>6350) and ((FtR→NEB) Inf>2100) then 850
else if ((FtR→HER) Inflow>6350) then 1300
else if ((FtR→HER) Inflow<2200) and ((FtP→OAH) inf<2000) then 1300
else if ((FtR→HER) Inflow<2200) then 1850
else 1600

3.10.2 Rule Development

The procedure for obtaining an Oahe release rule for the month of June was similar to those of April and May. The Oahe release histogram for June (Figure 3.26) indicates that most releases are in the range of 1,400 to 2,000 KAF/month. The strategy then becomes one of isolating the tail ends of the distribution, by finding rules for these releases and then setting a value of release that will best estimate the modal range.

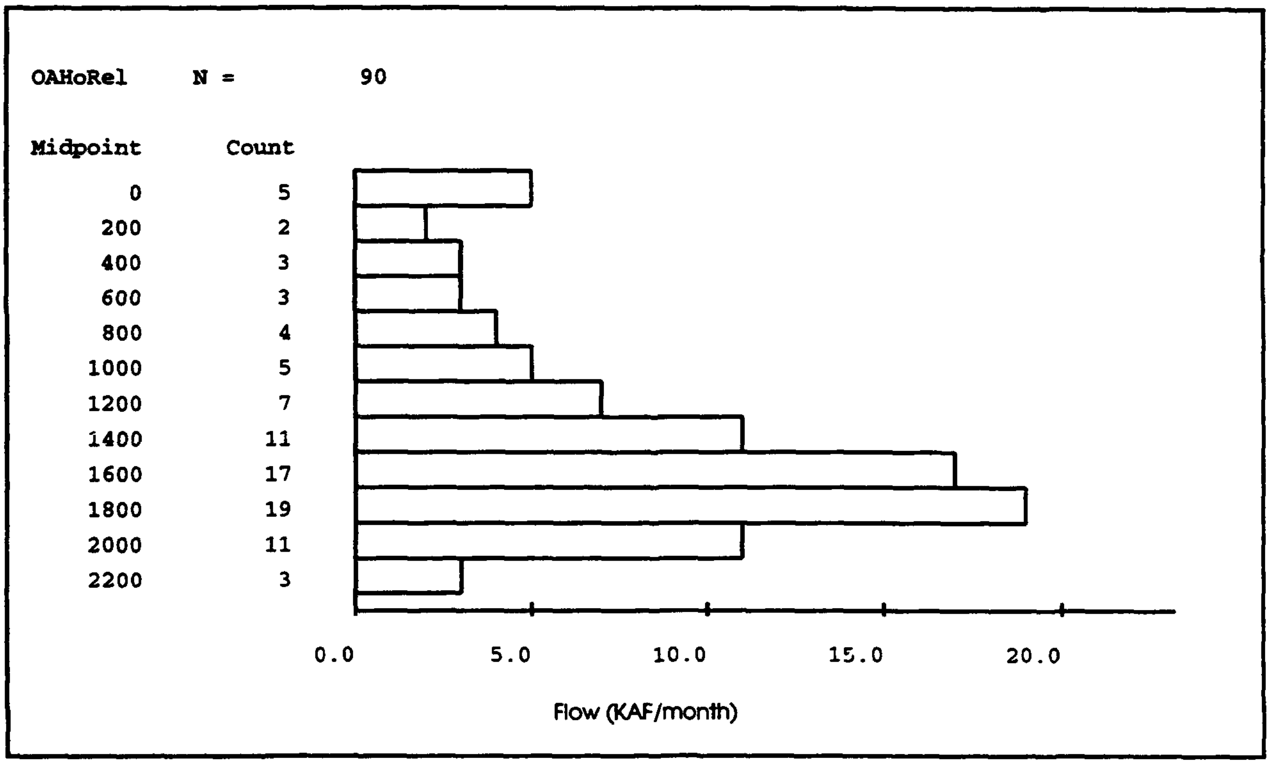


Figure 3.26 Histogram of Oahe Releases for June

The parameters used most extensively in the development of Oahe release rules were the combined inflows into the upper three reservoirs and the combined inflows at all nodes downstream from Oahe. June experiences the highest combined inflows both in the upper and in the lower basins. In the upper basin, the high inflows in June are caused by high latitude snowmelt and, in the lower basin, by mountain snowmelt compounded with rainstorms and high releases from tributary reservoirs.

Given that inflows into the upper three reservoirs are fairly high even during the major drought events, rules for release during the month of June become almost exclusively in terms of the total downstream inflows.

3.10.3 Drought Releases

Very high system inflows in June result in small Oahe release reduction during droughts (Figure 3.27). The rule developed for drought releases is :

if (FtRÆHER) inf < 2200 and (FtPÆOAH) inf < 2000 then Oahe Release = 1300 KAF

and the data from which this rule was derived is presented in Table 3.20.

Table 3.20
Numerical Data for June Drought Releases (KAF/month)

Year	OAHE opt Release	Total Dstr Inflow	(FtP→OAH) Inflow	Release	Error
1931	1,513	1,286	1,526	1,300	-213
1934	1,084	615	1,301	1,300	216
1936	1,210	925	1,941	1,300	90
1940	1,488	1,527	1,942	1,300	-188

3.10.4 Flood Control Releases

In June, therefore, the main response of HEC-PRM to conditions of the system, is a reduction of releases to avoid floods downstream. The pattern is evident in the time-series of Oahe releases, and total downstream inflow (Figure 3.27). A sharp drop in Oahe releases will occur whenever the total downstream inflow is large. This makes for a fairly straightforward set of rules.

if (FtR→HER) inf >11000 and (FtR→SUX) inf>900
or (FtR→SUX) inf>1500 then Oahe Release = 10 KAF
else if T(FtR→HER) inf > 10200 and (FtP→OAH) inf < 5000 then Oahe Release = 200 KAF
else if(FtR→HER) inf > 6350 and (FtR→NEB) inf > 2100 then Oahe Release = 850 KAF
else if (FtR→HER) inf > 6350 then Oahe Release = 1300 KAF

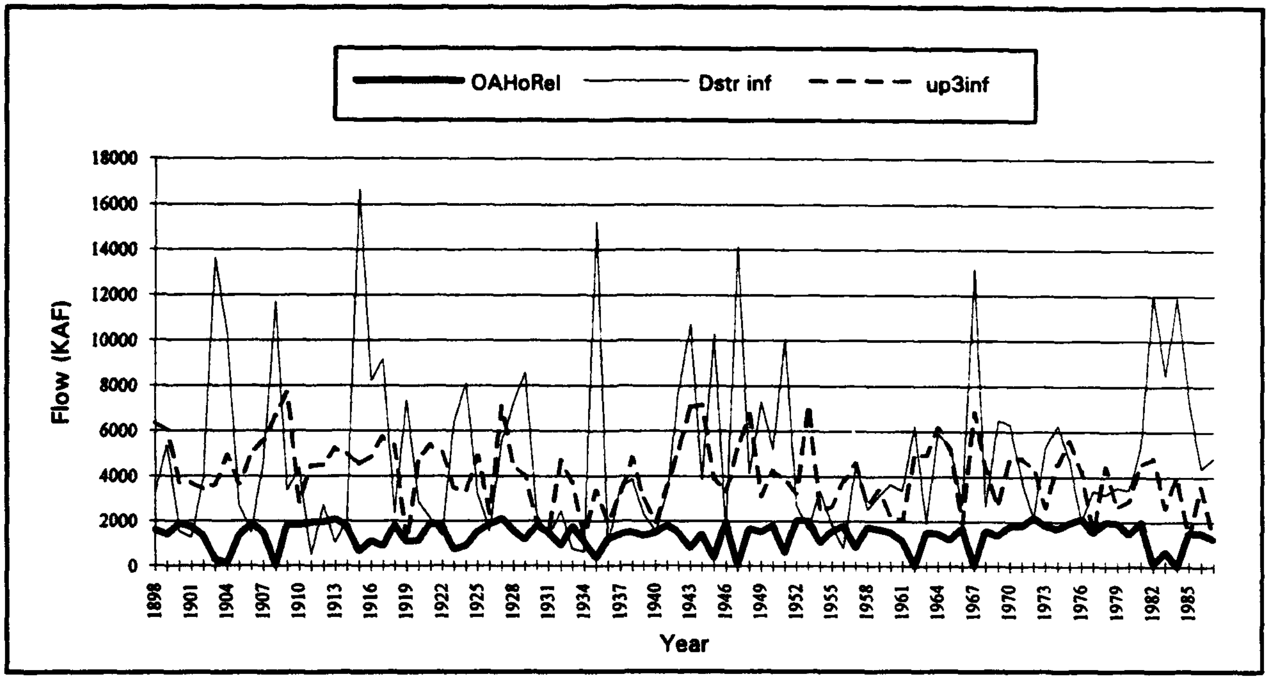


Figure 3.27 Time-Series of Optimal June Releases, Total Inflow Into the Upper Three Reservoirs, and Total Inflow Downstream of Oahe

For a very high total inflow downstream from Oahe (greater than 11,000 KAF/month) and high combined inflow into Fort Randall, Gavins Point and Sioux City, HEC-PRM releases from Oahe are reduced considerably. In this manner, floods are minimized at all downstream locations. This portion of the flood control rule selects all five releases which are less than 50 KAF/month, with no incorrect selections made (Table 3.21).

Table 3.21
Numerical Data for June Flood Control Releases (KAF/month)

Year	OAHE opt Release	(FtR→SUX) Inflow	SUX opt Flow	Total Dstr Inflow	(FtP→OAH) Inflow	Release Rule	Error
1903	311	318	626	13,654	3,651	200	-111
1904	135	561	626	10,201	4,909	200	65
1908	5	919	676	11,716	6,673	10	5
1915	656	826	626	16,666	4,529	200	-456
1935	371	267	626	15,273	3,352	200	-171
1945	355	675	2,125	10,291	3,867	200	-155
1947	43	1,064	626	14,167	5,242	10	-33
1962	5	1,865	1,774	6,242	4,951	10	5
1967	7	1,348	626	13,172	6,848	10	3
1982	137	500	626	12,029	4,829	00	63
1984	8	2,622	2,259	11,931	4,019	10	2

When the combined inflow downstream of Oahe is large, but the combined inflows at Fort Randall, Gavins Point and Sioux City ((FtR...SUX) inf) is small, Oahe releases can be increased resulting in the second part of the flood control rule. This second part of the rule correctly selects all five releases in the range 100 to 400 KAF/month, but incorrectly selects one release of 805 KAF/month (Table 3.21).

For both flood control releases, HEC-PRM re-regulates the flow downstream of Oahe to have a flow of 626 KAF/month at Sioux City. This low flow precludes navigation in the channel but also minimizes flood damage further downstream.

The third and fourth portions of the flood control rule allow for an increase in the release because inflows downstream are not excessively high. Once again the attempt at minimizing flood damage is clear. If the combined inflow into the five nodes between Fort Randall and Nebraska City is high, in this case greater than 2,100 KAF/month, then Oahe release is set at a lower level of 850 KAF/month, otherwise, the release is set at 1,300 KAF/month. Table 3.22 presents the numerical data concerning this part of the flood control rule.

Table 3.22
Numerical Data for June Normal Releases (KAF/month)

Year	OAHE opt Release	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release	Error
1900	1,896	1,539	3,720	1,850	-46
1901	1,745	1,271	3,700	1,850	105
1906	1,878	1,493	5,002	1,850	-28
1911	1,936	493	4,455	1,850	-86
1913	2,080	1,044	5,217	1,850	-230
1914	1,741	2,035	4,989	1,850	109
1921	1,923	2,082	5,361	1,850	-73
1922	1,770	1,348	5,018	1,850	80
1926	1,862	1,520	2,321	1,850	-12
1931	1,513	1,286	1,526	1,300	-213
1933	1,751	755	3,709	1,850	99
1934	1,084	615	1,301	1,300	216
1936	1,210	925	1,941	1,300	90
1940	1,488	1,527	1,942	1,300	-188
1946	1,973	1,510	3,319	1,850	-123
1953	2,022	1,617	7,129	1,850	-172
1955	1,560	1,825	2,677	1,850	290
1956	1,802	801	3,826	1,850	48
1963	1,513	1,910	4,960	1,850	337
1972	2,192	2,181	4,367	1,850	-342
1976	2,130	2,004	4,257	1,850	-280

3.10.5 Normal Releases

When the combined inflow downstream from Oahe is low, optimized Oahe releases range from 1,100 to 2,200 KAF/month, depending on the combined inflows into the upper three reservoirs. The release rule is:

else if (FtR→HER) inf < 2200 then Oahe Release = 1850 KAF

Data concerning this rule is included in Table 3.22.

For the remaining years, the release rule is:

else Oahe Release = 1600 KAF

3.11 July Release Rule for Oahe

3.11.1 Rule Summary

if ((FtR→HER) inf>13000) then 400
else if ((FtR→HER) inf>8700) then 700
else if ((FtR→HER) inf<2070) and ((FtP→OAH) inf>1530) then 1850
else if ((FtR→HER) inf<2070) then 1507
else if ((FtP→OAH) inf<2245) then 1600
else if ((FtR→HER) inf<5400) and ((FtR→NEB) inf<1100) then 1850
else 1450

3.11.2 Rule Development

As in the three months before it, the procedure for deriving release rules for July was one of determining rules for the high and low releases and then setting releases in remaining years to a middle value. July has a similar pattern of releases to those of June, with releases predominantly dependent on the value of the combined inflow at the downstream nodes. The histogram of Oahe Releases for July (Figure 3.28) shows a fairly tight distribution, with seventy-eight percent of the releases between 1,500 and 2,100 KAF/month.

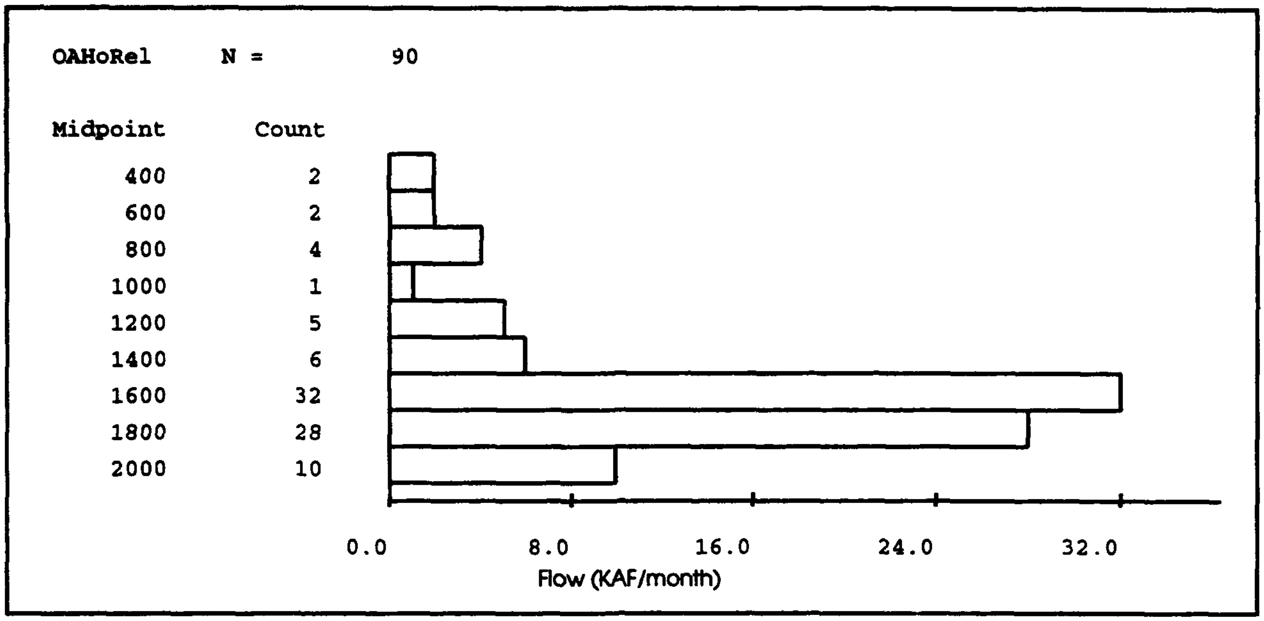


Figure 3.28 Histogram of Oahe Releases for July

3.11.3 Flood Control Releases

Similar to June, all low releases from Oahe are done to avoid or reduce floods downstream. This pattern can be observed in the time-series plots of total downstream inflow and HEC-PRM releases (Figure 3.29). The flood control release rule for July is

> *else if (FtR→HER) inf > 11000 then Oahe Release = 400 KAF*
> *else if (FtR→HER) inf > 8700 then Oahe Release = 700 KAF*

The numerical data from which this rule was derived is presented in Table 3.23. This flood control rule allows for increasing releases as the inflows downstream are reduced, in the same manner as done in June.

Table 3.23
Numerical Data for July Flood Control Releases (KAF/month)

Year	OAHE opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1902	804	600	186	8,786	1,979	700	-104
1904	804	600	321	9,772	2,899	700	-104
1909	638	600	576	9,525	4,508	700	62
1915	385	600	607	14,458	3,349	400	15
1951	412	612	726	24,114	2,476	400	-12
1958	663	600	241	9,584	1,786	700	37
1969	711	749	564	10,192	3,598	700	-11

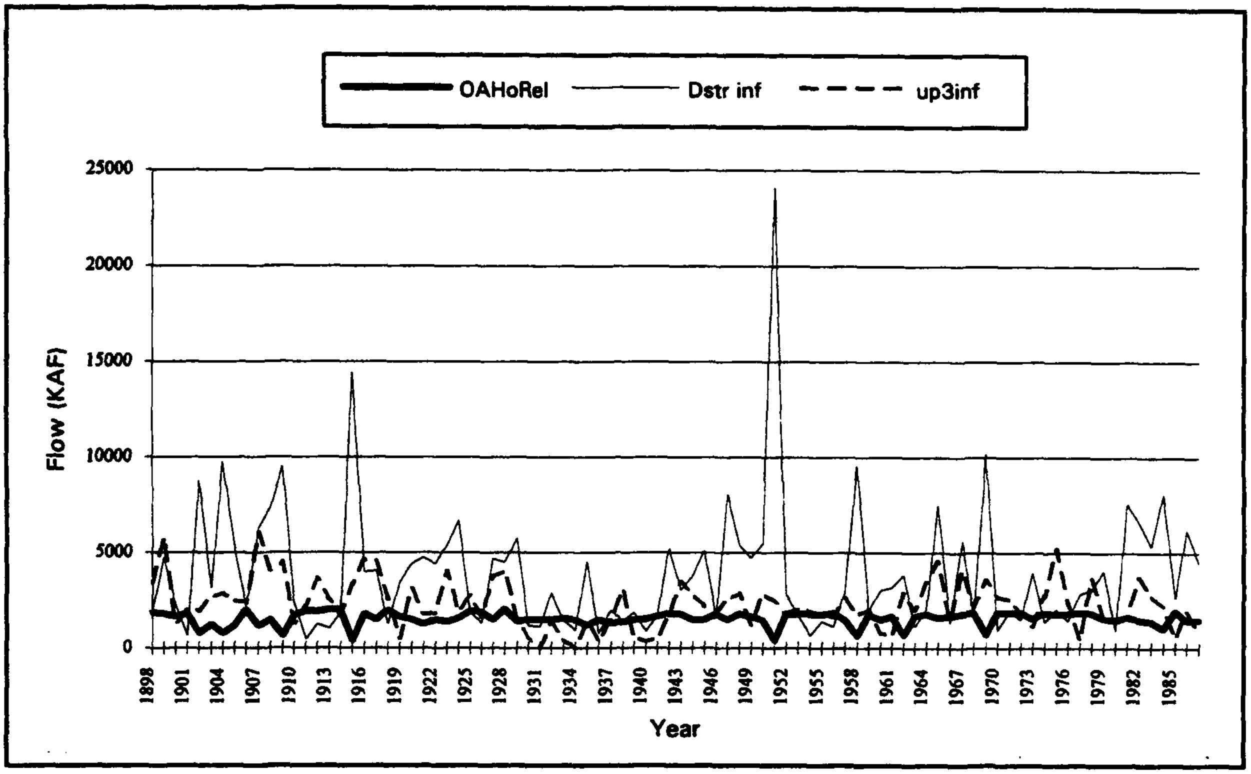


Figure 3.29 Time-Series of Optimal July Releases, Total Inflow Into the Upper Three Reservoirs, and Total Downstream Inflow

As the data in Table 3.24 indicates, for high values of total downstream inflow, the values of the combined inflow into Fort Randall, Garrison and Oahe were always less than 750 KAF/month, thus not requiring a further release reduction.

3.11.4 High Releases

For high releases the following rule was derived as:

> *else if (FtR→HER) inf < 2070 and (FtP→OAH) inf > 1530 or*
> *(FtR→HER) inf < 5400 and (FtR→NEB) inf < 1100 then Oahe Release = 1850 KAF*

The first part of this rule allows for Oahe releases to be increased if the inflow into the upper three reservoirs is not too small (lower quartile = 1,550 KAF/month), and the inflows downstream are low enough to avoid flood damage. As the data in Table 3.24 indicates this rule is a fairly good indicator of releases in this range.

Table 3.24
Numerical Data for July High Releases (KAF/month)

Year	OAHE opt Release	(FtR→NEB) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1898	1,887	580	1,871	3,438	1,850	-37
1901	1,834	396	652	1,994	1,850	16
1911	1,969	203	459	2,172	1,850	-119
1912	1,936	524	1,272	3,664	1,850	-86
1913	2,044	518	1,044	2,556	1,850	-194
1914	2,024	772	1,830	1,761	1,850	-174
1918	1,997	631	1,302	2,592	1,850	-147
1925	1,953	760	1,887	2,740	1,850	-103
1926	1,929	277	1,335	1,632	1,850	-79
1938	1,385	611	1,427	3,082	1,850	465
1946	1,820	334	1,657	1,890	1,850	30
1953	1,802	707	1,788	2,069	1,850	48
1954	1,802	293	684	1,955	1,850	48
1955	1,771	292	1,423	1,822	1,850	79
1956	1,864	151	1,146	1,652	1,850	-14
1959	1,807	405	1,994	2,029	1,850	43
1963	1,700	432	11,45	2,026	1,850	150
1964	1,820	544	2,069	3,491	1,850	30
1968	1,899	390	1,740	2,193	1,850	-49
1970	1,878	258	950	2,711	1,850	-28
1971	1,883	787	1,977	2,565	1,850	-33
1972	1,882	919	1,519	1,908	1,850	-32
1974	1,875	197	1,396	2,795	1,850	-25
1975	1,806	479	2,053	5,226	1,850	44
1976	1,817	305	1,443	2,364	1,850	33

3.11.5 Normal Releases

For releases in the median range the following rule was derived as:

else if (FtR→HER) inf < 2070 then Oahe Release = 1507 KAF
else if (FtP→OAH) inf < 2245 then Oahe Release = 1600 KAF

Table 3.25
Numerical Data for July Normal Releases (KAF/month)

Year	OAHE opt Release	(FtR→HER)Inflow	(FtP→OAH) Inflow	Release	Error
1900	1,672	2,276	1,291	1,600	-72
1910	1,709	2,447	1,312	1,600	-109
1919	1,674	3,461	517	1,600	-74
1921	1,262	4,761	1,787	1,600	338
1922	1,506	4,424	1,845	1,600	94
1924	1,580	6,710	1,923	1,600	20
1929	1,417	5,769	1,575	1,600	183
1930	1,507	1,193	588	1,507	0
1931	1,507	1,135	9	1,507	0
1932	1,507	2,904	1,360	1,600	93
1933	1,587	1,469	433	1,507	-80
1934	1,507	966	36	1,507	0
1935	1,220	4,532	1,480	1,600	380
1936	1,507	763	365	1,507	0
1937	1,337	1,989	1,511	1,507	170
1939	1,507	1,867	548	1,507	0
1940	1,538	898	365	1,507	-31
1941	1,680	1,703	522	1,507	-173
1942	1,820	5,219	1,769	1,600	-220
1945	1,507	5,098	2,240	1,600	93
1949	1,671	4,730	1,254	1,600	-71
1952	1,786	2,838	1,856	1,600	-186
1960	1,507	3,062	836	1,600	93
1961	1,707	3,198	694	1,600	-107
1966	1,684	1,364	1,443	1,507	-177
1973	1,573	3,999	1,195	1,600	27
1977	1,895	2,866	466	1,600	-295
1979	1,580	4,066	1,636	1,600	20
1980	1,507	946	,524	1,507	0
1981	1,666	7,589	1,759	1,600	-66
1984	1,028	8,076	2,226	1,600	572
1985	1,968	2,643	580	1,600	-368
1986	1,507	6,199	1,945	1,600	93
1987	1,507	4,502	888	1,600	93

For the remaining years the rule is:

else Oahe Release = 1450 KAF

3.12 August Release Rule for Oahe

3.12.1 Rule Summary

if ((FtP→OAH) inf<360) then 1300
else if (890<(FtP→OAH) inf<950) and (1000<(FtR→HER) Inflow<1700) then 2400
else if (700<(FtP→OAH) inf<1200) and ((FtR→HER) Inflow<900) then 1850
else if ((FtP→OAH) inf>1200) and ((FtR→HER) Inflow<900) then 2100
else if ((FtR→HER) Inflow>10000) then 13
else 1500

3.12.2 Rule Development

August is a transition month in terms of how Oahe release rules are derived. Although there are occasional high inflows downstream of Oahe which necessitate a reduction of releases to avoid flood damages, inflows into the upper three reservoirs are much smaller than in the preceding months. While the median value for the total inflow into the upper three reservoirs in July is 2,172 KAF/month, the median drops to 957 KAF/month in August. Therefore, whereas Oahe releases from April through July are predominantly dependent on inflow volumes at the lower Missouri basin, August optimized releases from Oahe start demonstrating a greater dependence upon upper basin inflows. A fairly tight range of Oahe releases can be seen in Figure 3.30.

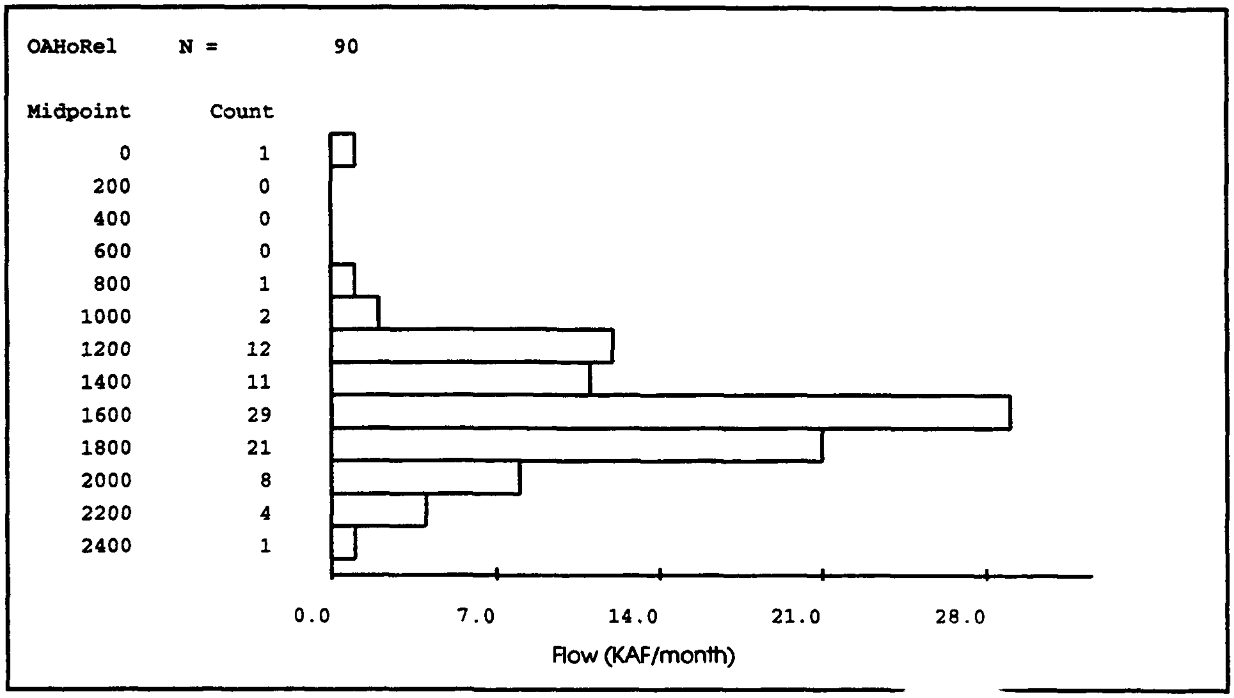


Figure 3.30 Histogram of Oahe Releases for August

3.12.3 Drought Releases

Similar to the drought releases of April through July, Oahe releases are not greatly reduced in August during drought years. This pattern is clear in the time-series of Oahe releases and inflow into the upper three reservoirs presented in Figure 3.31. Despite the low inflows into the upper three reservoirs, Oahe releases during the 1930's drought, albeit reduced, are not as low as the drought releases of the same period for the months of September through March. Because of these higher releases, flows are generally high enough to allow navigation to continue through August in all years except 1932, 1934, and 1936. The drought rule derived for August is:

if (FtP→OAH) inf < 360 then Oahe Release = 1300 KAF

The numerical values from which this rule was derived is presented in Table 3.26.

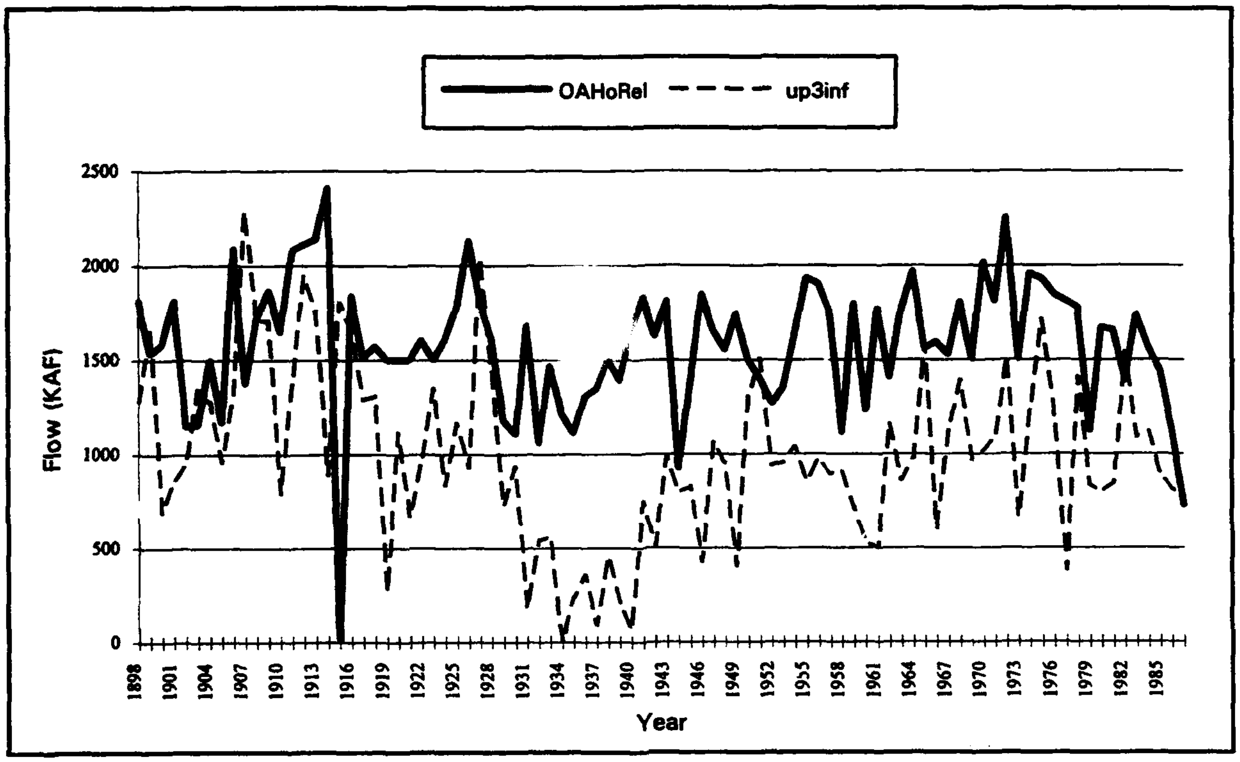


Figure 3.31 Time-Series of Optimal August Releases and Total Inflow into the Upper Three Reservoirs

Table 3.26
Numerical Data for August Drought Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1919	1,501	1,824	2,017	278	1,300	-201
1931	1,685	1,643	896	183	1,300	-385
1934	1,217	1,221	772	6	1,300	83
1935	1,114	1,643	1,214	239	1,300	186
1936	1,307	1,220	537	357	1,300	-7
1937	1,348	1,549	1,752	95	1,300	-48
1939	1,391	1,643	1,591	213	1,300	-91
1940	1,656	1,625	1,573	69	1,300	-356

3.12.4 Flood Control Releases

Unlike the preceding months, the inflows downstream of Oahe in August are generally not excessive. The highest value of the total downstream inflow in the hydrologic record used in this study was 11,479 KAF/month, but such a high value only occurred once, in 1915. In all other years the combined downstream inflows were less than 6,600 KAF/month, with a distribution of inflows at the downstream nodes such that there was minimal danger of urban flooding and practically no flooding of agricultural lands.

The only year with excessive downstream inflows was 1915. Therefore, a large reduction of releases from Oahe was made. Given that there was only one year in which such a high inflow occurred in the period of record, the rule for reducing releases from Oahe due to high downstream inflows was determined similar to those of June and July. The rule is:

else if (FtR→HER) inf > 11000 then Oahe Release = 10 KAF

Table 3.27
Numerical Data for August Flood Control Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule
1915	13	600	11,479	1,802	10

3.12.5 High Releases

Given the narrow range of releases from Oahe in August, an attempt was made to derive rules for the higher Oahe releases. The rule is:

else if 700 < (FtP→OAH) inf < 1200 and (FtR→HER) inf < 900 then Oahe Release = 1850 KAF
else if (FtP→OAH) inf > 1200 and (FtR→HER) inf < 900 then Oahe Release = 2100 KAF
else if 890 < (FtP→OAH) inf < 950 and 1000 < (FtR→HER) inf < 1700
then Oahe Release = 2400 KAF

The first part of this rule states that for median values of inflow into the upper three reservoirs (median = 957 KAF/month) and small values of total downstream inflow (lower quartile = 1,223 KAF/month), release should be higher than normal at approximately 1,850 KAF/month. If the inflow into the upper three reservoirs is higher (upper quartile = 1,306 KAF/month) with low inflows downstream, then the release can be increased to 2,100 KAF/month. The third part of this rule captures two of the remaining high optimized Oahe releases. This rule simply works, with no apparent justification. Data is contained in Table 3.28.

Table 3.28
Numerical Data for August High Releases (KAF/month)

Year	OAH opt Release	SUX opt Release	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1901	1,813	2,024	660	861	1,850	37
1911	2,082	2,123	449	1,371	2,100	18
1912	2,115	2,290	804	1,946	2,100	-15
1913	2,142	2,253	619	1,759	2,100	-42
1914	2,415	2,467	1,022	891	2,400	-15
1926	2,133	2,143	1,676	931	2,400	267
1941	1,833	1,864	736	741	1,850	17
1955	1,934	2,025	649	855	1,850	-84
1956	1,903	1,933	755	972	1,850	-53
1957	1,742	1,913	763	895	1,850	108
1963	1,762	1,874	835	861	1,850	88
1964	1,971	2,165	820	978	1,850	-121
1976	1,849	2,038	664	1,198	1,850	1

For cases which do not fall into any of the previous rules:

else Oahe Release = 1500 KAF

3.13 September Release Rule for Oahe

3.13.1 Rule Summary

if (FtP→OAH) inf<400 then 560
else if ((FtR→HER) inf <1620) and ((FtP→OAH) inf>730) then 1950
else if ((FtR→HER) inf >4500) and ((FtR→NEB) Inf>1400) then 550
else if (1850<(FtR→HER) inf<4000) and (740<(FtP→OAH) inf<1400) then 1700
else 1100

3.13.2 Rule Development

Similar to August, September is a transition month, with Oahe releases depending not only on the lower basin, but also on total inflow into the upper three reservoirs. Large reductions of Oahe release during the 1930's drought start to become apparent in September and then become increasingly noticeable until high spring flows render drought releases unnecessary. September still experiences reduction of Oahe releases due to large inflows downstream. Both the low inflow upstream and the high inflow downstream explain the low releases observed in the histogram (Figure 3.32) and in the time-series (Figure 3.33) of optimized Oahe releases.

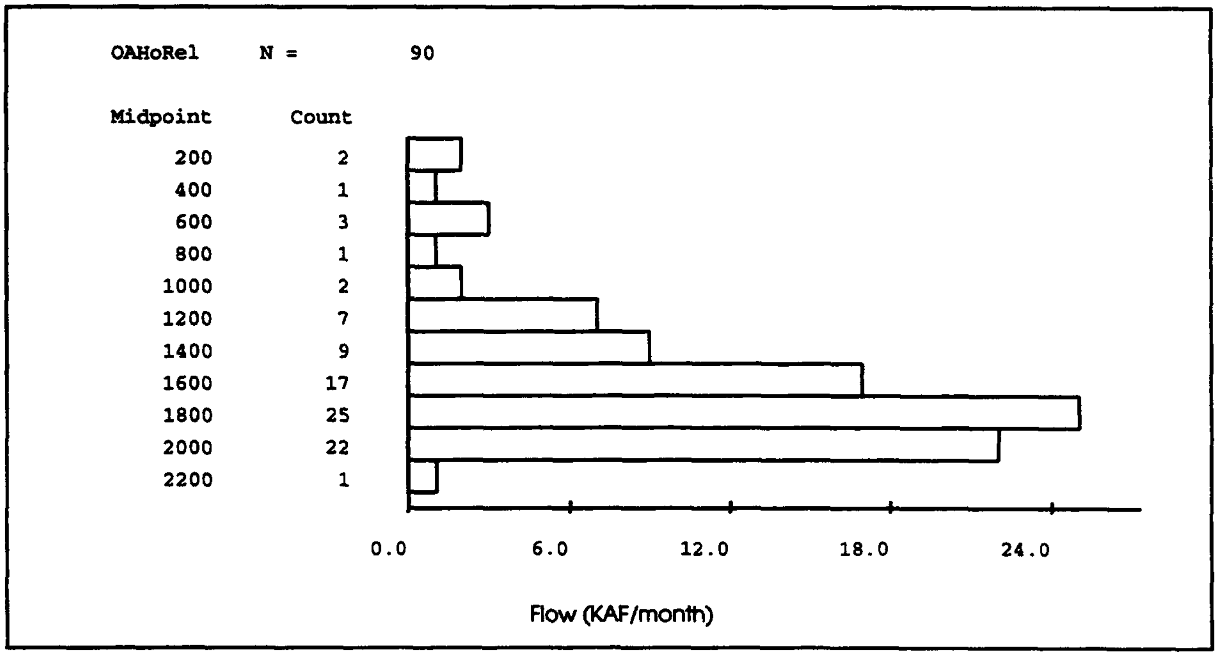


Figure 3.32 Histogram of Oahe Releases for September

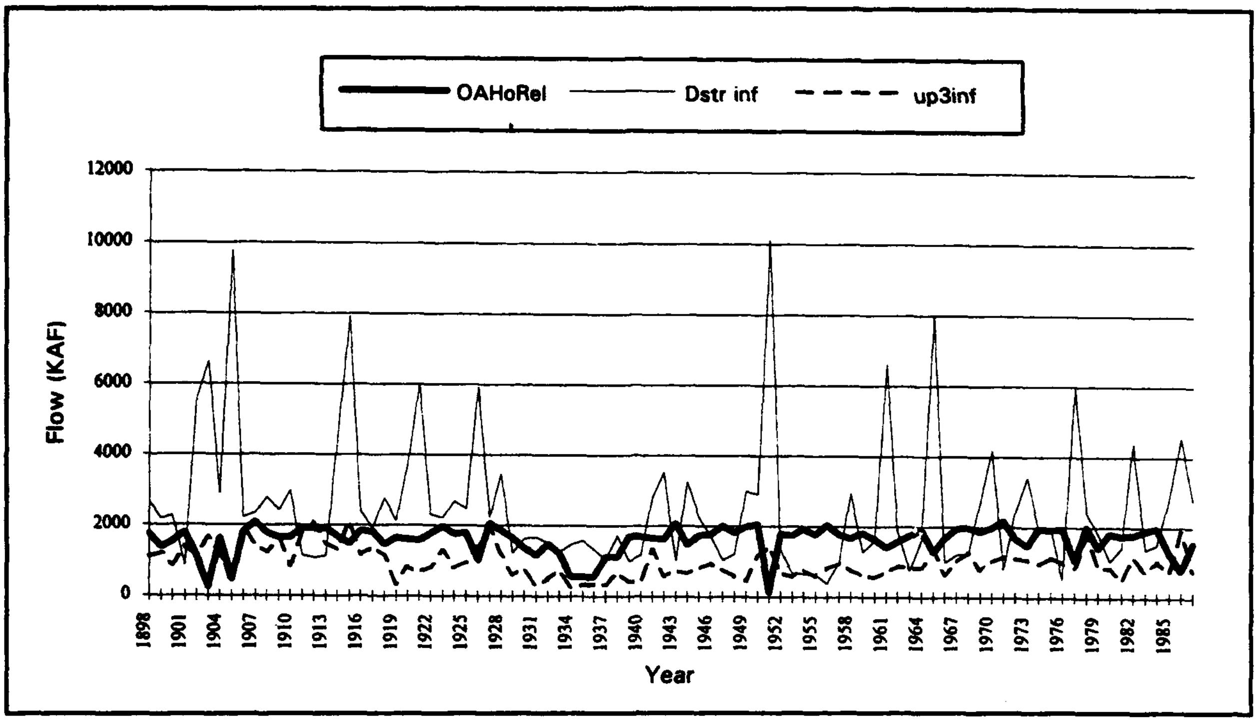


Figure 3.33 Time-Series of Optimal September Releases, Total Inflow Into the Upper Three Reservoirs, and Total Downstream Inflow

3.13.3 Drought Releases

As can be seen in Figure 3.33, drought releases correspond to years of low inflows into the upper three reservoirs. However, given that this reduction of release implies a shortening of the navigation season, drought releases are only effected in 1934, 1935, and 1936, even though low inflows into the upper three reservoirs also occur in 1931 and 1937. For these three years of drought releases a flow of 600 KAF/month is met at Sioux City, implying that the navigation season must end in August. The drought release rule for September is:

if (FtP→OAH) inf < 400 then Oahe Release = 560 KAF

The numerical data from which this rule was derived is presented in Table 3.29.

3.13.4 Flood Control Releases

From the time-series of Oahe releases (Figure 3.33), it is also possible to infer that Oahe releases are greatly reduced when the combined inflow at all nodes downstream of Oahe is high. This observation resulted in the rule *else if (FtR→HER) inf > 4500 and (FtR→NEB) inf > 1400 then Oahe Release = 550 KAF*

Table 3.29
Numerical Data for September Drought Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→NEB) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1919	1,661	1,748	600	2,133	340	560	-1,101
1931	1,158	1,208	304	1,682	316	560	-598
1934	566	600	249	1,473	275	560	-6
1935	557	600	261	1,588	334	560	3
1936	552	600	334	1,332	342	560	8
1937	1,123	1,234	303	1,037	336	560	-563

As in months of high inflows, as the total inflow increases downstream of Oahe, the release from Oahe decreases. Data associated with this rule is contained in Table 3.30.

Table 3.30
Numerical Data for September Flood Control Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→NEB) Inflow	NEB opt Flow	(FtP→OAH) Inflow	Release Rule	Error
1903	243	647	1,877	2,087	6,650	550	307
1905	464	600	1,489	1,920	9,782	550	86
1926	1,015	1,186	1,466	2,448	5,931	550	-465
1986	764	1,626	1,695	2,424	4,557	550	-214

3.13.5 Normal Releases

For releases in the modal range, the following rule was developed.

else if (1850(FtR→HER) inf <4000) and (740<(FtP→OAH) inf<1400) then 1700 KAF

The numerical data from which this rule was derived is presented in Table 3.31.

Table 3.31
Numerical Data for September Normal Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→NEB) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1898	1,748	1,868	2,666	1,108	1,700	-48
1899	1,372	1,960	2,177	1,206	1,700	328
1900	1,537	1,778	2,277	865	1,700	163
1904	1,641	1,887	2,896	1,129	1,700	59
1908	1,798	2,400	2,791	1,234	1,700	-98
1910	1,658	1,805	2,985	844	1,700	42
1916	1,841	2,100	2,428	1,161	1,700	-141
1917	1,834	2,184	1,914	1,376	1,700	-134
1918	1,459	1,600	2,774	1,136	1,700	241
1920	1,617	1,778	3,698	823	1,700	83
1922	1,778	1,850	2,318	821	1,700	-78
1923	1,984	2,255	2,217	1,294	1,700	284
1924	1,763	1,899	2,682	803	1,700	-63
1925	1,797	1,832	2,481	967	1,700	-97
1928	1,864	2,178	3,478	1,180	1,700	-164
1941	1,660	1,772	2,815	1,328	1,700	40
1945	1,737	1,987	2,279	798	1,700	-37
1950	2,070	2,475	2,913	1,146	1,700	-370
1958	1,668	1,699	2,950	771	1,700	32
1962	1,575	1,748	1,894	892	1,700	125
1969	1,882	2,117	2,749	789	1,700	-182
1972	1,688	1,949	2,425	1,117	1,700	12
1973	1,474	1,748	3,422	1,077	1,700	226
1974	1,956	2,117	1,952	953	1,700	-256
1975	1,933	2,129	1,980	1,145	1,700	-233
1987	1,555	1,742	2,770	786	1,700	145

3.13.6 High Releases

For the high range of releases, the following rule was inferred:

else if (FtP→OAH) inf>730 and (FtR→HER) inf <1620 then Oahe Release = 1950 KAF

which allows for an increase in streamflow at the lower basin if the inflow into the upper three reservoirs is high. Also, by restricting the total downstream flow to less than 1,620 KAF/month, floods are avoided in the downstream reaches. The data associated with this rule is included in Table 3.32.

Table 3.32
Numerical Data for September High Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1901	1,804	2,126	862	1,385	1,950	146
1911	1,913	2,126	1,139	1,768	1,950	37
1912	1,908	2,237	1,073	2,065	1,950	42
1913	1,924	2,231	1,127	1,498	1,950	26
1943	2,081	2,117	1,002	731	1,950	-131
1947	2,017	2,182	1,040	781	1,950	-67
1954	1,941	1,965	649	774	1,950	9
1956	2,059	2,026	380	823	1,950	-109
1957	1,779	1,860	977	949	1,950	171
1963	1,749	1,855	749	839	1,950	201
1964	1,923	2,069	1,611	841	1,950	27
1967	1,955	2,117	1,217	1,015	1,950	-5
1968	1,995	2,120	1,234	1,275	1,950	-45
1971	2,199	2,419	799	1,172	1,950	-249
1976	1,958	2,177	526	997	1,950	-8
1980	1,833	1,958	1,041	840	1,950	117
1983	1,903	2,273	1,367	737	1,950	47
1984	1,982	2,168	1,502	1,044	1,950	-32

For all other releases the rule is:

else Oahe Release = 1600 KAF

3.14 October Release Rule for Oahe

3.14.1 Rule Summary

if ((FtP→OAH) Inf < 792) and ((FtR→NEB) Inf < 274) then 250
else if ((FtR→HER) Inflow > 9000) then 350 else 1800

3.14.2 Rule Development

Winter patterns start to emerge in October. Large inflows become infrequent and optimized Oahe releases once again respond to inflow into the upper three reservoirs. As can be seen from the histogram of Oahe releases for the month of

October (Figure 3.34), most of the releases (seventy-two percent) are in the range of 1,500 to 2,100 KAF/month, with another cluster of releases less than 600 KAF/month. Of the eleven releases less than 600 KAF/month, three are due to high inflows downstream and the other eight are drought releases.

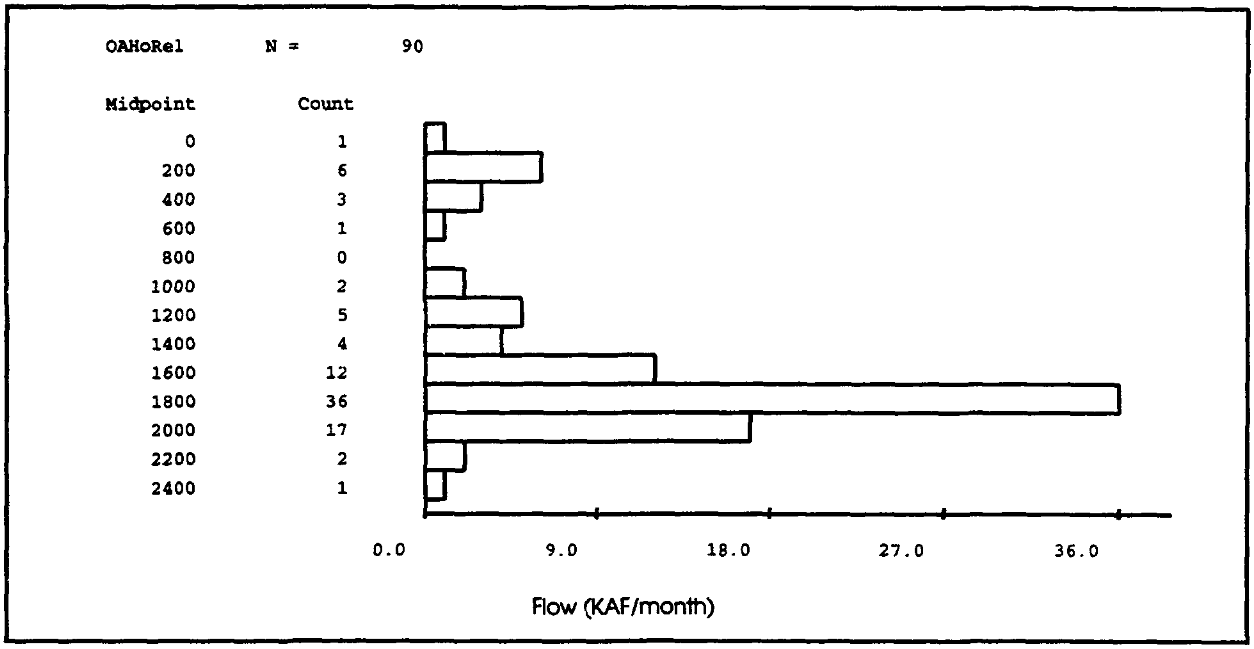


Figure 3.34 Histogram of Oahe Releases for October

3.14.3 Drought Releases

It is interesting to note that drought releases during the 1930's drought were only in effect for eight years as compared to twelve or thirteen years for December, January, and February. Also, Oahe releases in October during the 1950s drought were kept at normal levels (Figure 3.35). This normal release is most probably due to the less severe nature of this drought (when compared to that of the 1930s) as well as the fact that navigation penalty functions, which place a high value on the reduction of flow, are still in operation. HEC-PRM drought releases for October varied from 245 KAF/month to 597 KAF/month. The drought rule derived from the data is

if ((FtP→OAH) inf < 792) and ((FtR→NEB) inf < 274) then Oahe Release = 250 KAF

which picks all eight drought releases effected in October, all during the 1930s drought. Data concerning the drought release rule is included in Table 3.33. No incorrect selections are made by this rule.

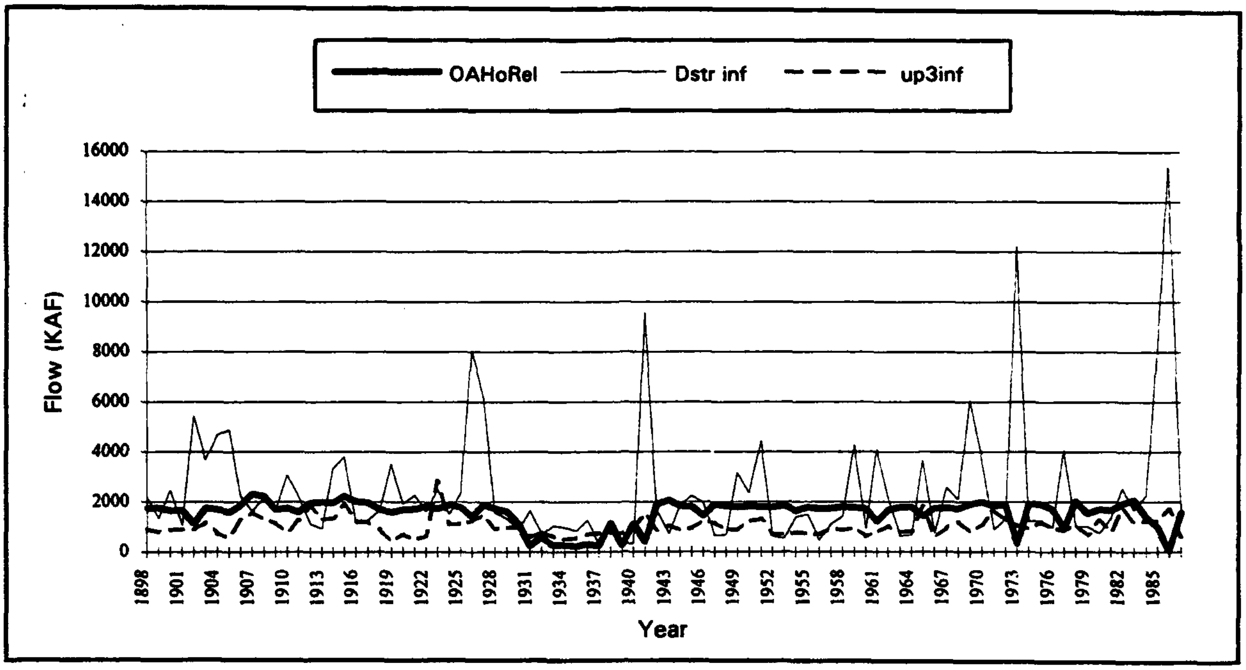


Figure 3.35 Time-Series of Optimal October Releases, Total Inflow Into the Upper Three Reservoirs, and Total Downstream Inflow

Table 3.33
Numerical Data for October Drought Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→NEB) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1931	245	600	200	1,648	612	250	5
1932	597	956	273	735	791	250	-147
1933	288	600	271	1,061	643	250	-38
1934	283	600	195	989	519	250	-33
1935	233	600	199	846	561	250	17
1936	319	600	162	1,270	714	250	-69
1937	248	600	180	352	762	250	2
1939	255	600	176	368	751	250	-5

3.14.4 Flood Control Releases

October is the last month in the year in which large inflows still occur. To avoid or minimize floods in the lower basin, Oahe releases are reduced so that the flow at Sioux City is no less than 600 KAF/month (Table 3.34). Despite this lowering of Oahe release, under HEC-PRM, flooding was not avoided between Boonville and the mouth of the Missouri River in 1973 and 1986. The flood control release rule is :

else if ((FtR→HER) inf > 9000) then Oahe Release = 350 KAF

Table 3.34
Numerical Data for October Flood Control Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→NEB) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1941	396	600	416	9,572	1,529	350	-46
1973	328	600	1,442	12,236	1,079	350	22
1986	51	600	2,194	15,408	1,720	350	299

This rule correctly selects all three reduced releases due to high downstream flows. This rule does not select any periods incorrectly.

3.14.5 High Releases

The majority of releases greater than 1,900 KAF/month, and certainly all releases greater than 2,000 KAF/month, were HEC-PRM's response to future high inflows. The June 1908 flood in Montana and North Dakota clearly exemplifies how HEC-PRM operates the larger reservoirs when floods are expected in the spring or summer months. In June 1908, the total inflow into the upper three reservoirs was 6,673 KAF/month and the total downstream inflow was 11,716 KAF/month. To minimize flood damages in the lower basin in June, HEC-PRM increased releases from Fort Peck, Garrison, and Oahe from as early as September 1907. By beginning of June 1908 the storages in Fort Peck, Garrison, and Oahe are down to 14,123, 18,592 and 19,430 KAF/month, respectively, thus enabling these reservoirs to store the high inflows and release only five KAF/month from Oahe in June. This strategy is only possible, however, with knowledge of future inflows. For this reason, it was not possible to develop a rule for high release from Oahe in October.

The rule for all other conditions is:

else Oahe Release = 1800 KAF

The fall months were the least complex months for which to derive rules since inflows are generally small and flood control operations such as the one described for the 1908 flood are less frequent this far before high inflows occur.

3.15 November Release Rule for Oahe

3.15.1 Rule Summary

if ((FtP→OAH) inf < 820) and ((FtR→NEB) Inf < 336) then 20
else if ((FtP→OAH) inf>1700) then 1020
else (FtP→OAH) inf

3.15.2 Rule Development

HEC-PRM Oahe releases in November turned out to be the most unique of the twelve months. By November, inflows are at low winter levels and high spring inflows are not due for another four months. As in October, flood control operations rarely occur. The time-series of Oahe releases and total inflow into the upper three reservoirs (Figure 3.36) indicate that, with exception of the 1930s drought and years in which storage must be made available for future high flows, optimized Oahe releases are kept very close to the combined inflow into the upper three reservoirs.

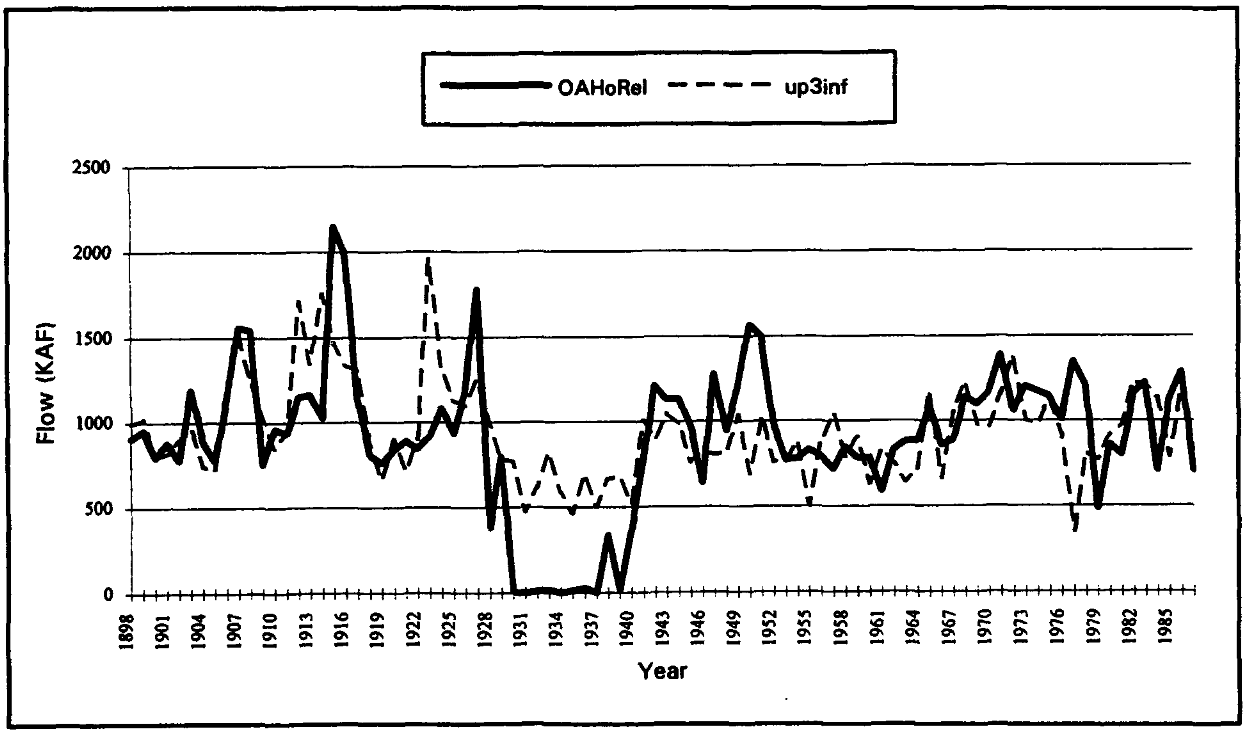


Figure 3.36 Time-Series of Optimal November Releases and Total Inflow Into the Upper Three Reservoirs

3.15.3 Drought Releases

Because it is not possible to determine when to activate a flood control release, the strategy for November is simply one of determining a drought rule and a rule for when the releases greatly diverge from the inflow into the upper three reservoirs. The drought rule is:

> *if (FtP→OAH) inf < 820 and (FtR→NEB) inf < 336 then Oahe Release = 20 KAF*

This rule correctly selects ten of a total of twelve drought releases. The data from which it was derived is contained in Table 3.35.

Table 3.35
Numerical Data for November Drought Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→NEB) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release	Error
1931	0	574	310	4,716	473	20	20
1932	13	574	326	832	616	20	7
1933	21	574	254	515	818	20	-1
1934	0	574	263	1,490	587	20	20
1935	14	574	335	2,290	464	20	6
1936	29	574	176	1,386	691	20	-9
1937	0	574	196	439	502	20	20
1938	338	1,262	277	819	666	20	-318
1939	18	574	163	352	675	20	2
1940	371	1,238	249	538	520	20	-351
1955	831	1,748	342	904	503	20	-811

From Figure 3.36 it is possible to see that, outside the range of drought and flood control releases, the greatest difference between the combined inflow into the upper three reservoirs and optimized Oahe release is for high values of inflow into the upper three reservoirs. This observation and a study of the numerical data give rise to the rule:

> *if (FtP→OAH) inf > 1700 than Oahe Release = 1020 KAF*

Table 3.36
Numerical Data for November Low Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→NEB) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release	Error
1912	1,148	2,178	582	1,438	1,710	1,020	-128
1914	1,023	2,196	439	836	1,756	1,020	-3
1923	920	2,065	428	1,545	1,960	1,020	100

For all other releases:

else Oahe Release = (FtP→OAH) inf

3.16 December Release Rule for Oahe

3.16.1 Rule Summary

if ((FtP→OAH) inf<550) and (50<(FtP→OAH) Inf<109) then 500
else if ((FtR→HER) Inflow < 870) and (100<(FtP→OAH) Inf<160) then 500
else if (FtP→OAH) inf<900 and ((FtP→OAH) Inf>306) then 900
else if ((FtR→HER) Inflow<1430) and ((FtR→NEB) Inf>330) then 1500
else if ((FtR→HER) Inflow<1650) and ((FtR→NEB) Inf>370) then 1100
else 1900

3.16.2 Rule Development

HEC-PRM releases from Oahe in December have a very similar pattern to those of January. The histogram of Oahe releases for December show the same range of releases as January (Figure 3.37). The distribution, however, is somewhat more uniform than that of January. Although, not as apparent as in the January histogram (Figure 3.37), Oahe releases in December may be classified into four levels:

1) Drought releases: Releases less than 600 KAF/month;
2) Normal releases: Releases in the range of 600 to 1,800 KAF/month;
3) Future inflows above normal: Releases in the range 1,800 to 2,100 KAF/month;
4) Excessive future inflows: Releases generally greater than 2,100 KAF/month.

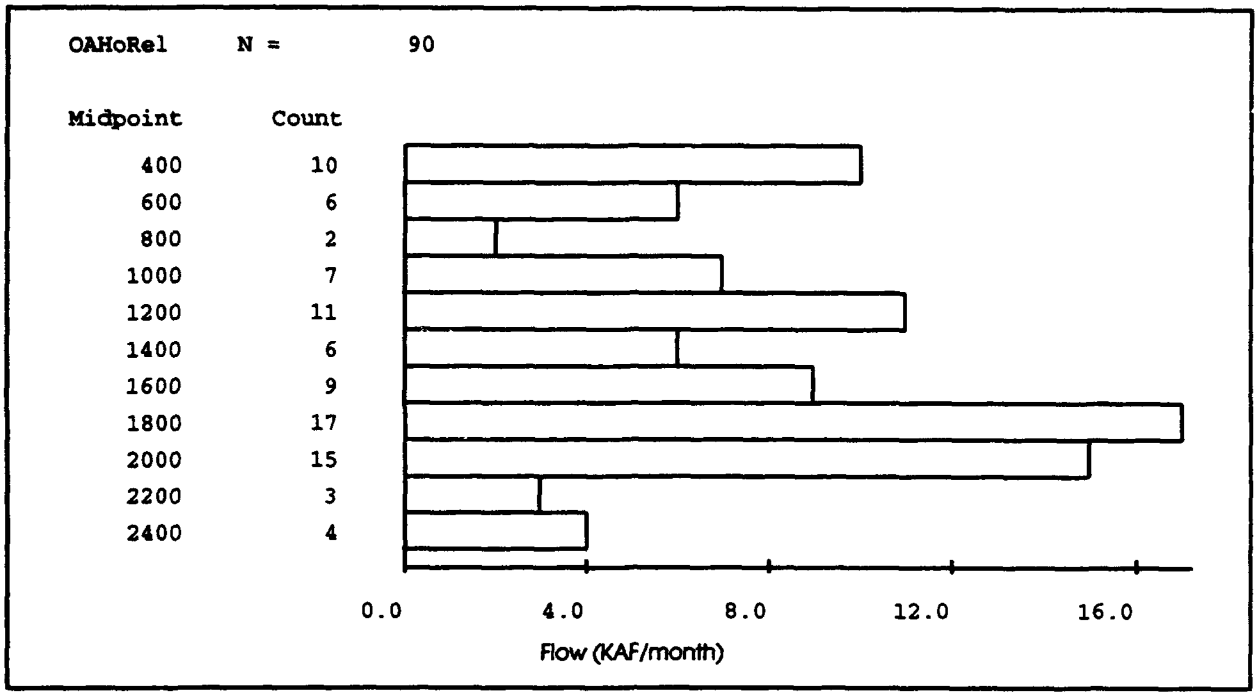


Figure 3.37 Histogram of Oahe Releases for December

3.16.3 Drought Release Rule

Drought releases are conspicuous during the twelve years of the 1930's drought as well as five years of the 1950's drought. This is because the navigation season ends in early December, thus allowing the system to reduce releases in order to retain water during dry periods. The time-series plot of Oahe releases for the month of December (Figure 3.38) clearly depict drought releases in the 1930s and 1950s. Associated with these drought releases are the low inflows into the upper three reservoirs.

As in other winter months, drought releases correspond to low inflows. Upon close inspection of the numerical data (Table 3.37), drought rule for December is

if ((FtP→OAH) inf < 550 and 100 < (FtR→SUX) inf < 160) or
(FtR→HER) inf < 870 and 50 > (FtR→SUX) inf > 100) then Oahe Release = 500 KAF

The December inflow values turned out to be the most reliable in establishing drought conditions. December drought rule correctly selects all years of the 1930's drought as well as 1952, 1953, 1955, 1956, and 1960. The only December drought release which this rule did not pick up was in 1954. For this reason, December inflow conditions were used as an additional drought rule for January, February, and March, the other months also not subject to navigation constraints.

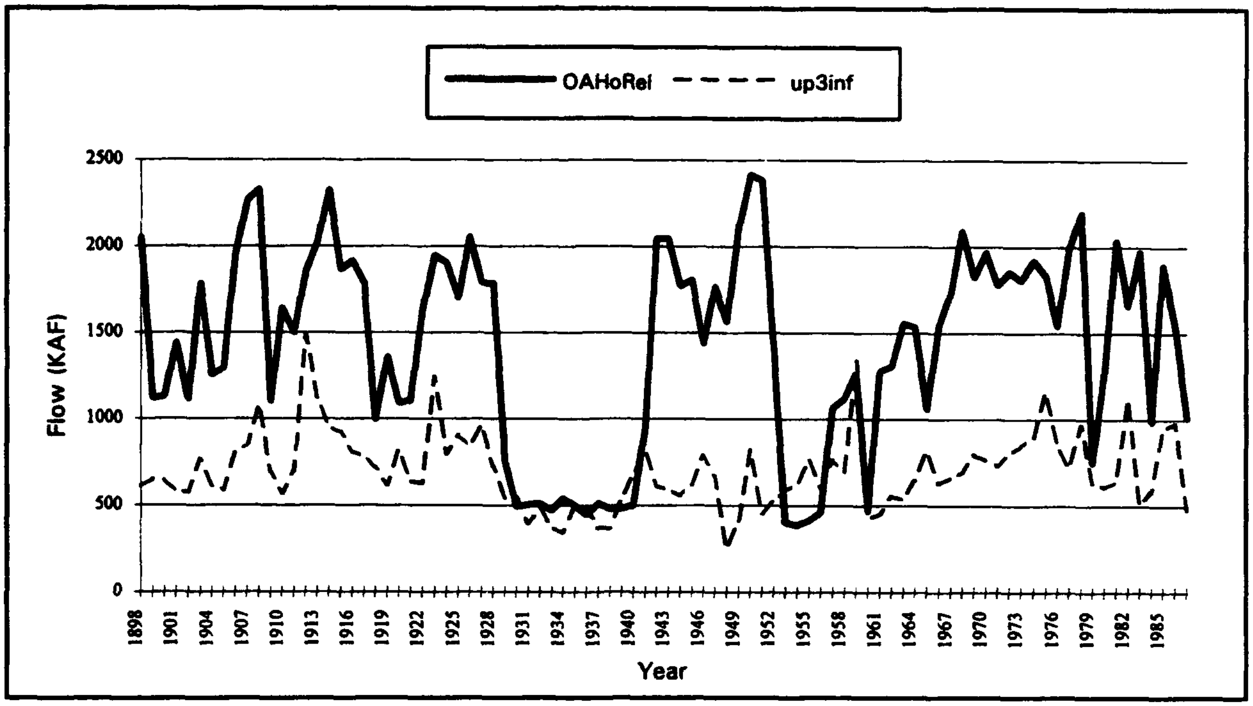


Figure 3.38 Time-Series of Optimal December Releases and Total Inflow Into the Upper Three Reservoirs

Table 3.37
Numerical Data for December Drought Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release Rule	Error
1929	757	861	95	781	542	500	-257
1930	492	574	107	1,191	545	500	8
1931	506	574	103	3,609	397	500	-6
1932	512	574	65	1,444	484	500	-12
1933	471	574	79	812	372	500	29
1934	543	574	85	2,368	345	500	-43
1935	500	574	77	1,595	506	500	0
1936	446	574	157	865	487	500	54
1937	511	574	101	473	372	500	-11
1938	477	574	103	782	366	500	23
1939	481	574	103	397	539	500	19
1940	501	574	111	522	681	500	-1
1952	,409	1,489	69	1,035	526	500	-909
1953	405	574	158	693	590	500	95
1955	414	574	158	571	767	500	86
1956	463	574	129	554	602	500	37
1960	471	574	92	1,256	428	500	29
1961	1,279	1,317	56	2,252	455	500	-779

3.16.4 Normal Releases

A rule that establishes releases in the normal range was less simple to determine. Of the forty-four releases in the range of 600 to 1,800 KAF/month, only seventeen were picked up with the rule (Table 3.38):

if (FtP→OAH) inf < 900 and (FtR→SUX) inf >306 then Oahe Release = 900 KAF
else if (FtR→HER)Inflow < 1430 and (FtR→NEB) inf > 330 then Oahe Release = 1500 KAF
else if (FtR→HER)Inflow < 1650 and (FtR→NEB) inf > 370 then Oahe Release = 1500 KAF

Table 3.38
Numerical Data for December Normal Releases (KAF/month)

Year	OAH opt Release	SUX opt Flow	(FtR→SUX) Inflow	(FtR→HER) Inflow	(FtP→OAH) Inflow	Release	Error
1899	1,118	1,262	502	1,574	650	1,100	-18
1901	1,444	1,563	396	923	577	1,500	56
1904	1,254	1,371	394	1,446	613	1,100	154
1912	1,857	2,159	390	616	1,486	1,500	357
1919	1,362	1,471	375	1,467	617	1,100	262
1920	1,092	1,246	512	1,484	817	1,100	8
1921	1,106	1,212	464	1,636	638	1,100	-6
1947	1,772	1,816	393	1,423	670	1,500	272
1948	1,565	1,657	331	1,164	255	1,500	-65
1952	1,409	1,489	400	1,035	526	1,500	91
1954	388	574	434	974	624	1,500	1,112
1957	1,068	1,218	442	1,584	765	1,100	32
1959	1,265	1,478	498	1,572	1,339	1,100	-165
1962	1,309	1,489	462	1,161	555	1,500	191
1963	1,557	1,862	449	767	538	1,500	-57
1964	1,537	1,779	497	1,141	648	1,500	-37
1965	1,058	1,376	307	1,842	816	900	-158
1966	1,546	1,770	467	1,084	630	1,500	-46
1976	1,541	1,704	407	906	850	1,500	-41
1979	748	1,225	466	2,092	632	900	152
1980	1,265	1,494	493	1,640	610	1,100	-165
1984	986	1,319	336	3,948	584	900	-86

For all other periods the rule is:

else Oahe Release = 1900 KAF

Chapter 4

Testing and Refinement of Suggested Rules by Simulation

4.1 Simulation Modeling Effort

A mass balance model, SiMM (Simple Missouri Model), was created to test the operating rules derived from the Phase I HEC-PRM results for the Missouri River System.

SiMM has the same physical configuration used in the Missouri River System HEC-PRM studies, with twelve nodes, six of which are the main stem reservoirs and the other six the lower basin nodes. The inputs to this model are the time series of inflows at eleven nodes (Big Bend's only inflow is a release from Oahe) and evaporation from each reservoir. Fort Peck, Garrison, and Oahe each have a monthly maximum storage capacity, above which spills occur. Fort Peck and Garrison releases also have a maximum value. Maximum monthly storage and releases are those modeled by HEC-PRM. The output from SiMM include reservoir storages and releases, and flows at the downstream nodes. The SiMM simulation is described in Appendix B.

System operating rules described in Chapter 3 were tested in two stages. The first stage tested the most apparent patterns observed in the output of HEC-PRM - the storage target for the lower three reservoirs and the storage allocation amongst the upper three reservoirs. In the second stage all rules were tested, including the monthly release from Oahe.

4.2 Results

4.2.1 Storage Target Rules for Big Bend, Fort Randall, and Gavins Point

Comparison of HEC-PRM and SiMM storages for Big Bend, Fort Randall and Gavins Point are shown in Figures 4.1, 4.2, and 4.3, respectively. As expected from the storage histograms for these reservoirs, the storage target rules are fairly accurate.

From the economic function plots for storage in these reservoirs (USACE, 1990), it appears that HEC-PRM modal monthly storage is the storage values for which the penalty function associated with that reservoir storage attains a minimum value.

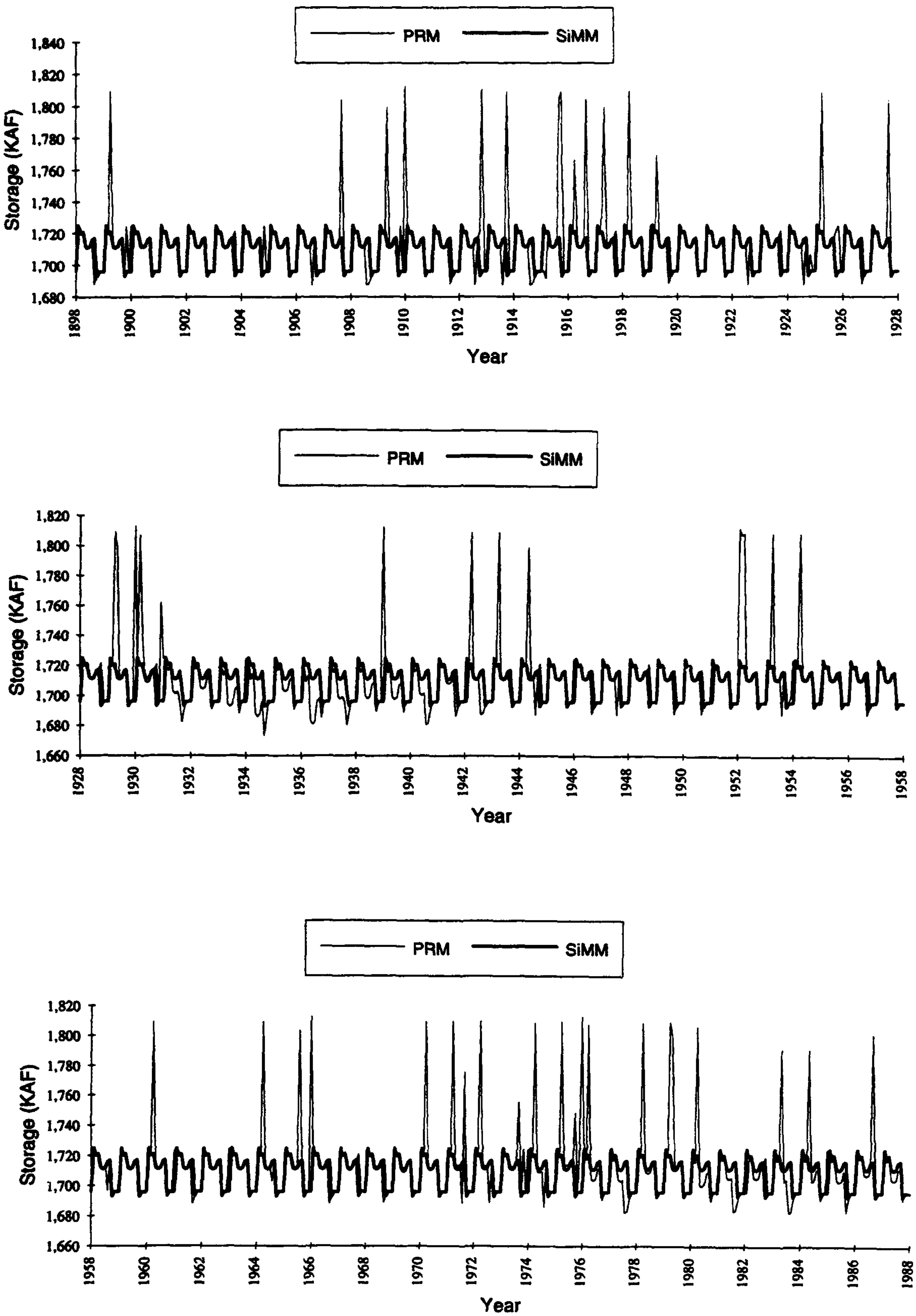
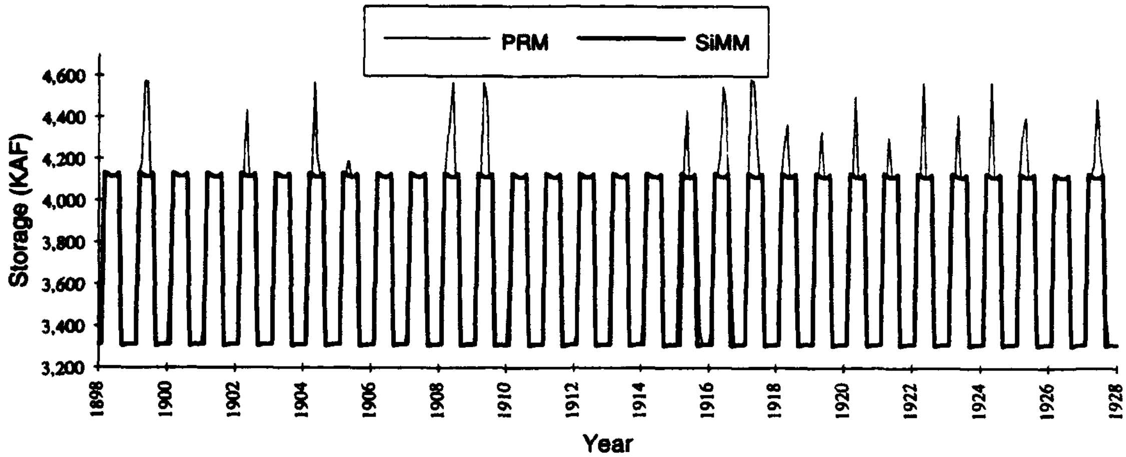
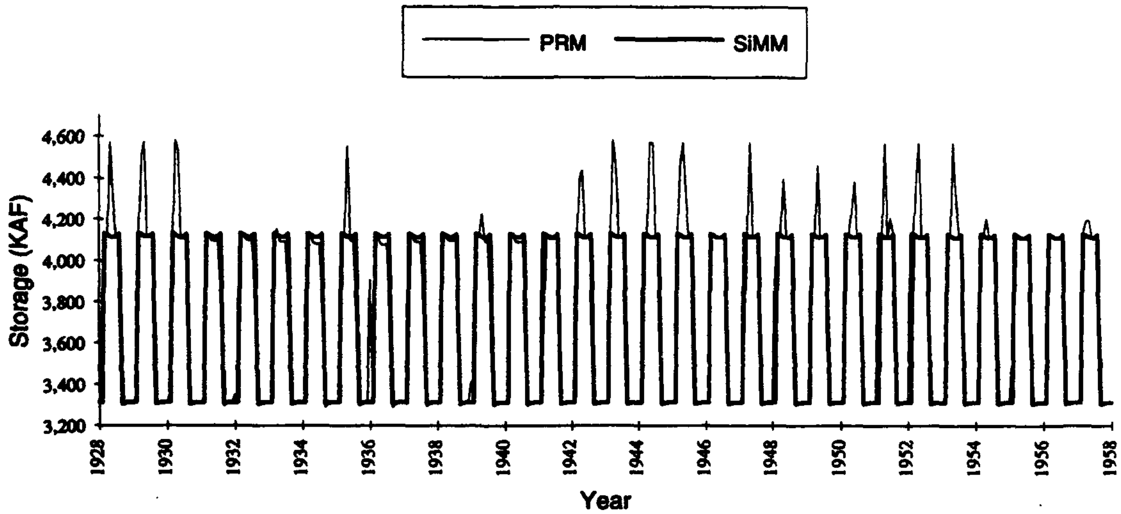


Figure 4.1 Time-Series of Big Bend Storage





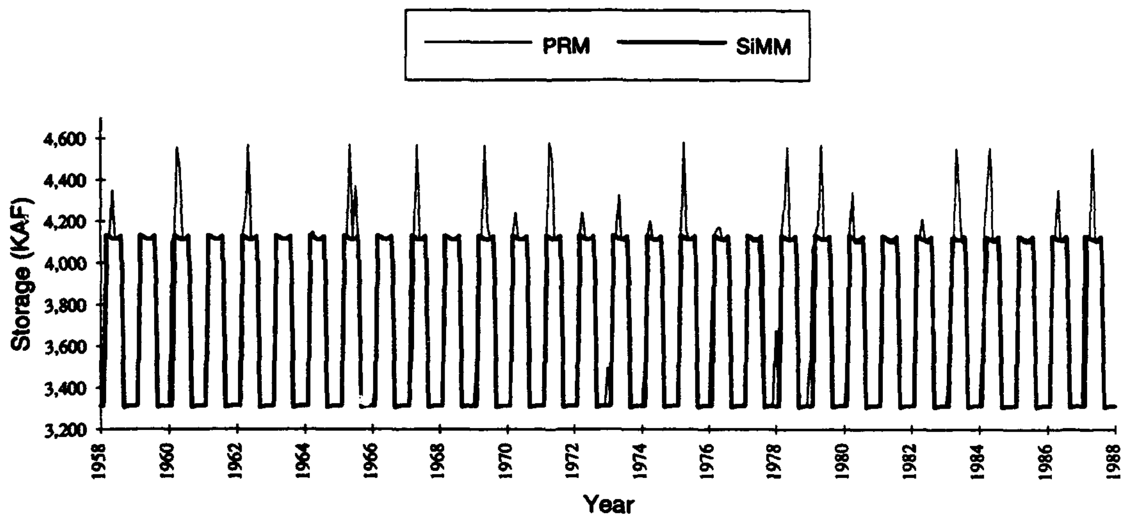
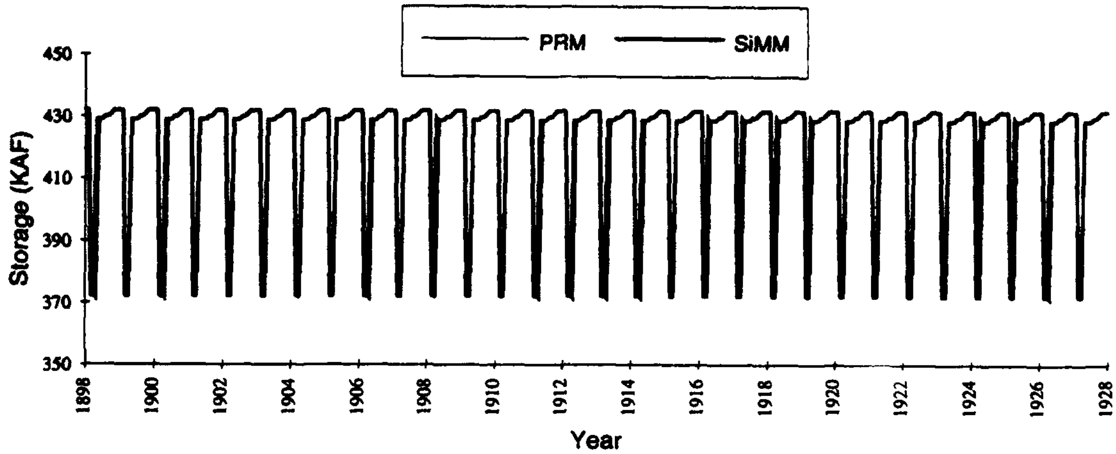
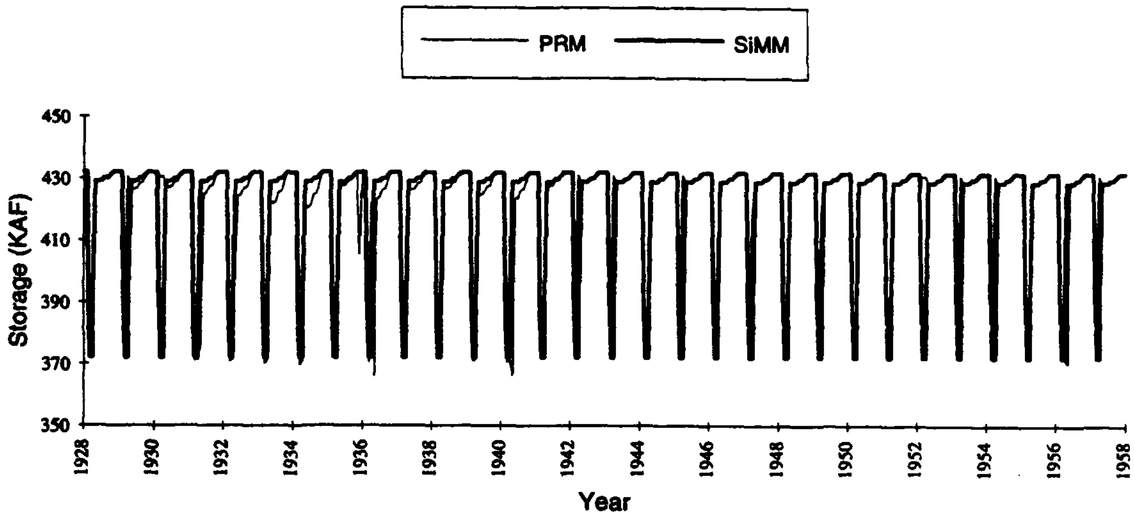


Figure 4.2 Time-Series of Fort Randall Storage





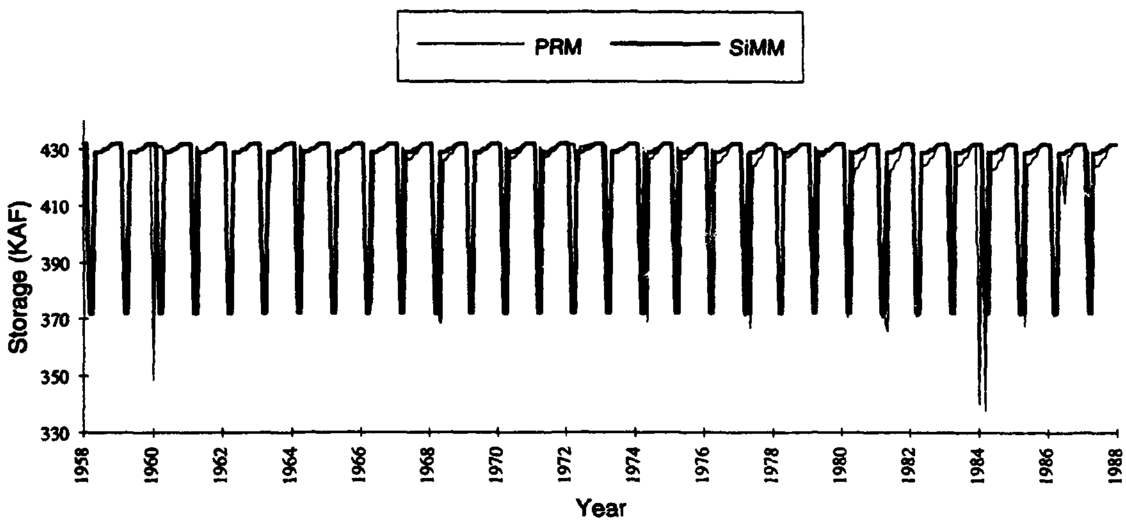


Figure 4.3 Time-Series of Gavins Point Storage

HEC-PRM storage time series for Big Bend, Fort Randall and Gavins Point show peaks for the first two reservoirs and an increase in storage for Gavins Point that differs from that modeled in SiMM. It appears that HEC-PRM uses this extra storage for flood control.

4.2.2 Storage Allocation Rule for Fort Peck, Garrison, and Oahe

To test the storage allocation rule, the upper three reservoirs are treated as a control volume, and HEC-PRM Oahe releases are used in SiMM. By using HEC-PRM releases for Oahe, the combined simulated storage in the upper three reservoirs is the same as in HEC-PRM. It is, therefore, possible to determine how well the allocation rule works without the added error introduced by using the Oahe release rules described in Chapter 3.

Once SiMM was debugged and run, the results were very encouraging. Comparison of HEC-PRM storages in all six reservoirs with those of SiMM are shown in Figures 4.1 through 4.6. The results displayed in these figures were obtained from the first run of SiMM, that is, without any attempt at calibrating the monthly storage allocation rules which were obtained by visually fitting lines to the scatter plots shown in Figures 3.4 through 3.15.

Both Fort Peck and Garrison were modeled with a maximum monthly storage. These values are the maximum storage for each month in HEC-PRM results. Because HEC-PRM Oahe releases were used in this first stage, it was not possible to include in SiMM a maximum storage for Oahe, since this would result in the total storage for the upper three reservoirs being different from that of HEC-PRM. Without a maximum storage in the model, SiMM Oahe storage, at times, exceeds Oahe maximum capacity.

Figures 4.4 through 4.6 indicate that the storage allocation rules work very well, reducing the problem of developing operating rules for the main stem Missouri River system from HEC-PRM results to one of finding release rules for Oahe.

4.2.3 Oahe Release Rules

Development of release rules for Oahe was by far the most complex part of this study. As mentioned in Chapter 3, Oahe release rules were developed after careful examination of time series plots and numerical data for each month, rather than any sophisticated data analysis method. Unlike the testing of rules in the first stage, many runs of SiMM were required for rule refinement in this second stage of operating rules testing.

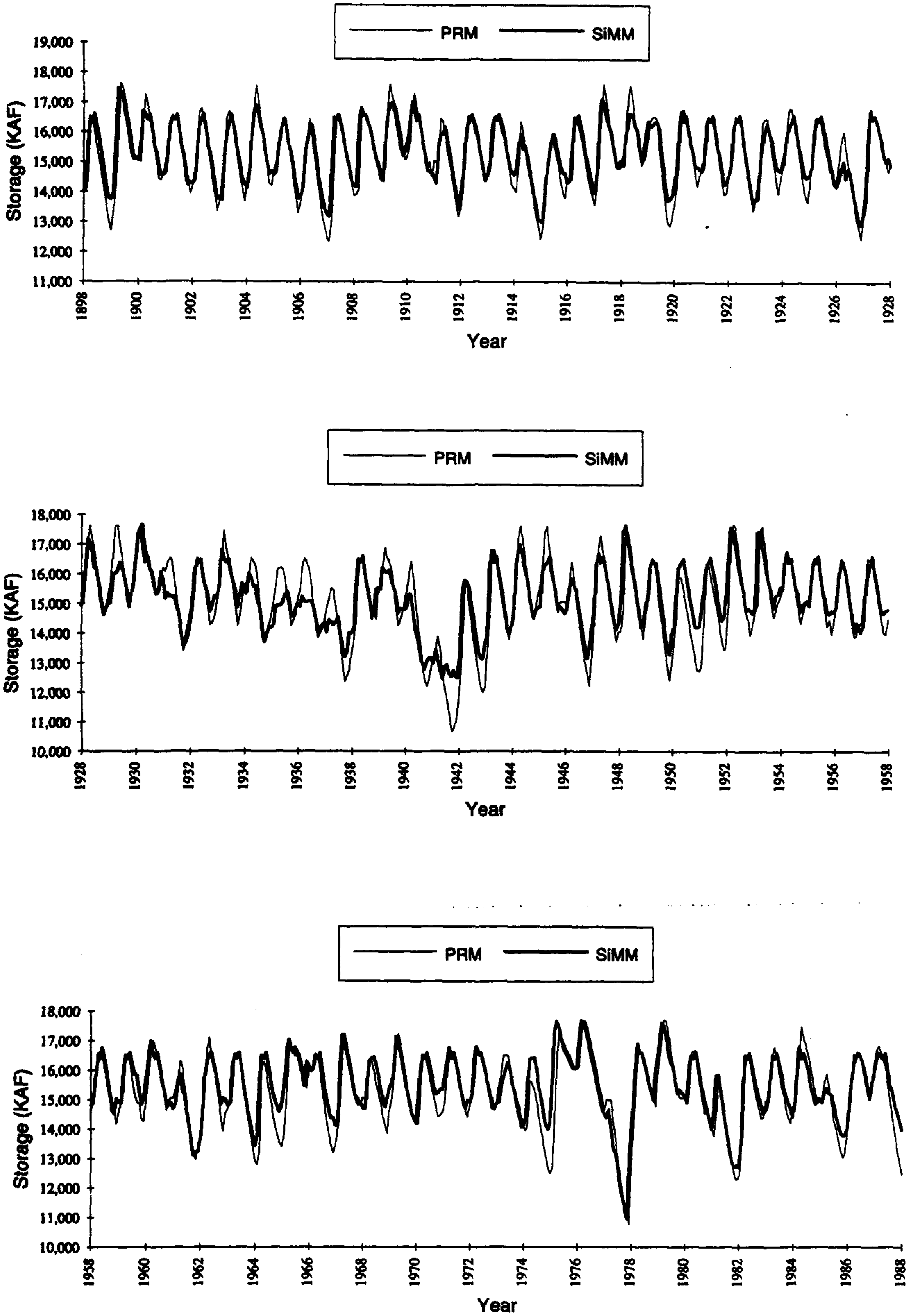


Figure 4.4 Allocation Rule Test: Fort Peck Storage

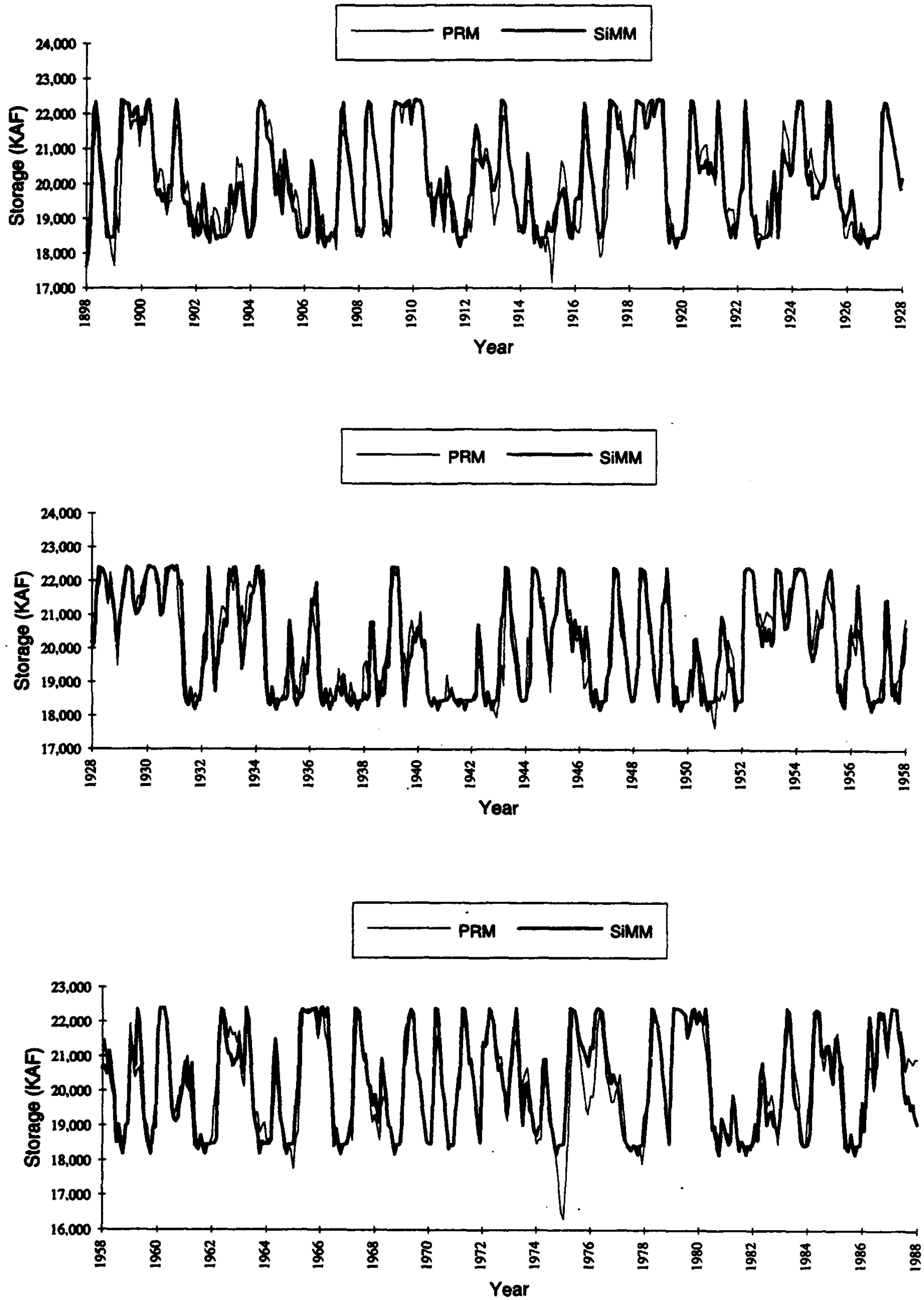
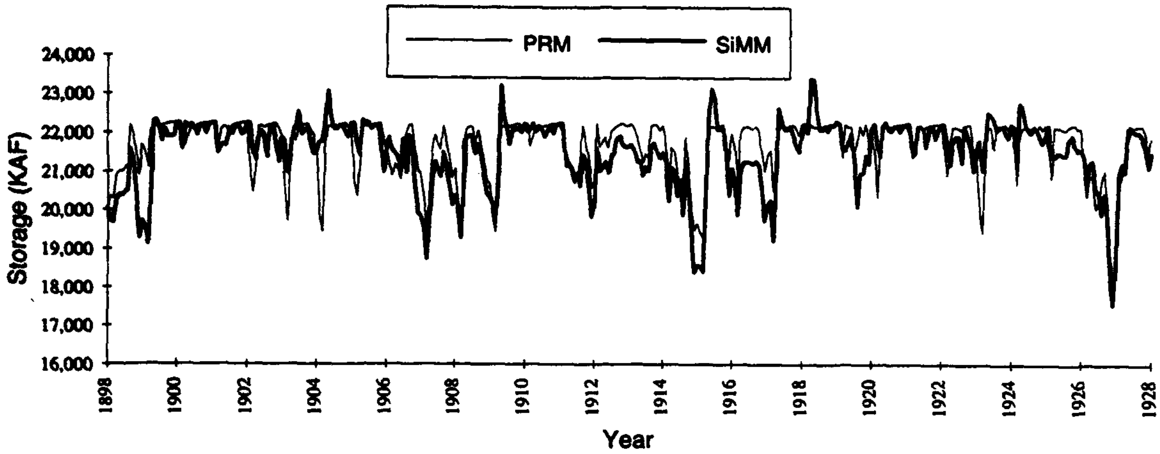
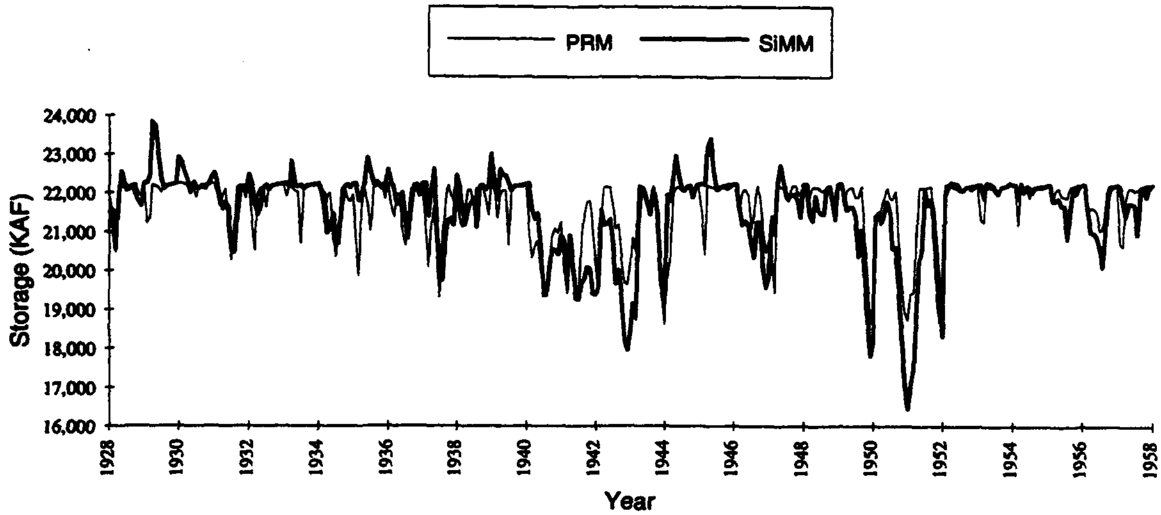


Figure 4.5 Allocation Rule Test: Garrison Storage





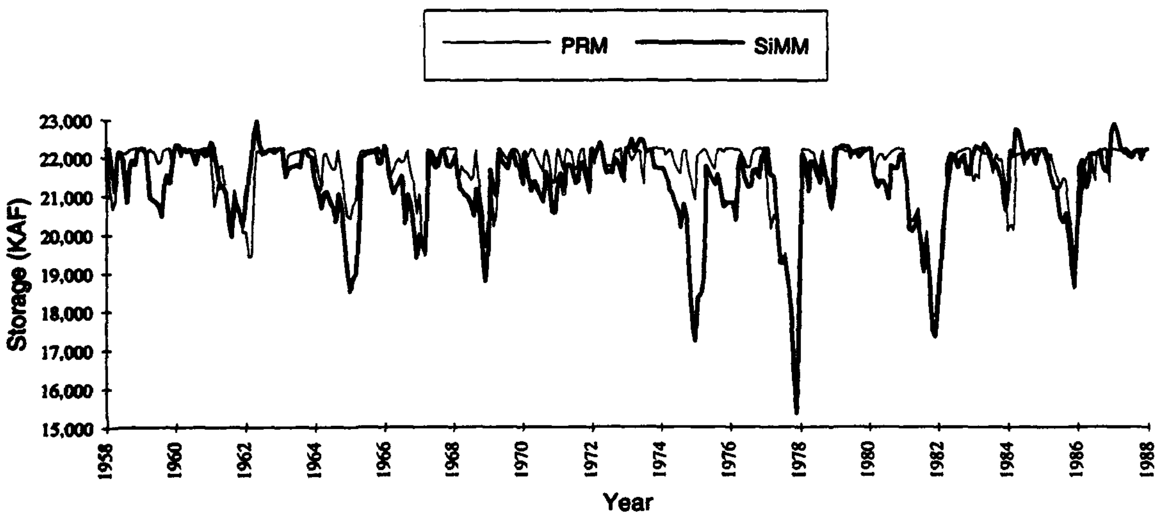


Figure 4.6 Allocation Rule Test: Oahe Storage

Oahe release rules were tested with SiMM by replacing HEC-PRM Oahe releases with the monthly rules derived from the numerical data. In addition to maximum monthly storages for Fort Peck and Garrison, a maximum monthly storage for Oahe was introduced in this second stage of SiMM.

Figures 4.7 through 4.9 compare the time series plots of Oahe releases for HEC-PRM, SiMM, and MRD simulation results. From these plots it appears that SiMM releases are generally closer to those of HEC-PRM than MRD releases. This observation is supported by the difference measure for reservoir releases presented in Table 4.1 for the full set of results and for the subset of results which exclude the 1930s and 1950s drought.

Table 4.1
Square Root of Mean Squared Difference for Reservoir Releases

	Full Time Series		1930s & 1950s Droughts Excluded	
Reservoir	SiMM	MRD	SiMM	MRD
Fort Peck	326	295	301	280
Garrison	546	646	536	573
Oahe	440	625	452	658
Fort Randall	480	699	494	759

The square root of the mean squared difference is defined to be:

$$\sqrt{\frac{1}{n}\sum_{j=1}^{n}(X_{PRM} - X_{SiMM})_j^2}$$

in which n is the number of data points compared, and x_{PRM} and x_{SIM} are the HEC-PRM and simulated data values for which the difference measure is calculated.

SiMM releases are closer to HEC-PRM releases than those of MRD for all reservoirs but Fort Peck. Time series of releases from the other reservoirs are presented in Appendix C.

4.2.4 Drought Operations

A comparison of HEC-PRM and SiMM Oahe releases during the two major droughts (Figures 4.8 and 4.9) indicates that the drought rule used in SiMM very closely reproduces optimized Oahe releases. An important difference between current drought operations of the Missouri River system and that suggested by HEC-PRM is

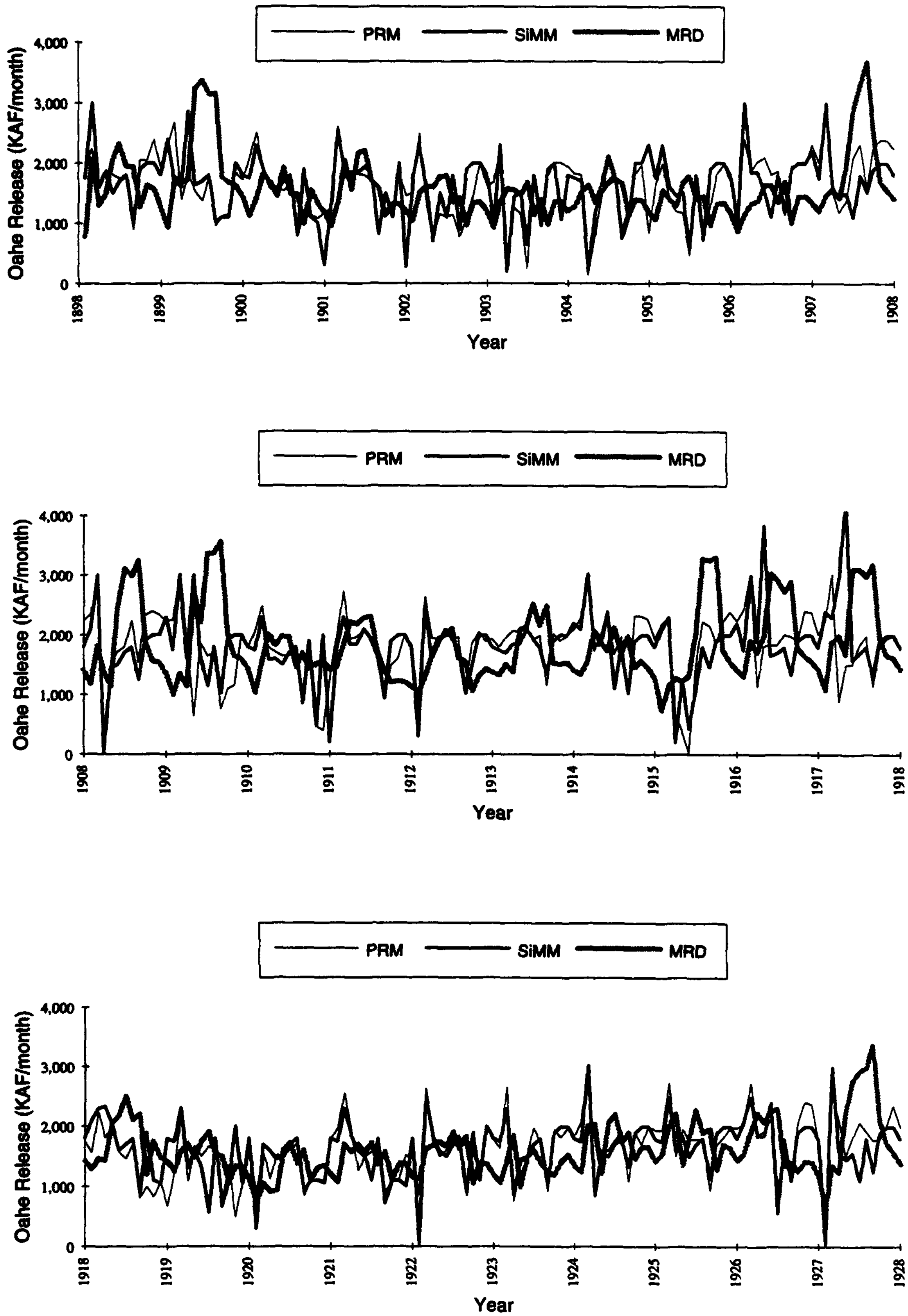
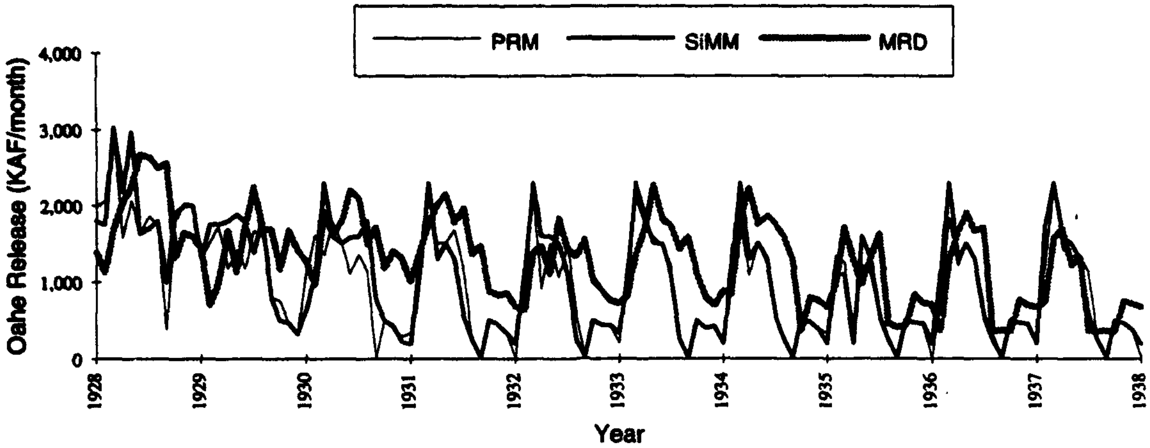
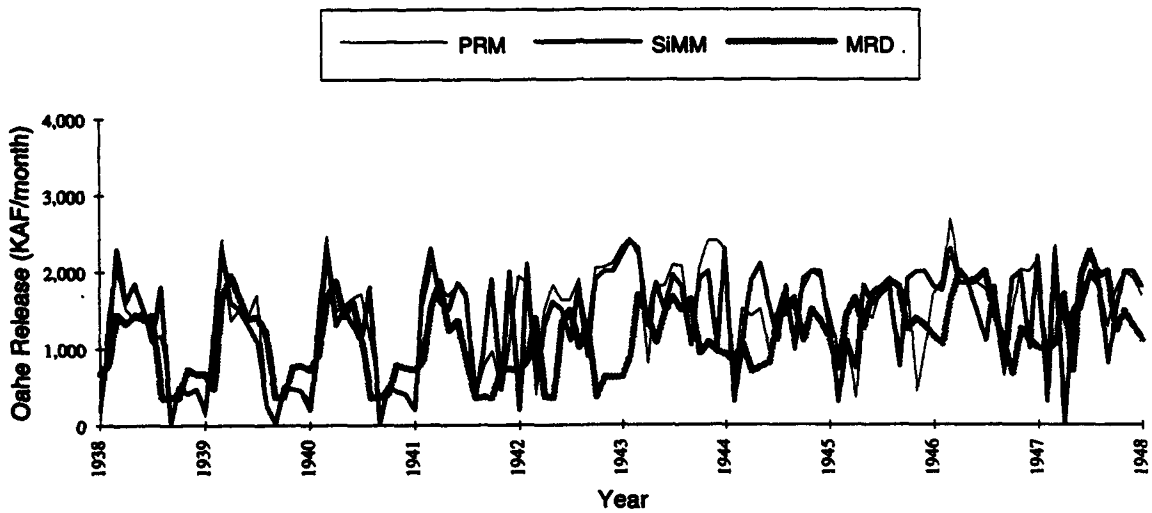


Figure 4.7 Full Operation Rules Test: Oahe Releases 1898-1928





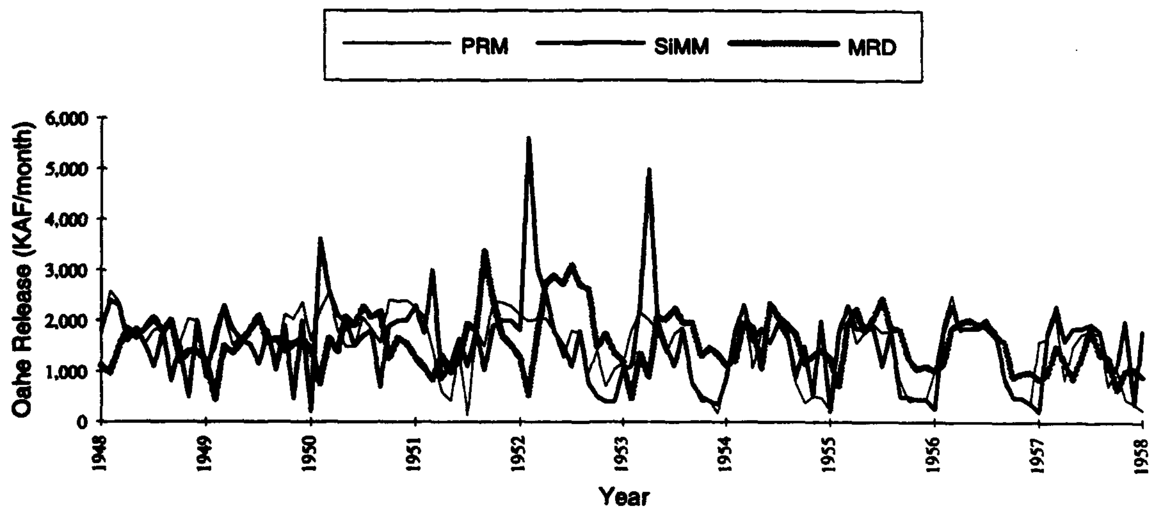


Figure 4.8 Full Operation Rules Test: Oahe Releases 1928-1958

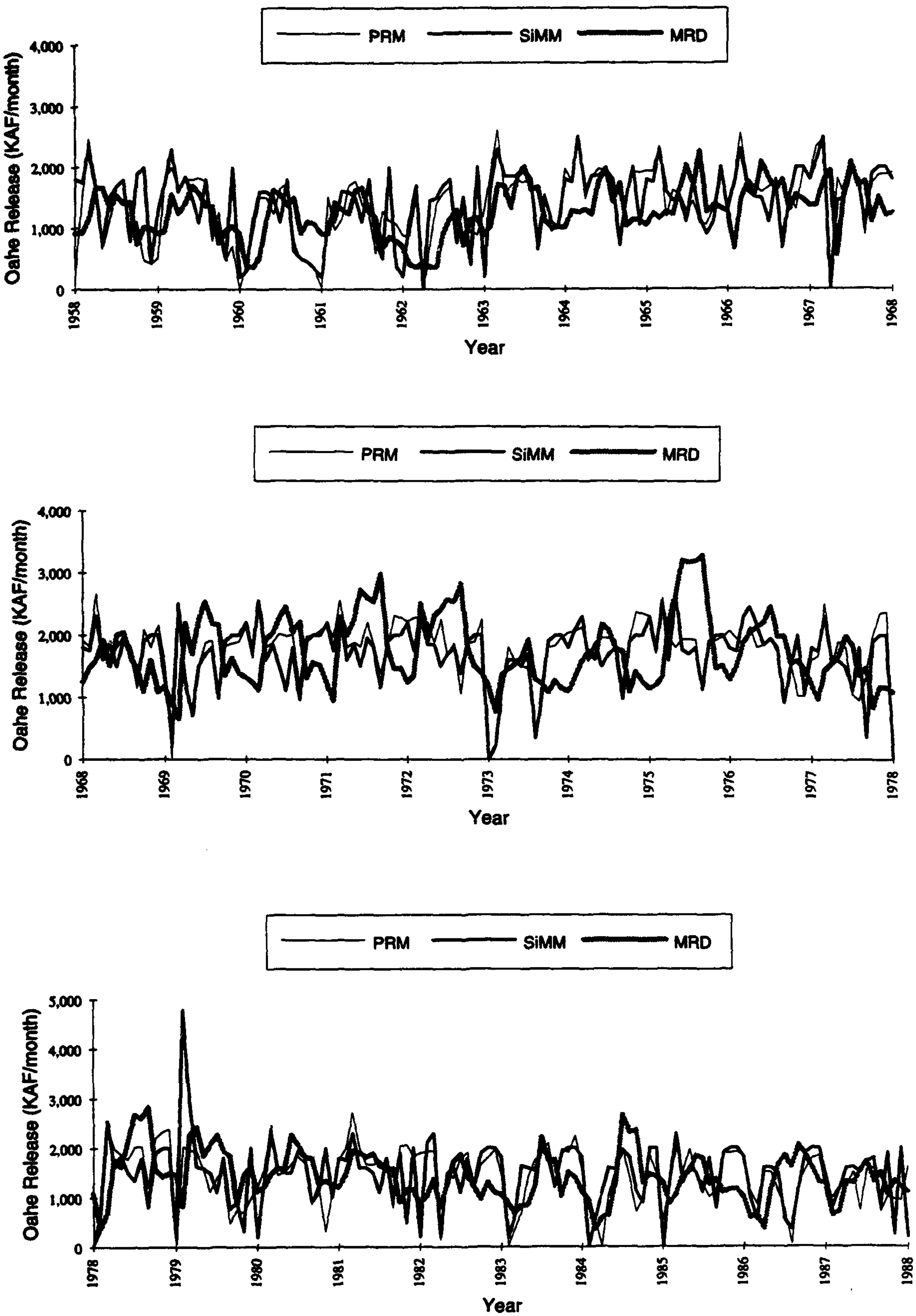


Figure 4.9 Full Operation Rules Test: Oahe Releases 1958-1988

apparent in these plots. MRD Oahe releases during the fall and winter months of the 1930s drought decreased as the drought progressed. This seems to imply that the release rule used in MRD model is dependent on the storage in the upper basin reservoirs, which decreases drastically during this drought. This is at odds with Oahe drought release rules presented in Chapter 3 and used in SiMM which, with exception of maximum monthly storage, are solely dependent on past and present inflows.

Figure 4.10 presents the time series plot of combined storage in Fort Peck, Garrison, and Oahe. SiMM results show a significant improvement over MRD results, further supporting the claim that drought release rules might be better based on inflow volumes only.

4.2.5 Flood Control Operations

Excessive SiMM releases from Oahe in 1916, 1917, 1952, 1953, and 1979, occur in months that experience large inflows into the upper basin reservoirs, and follow a period of a few months in which SiMM underestimates HEC-PRM releases. This demonstrates HEC-PRM's ability to look into the future and operate the system to reduce or avoid floods by increasing reservoir releases in the months preceding excessive inflows, something that cannot be reproduced in a simulation model. Snow pack survey data was not available for this study so that no preditions of future inflows could be included in SiMM. Table 4.2 presents the flows for which the maximum and minimum flood related penalty values are attained for each reach in the lower basin.

Table 4.2
Streamflow Values for Maximum and Minimum Flood Related Penalty Values (KAF/month)

	Urban Flood		Ag. Flood	
River Reach	Maximum	Zero	Maximum	Zero
Sioux to Omaha	24,343	13,706	27,919	5,789
Omaha to Nebraska	18,908	7,279	22,793	5,343
Nebraska to Kansas City	9,651	4,524	12,306	4,524
Kansas City to Boonville	38,606	9,651	21,474	3,619
Boonville to Hermann	23,948	7,543	23,948	7,543
Hermann to Mouth	28,773	17,855	28,773	8,867

Time series plots of streamflows in the Nebraska City to Kansas City river segment are shown in Figures 4.11 and 4.12. This is the lower basin main stem reach with the least channel capacity and thus the most likely to flood when excessive Oahe releases occur. For this reach, the urban flood penalty function has zero value at 4,524 KAF/month and reaches maximum value at 9,651 KAF/month. Much of the flood damage caused by the excessive releases in SiMM could have been offset by using some of the exclusive flood control pools in the reservoirs, giving the system an ability to capture an extra 2,000 to 3,000 KAF of flood waters.

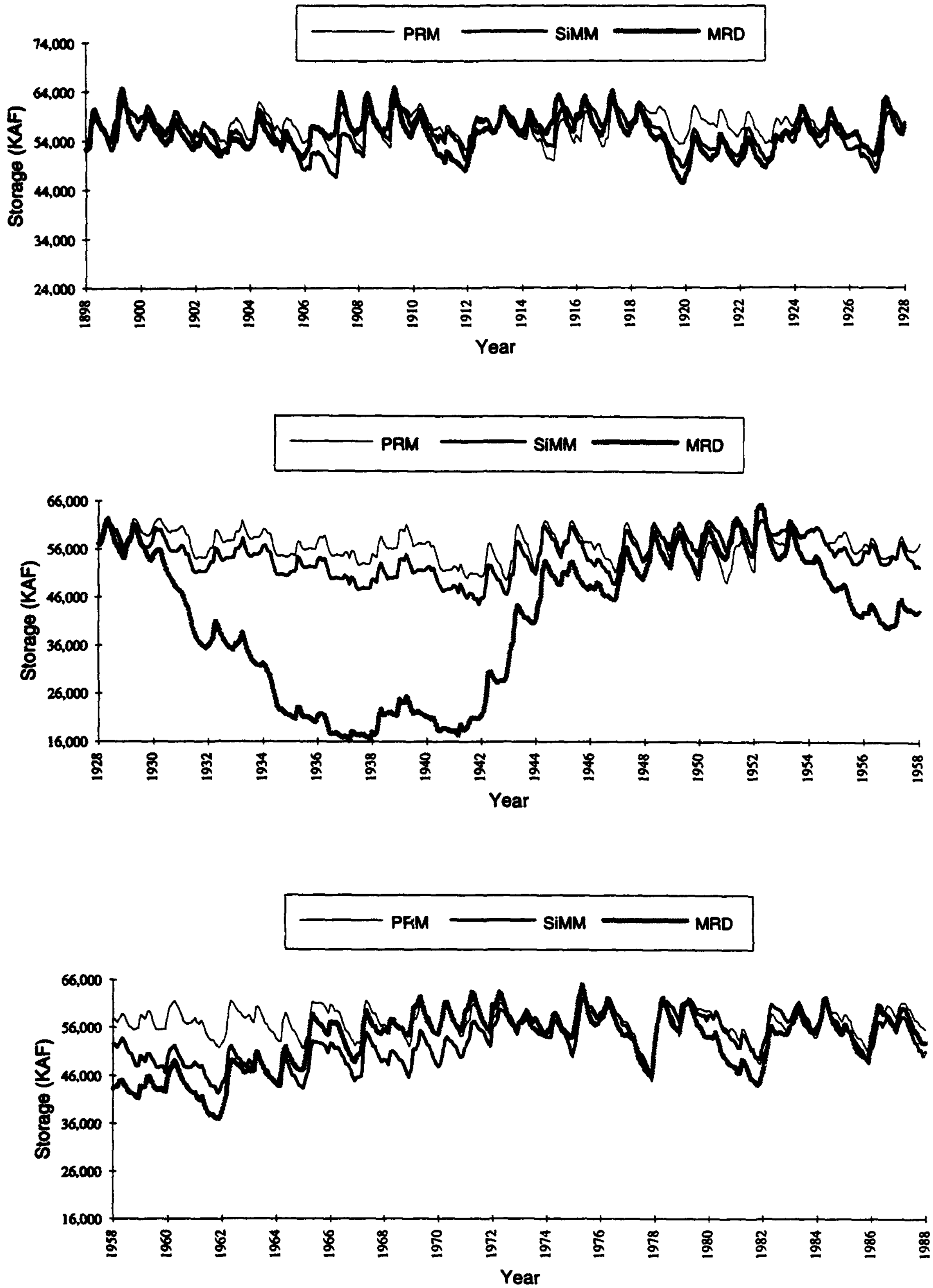
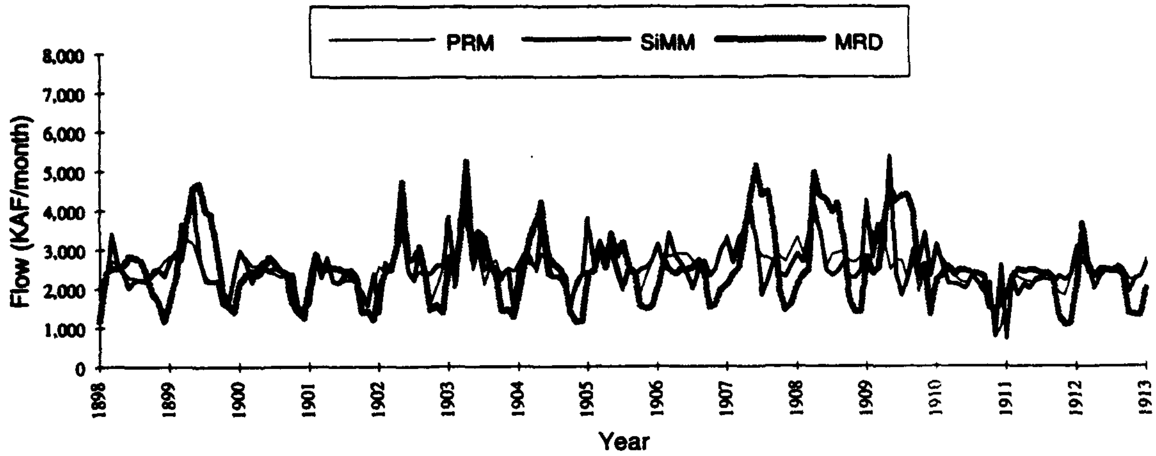
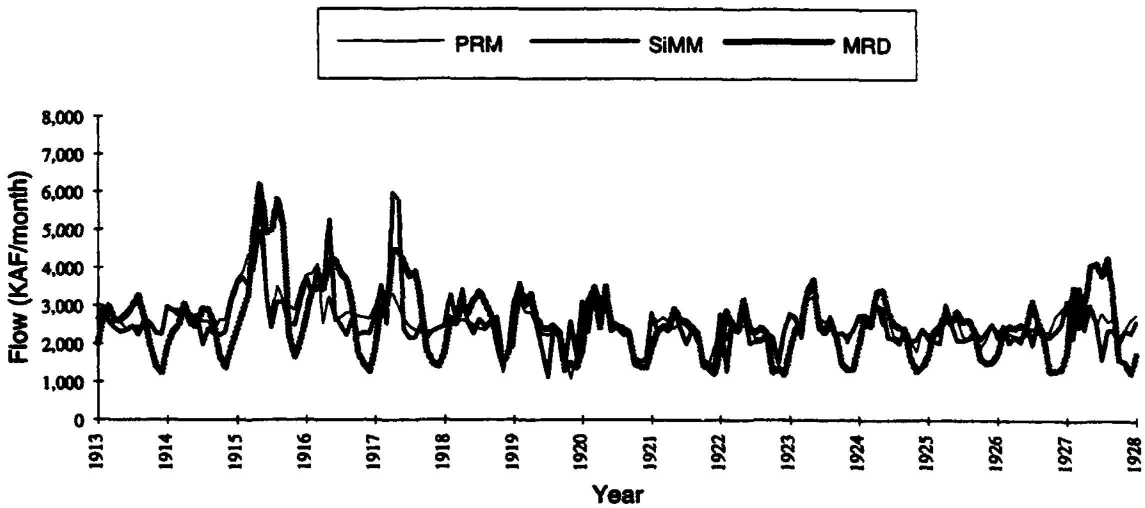


Figure 4.10 Full Operation Rules Test: Combined Storage of Fort Peck, Garrison, and Oahe





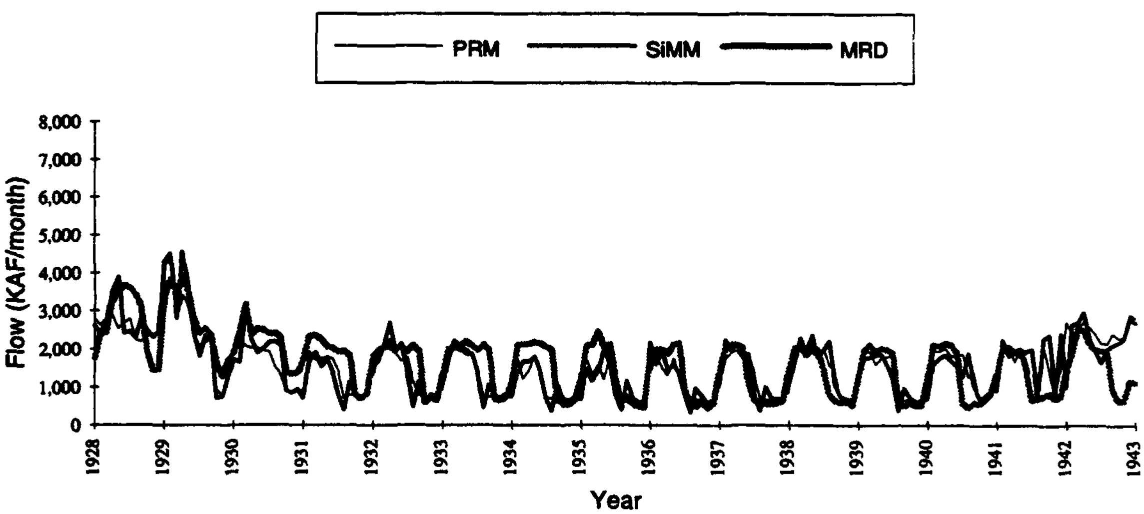


Figure 4.11 Full Operation Rules Test: Nebraska City to Kansas City Flow 1898-1943

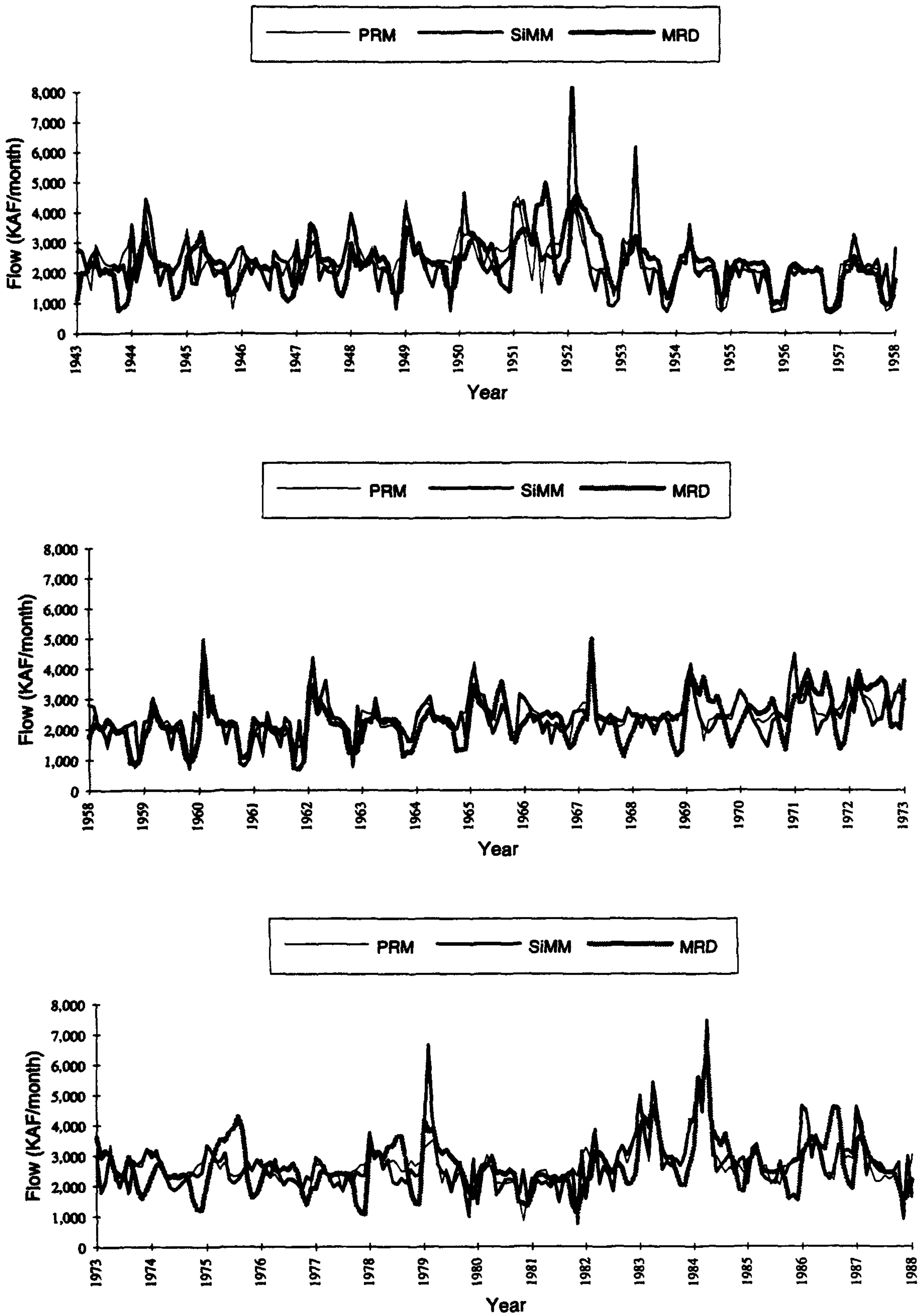


Figure 4.12 Full Operation Rules Test: Nebraska City to Kansas City Flow 1943-1988

Another lower basin river segment likely to flood is the reach from Boonville to Hermann, with a maximum flow capacity of 7,543 KAF/month. Figures 4.13 and 4.14 show HEC-PRM, SiMM, and MRD flows in the Boonville to Hermann reach. As can be seen in these figures, the maximum channel capacity of 7,543 KAF/month is exceeded several times by the flows modeled by all three models. This indicates floods could not have been avoided by the main stem operations and that they were caused by lower basin tributary inflows. Time series of modeled flows for other reaches is included in Appendix C.

Table 4.3 compares the difference of SiMM and MRD flows for all downstream nodes.

Table 4.3
Square Root of Mean Squared Difference for Streamflows at all Downstream Links

Full Time Series		1930s & 1950s Droughts Excluded	
SiMM	MRD	SiMM	MRD
481	711	495	777

4.2.6 Upper Three Reservoirs Storage

Time series plots of storages in Fort Peck, Garrison, and Oahe are shown in Figures 4.15, 4.16, and 4.17, respectively. It is clear from these figures that the three reservoirs are equally drawn down during drought periods by the present MRD simulation model. HEC-PRM, on the other hand, keeps Oahe practically full during most of the drought, reducing its storage for more than a single period only in the last one or two years of drought in anticipation of higher inflows indicating the end of the drought.

Fort Randall modeled storages are compared in Figure 4.18. MRD simulation keeps this reservoir emptier than both HEC-PRM and SiMM.

Table 4.4 compares the difference of SiMM and MRD storages to those of HEC-PRM, both for the full time series of results and the time series with the two major drought periods excluded.

4.3 Discussion

Like all other rules derived in this study, storage allocation rules were developed from HEC-PRM results. In HEC-PRM output, the combined storage for the upper three reservoirs never dropped below 60,087 KAF. Consequently, when SiMM storage dropped below this value the storages allocated to the reservoirs were a result of the model's extrapolation beyond the range attained in HEC-PRM. If the lines fitted in

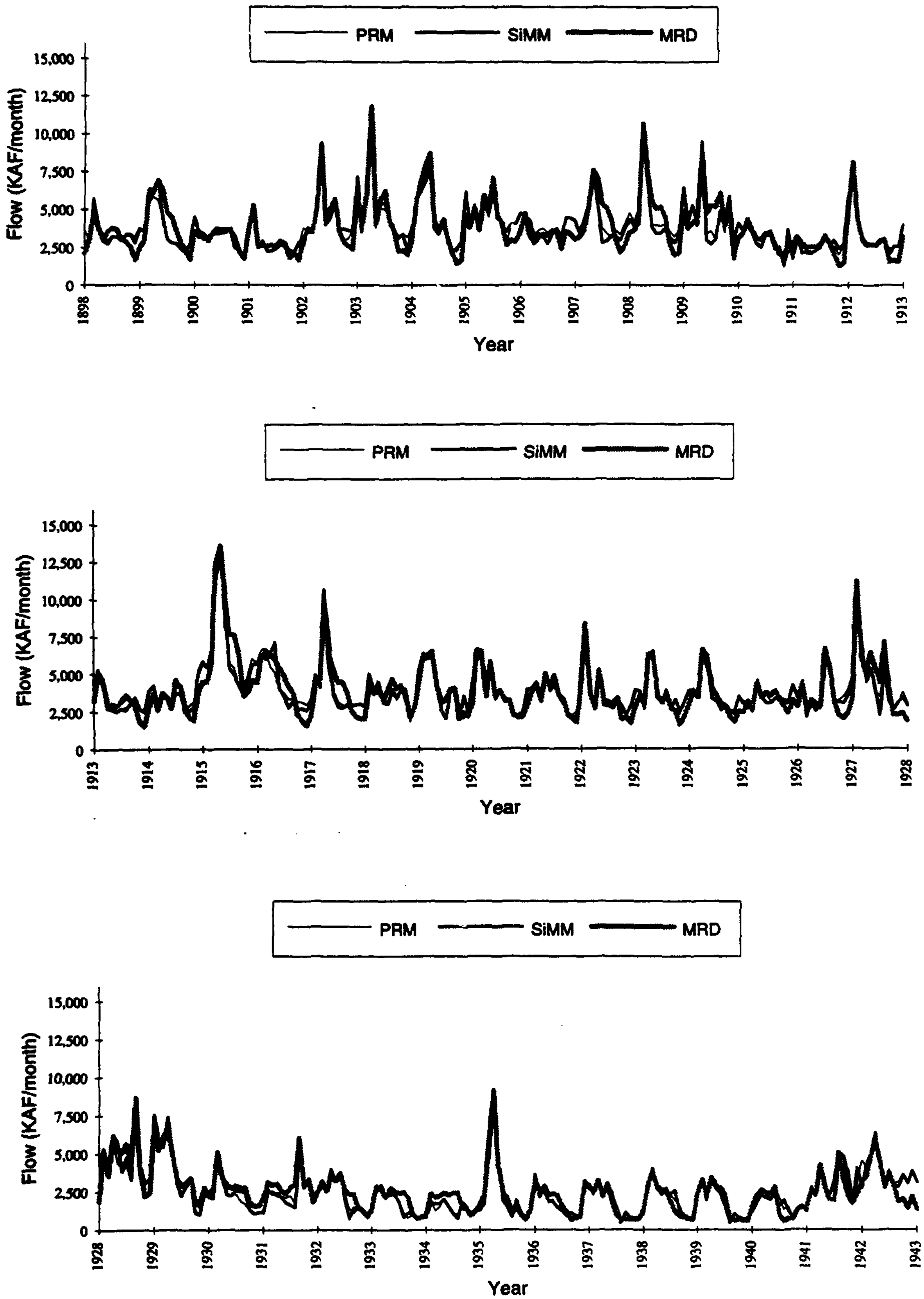


Figure 4.13 Full Operation Rules Test: Boonville to Hermann Flow 1898-1943

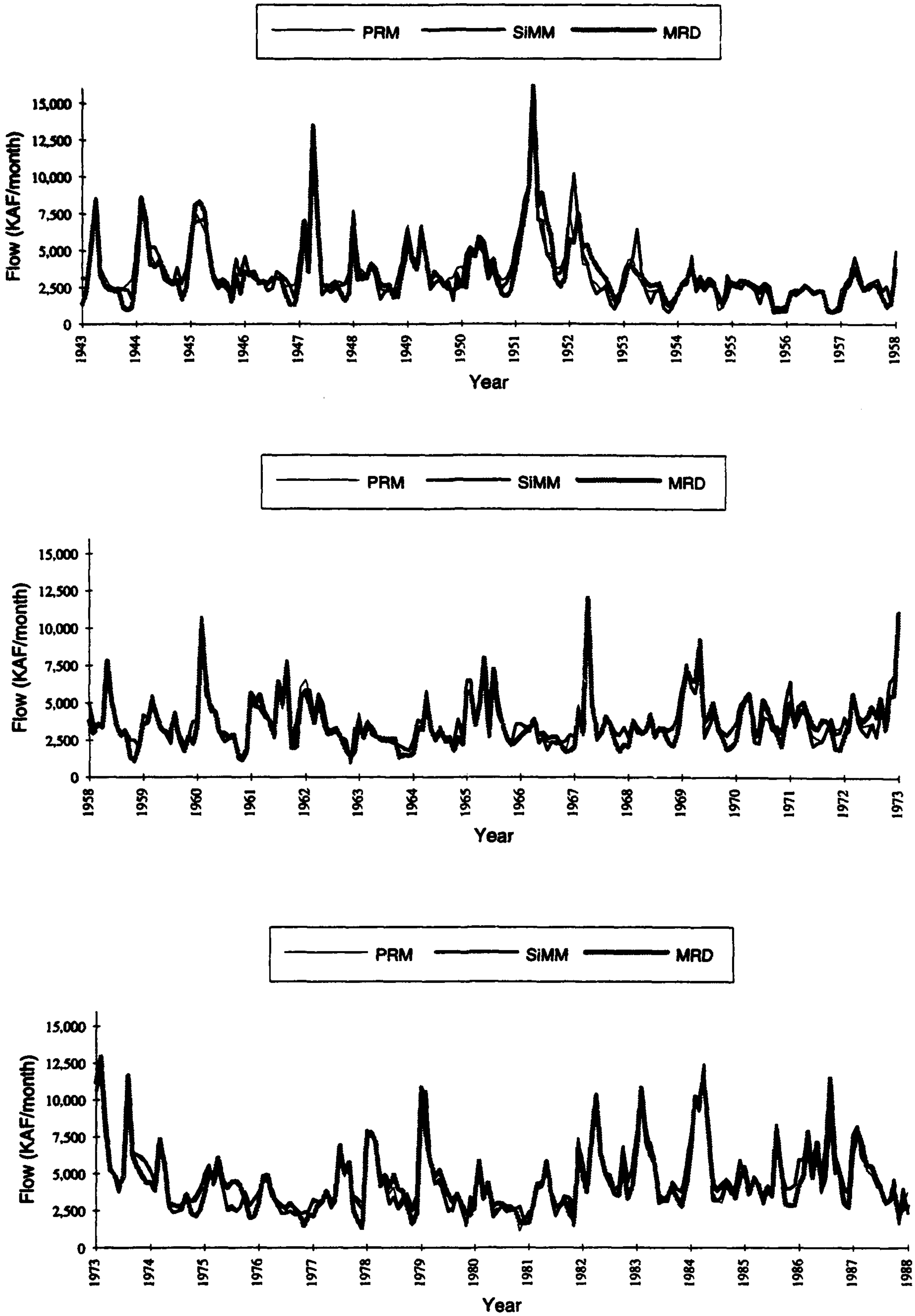
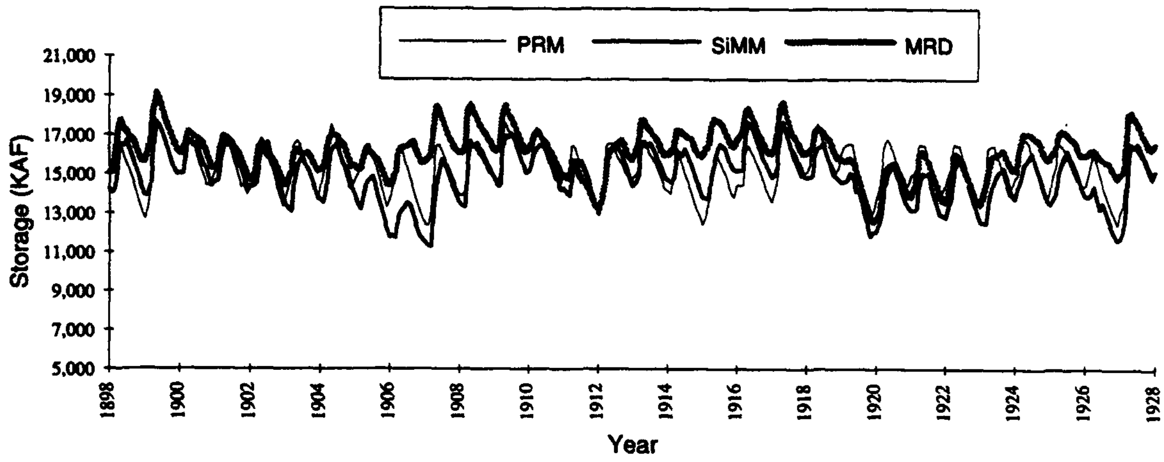
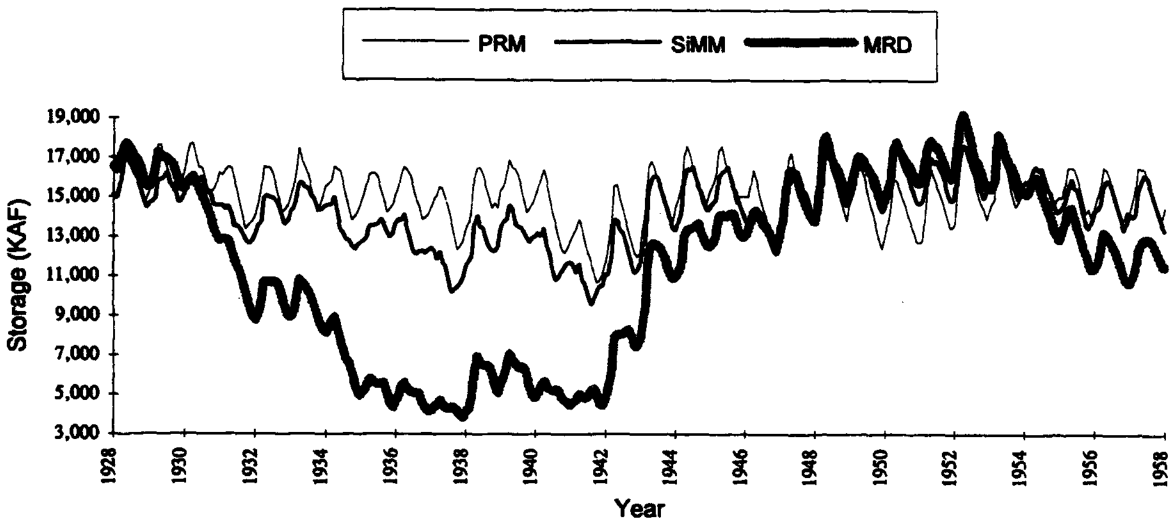


Figure 4.14 Full Operation Rules Test: Boonville to Hermann Flow 1943-1988





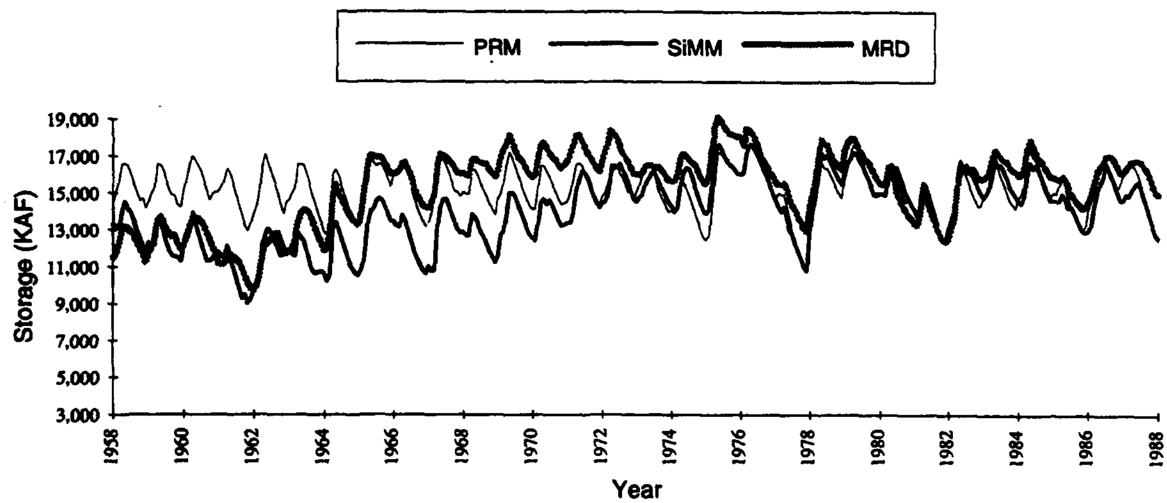


Figure 4.15 Full Operation Rules Test: Fort Peck Storage

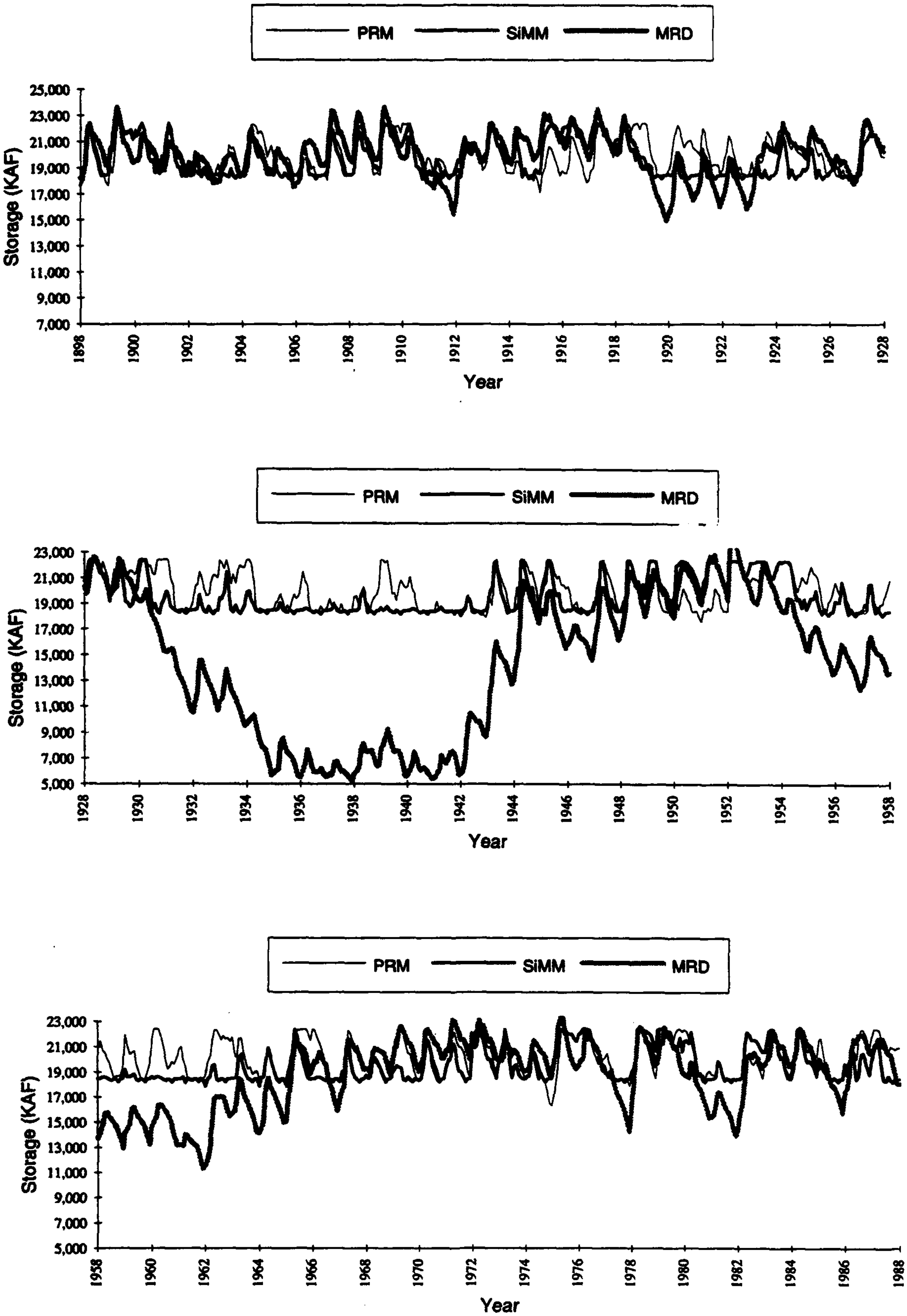
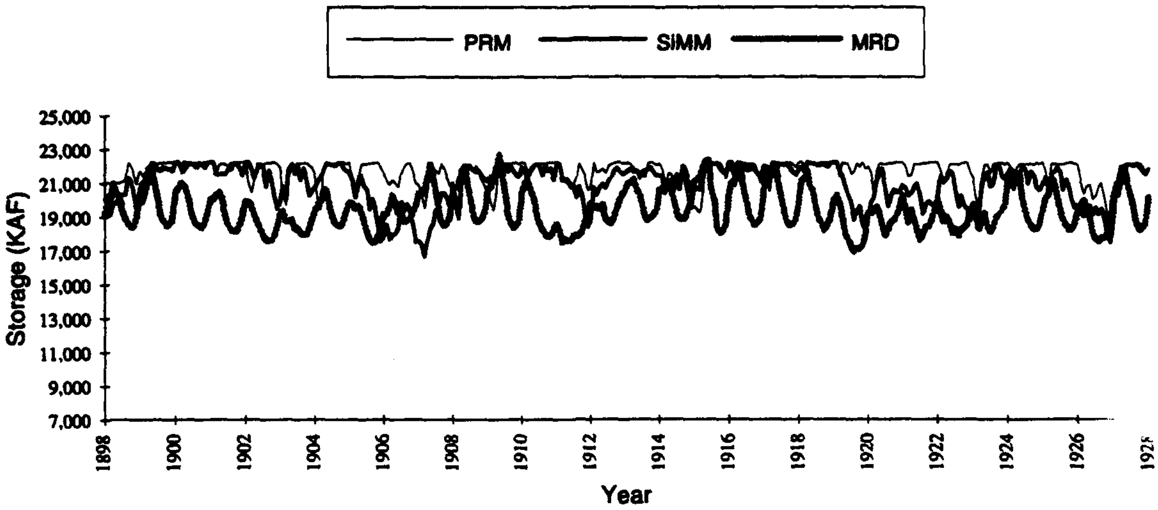
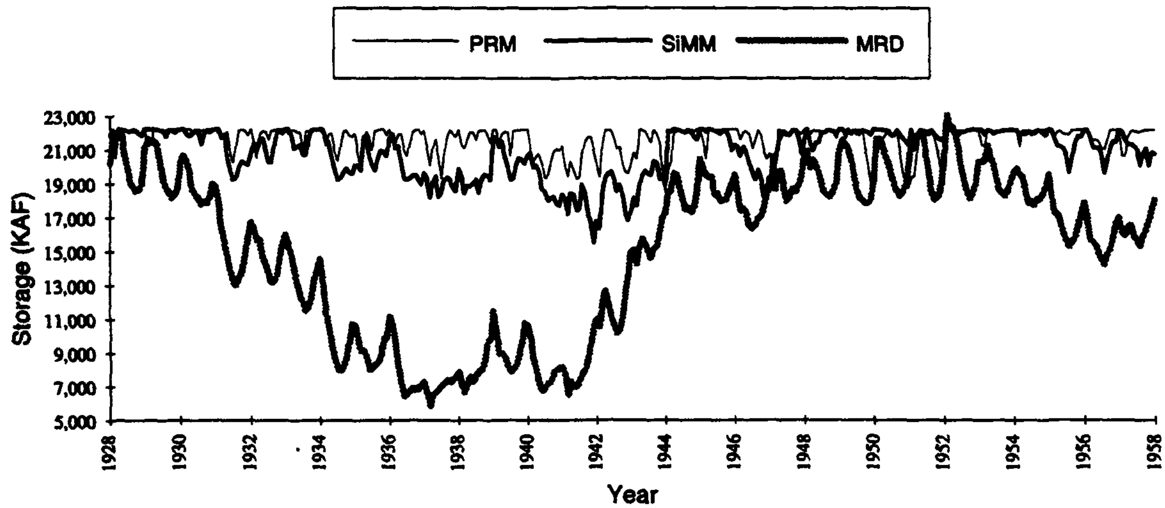


Figure 4.16 Full Operation Rules Test: Garrison Storage





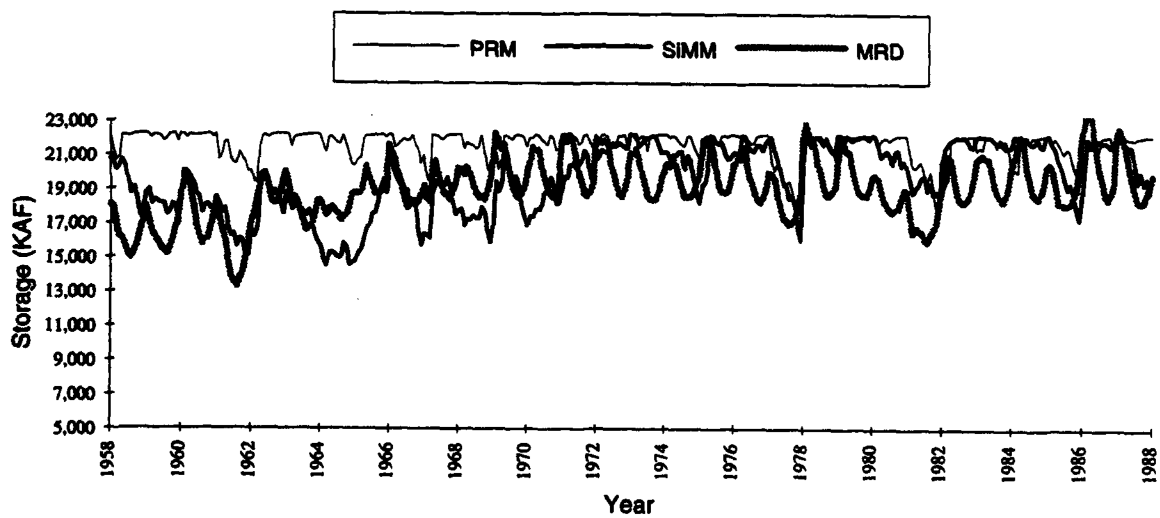


Figure 4.17 Full Operation Rules Test: Oahe Storage

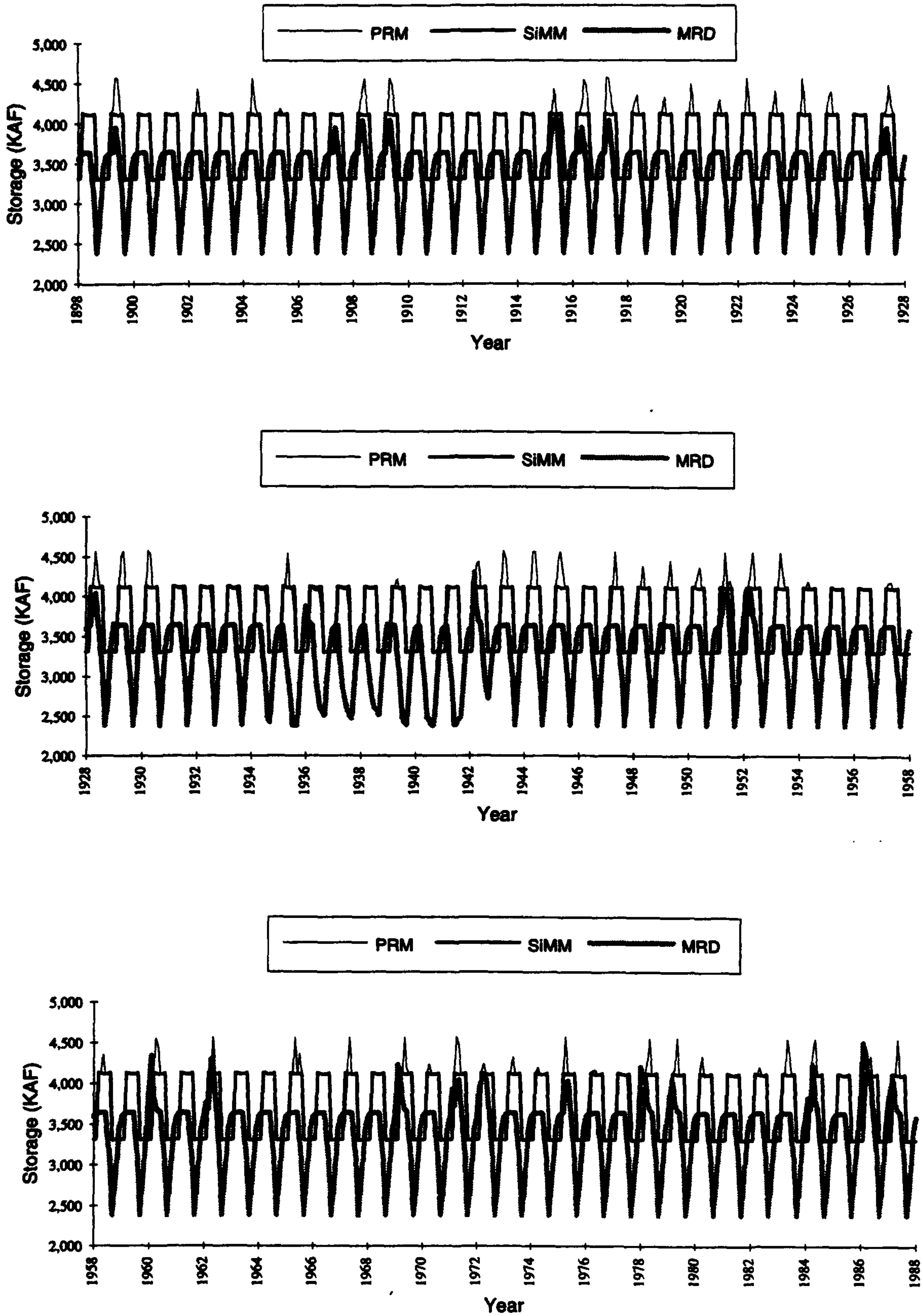


Figure 4.18 Full Operation Rules Test: Fort Randall Storage

Table 4.4
Square Root of Mean Squared Difference of Reservoir Storages

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

Figures 3.4 through 3.7 are extrapolated to values of total storage less than that shown in these figures, Garrison storage will remain constant in most months. This extrapolation explains the apparently minimum Garrison storage modeled by SiMM. Fort Peck and Oahe storages decreased at the end of the 1930s drought, Garrison maintained its storage at approximately 19,000 KAF. A way to avoid extrapolation would be to run HEC-PRM with a set of inflows that represent a drought that is severe enough for the total storage to drop below values obtained in this study.

A shortcoming of SiMM is that it does not include economic penalties or value functions. As a result, performance from each model run can only be evaluated by how close the output is to corresponding output in HEC-PRM, rather than by improvement measured by economic performance. This exclusion of economic functions in SiMM hampered the improvement of the release rules, since at a certain point in the fine tuning of the model, improvements can not be noticed on time series plots and mean square difference values for the various model outputs.

As an alternative to including the economic functions in the simulation model used for testing reservoir operation rules, results from the simulation model could be run through HEC-PRM post processor. Penalty function values could be obtained for current simulation results and HEC-PRM derived rules. This would allow for better assessment and comparison with HEC-PRM results.

Chapter 5

Summary and Conclusions

As demands on reservoir systems increase and diversify, reservoir system operations become a more pressing and controversial issue. A methodology is required to resolve the conflicting demands that invariably arise when resources are limited.

The possibility of developing reservoir operating plans from a deterministic optimization model was investigated by using the results of a network flow model, HEC-PRM, and simulation modeling. The system under study is the multi-purpose, multi-reservoir main stem Missouri River system. Several conclusions are suggested by this study.

1. HEC-PRM can be used to identify promising operation plans for a large complex system, such as the Missouri River system. The methodology used in the development of rules was simple: observation of patterns, trends in HEC-PRM input data, results, and a simple mass balance simulation model. A simple but flexible simulation model of the Missouri River system greatly aided the task of testing and refining the operation rules.

Reservoir operating rules suggested in this report are simple:

1. Monthly storage target rules for Big Bend, Fort Randall and Gavins Point reservoirs;
2. Monthly storage allocation rules for Fort Peck, Garrison, and Oahe;
3. Monthly release rules from Oahe.

Although only monthly operations were investigated in this study, there appears to be enough similarities among months to develop seasonal or combined months operation rules.

2. Missouri River system HEC-PRM results indicate operation procedures that are often qualitatively different from those used currently. The two most significant differences are the storage allocation among the upper three reservoirs and the drought operation rules. Whereas the simulation of current policies shows a linear balancing of storage among the upper three reservoirs, HEC-PRM results indicate a significantly different, non-linear, storage allocation rule. HEC-PRM keeps Oahe full while Fort Peck and Garrison have their storage reduced as the total volume in storage decreases. At some point Fort Peck and later Garrison stabilize their storage while Oahe's storage is reduced. This pattern was observed for every month (Figures 3.4 through 3.15).

3. Drought operations are significantly different. While current operation releases during the navigation season are dependent on the total system storage on March 15 and July 1, HEC-PRM reduces releases from Oahe when inflows into the upper three reservoirs are low in December and January. With exception of spills, volume in storage is not a factor in the determination of releases. HEC-PRM also reduces reservoir system releases during droughts in the winter months so that a minimum streamflow is met a Sioux City.

By reducing releases when combined inflow into the upper three reservoirs is low, HEC-PRM keeps the reservoir system much fuller during droughts than MRD simulation results indicate (Figures 4.10, 4.15, 4.16, and 4.17). Drought operations inferred from HEC-PRM results seem to imply that navigation is not as much of an economic priority within the overall Missouri River system as keeping the reservoirs level high for other uses.

4. Several shortcomings in the Missouri River HEC-PRM application exist. Although this study has pointed to possible improvements in the operations of the main stem Missouri River system, several shortcomings must be addressed before any set of rules developed with such an approach can be put into practice. First, it is essential that the reservoir system being studied be well represented in HEC-PRM. The Missouri River application of HEC-PRM used a preliminary set of penalty functions. No penalty functions associated with ice related flooding, a common problem in the Missouri River, were include in the Phase II study.

Streamflow penalty functions in HEC-PRM were constructed in such a way that reservoir releases were frequently zero or below a minimum required streamflow for the downstream channel. This is certainly an undesirable solution for environmental and water supply purposes.

Another change required in the Missouri River application is the use of an improved hydropower algorithm that better deals with the non linearity inherent in the hydropower formulation. This algorithm has been developed and successfully included in the HEC-PRM Columbia River application.

For the reasons mentioned above, further study of rules suggested here using more detailed simulation would be needed for a detailed evaluation.

5. A simulation model was essential for rule development and testing. The simulation model developed in this study, SiMM, provided a useful tool in testing and refining reservoir operation rules. However, it is a very simple model that does not include a detailed representation of the system. For simplicity, evaporation volumes were input in the model as a time series rather than calculated within the model. Another shortcoming of SiMM was the lack of penalty functions. As discussed in Chapter 4, the inclusion of HEC-PRM penalty functions in SiMM would have greatly aided the refinement of release rules.

Although the operation rules developed in this study cannot, for the reasons described above, be considered final, it is clear that HEC-PRM can be a useful analytical tool in reservoir systems planning studies. HEC-PRM offers a rigorous and yet simple approach in the development and updating of reservoir operation plans.

Appendix A

Methodologies for Developing Operation Rules from HEC-PRM Results

A.1 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).

A.2 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.

A.3 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.

A.4 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.

A.5 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.

A.6 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.

A.7 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.

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 o. 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

A.7.1 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.

A.7.2 Uses for Simulation

A.7.2.1 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.

A.7.2.2 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.

A.7.3 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.

A.8 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.

A.8.1 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.

A.8.2 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.

A.8.3 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.

A.8.4 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.

A.8.5 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.

A.8.6 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.

A.9 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

Simulation Model SiMM

The simulation model used to test operating rules for the Missouri River system was created with STELLA II^{TM} (High Performance Systems, 1992), an object-oriented simulation software. This simulation environment was chosen for its ease of use and flexibility. One of the main advantages of STELLA^{TM} is that, unlike models developed in FORTRAN or any other programming language, coding and debugging are reduced to a minimum (Palmer et al, 1993).

Figure B.1 illustrates the main components of SiMM: the six main stem reservoirs, the six downstream nodes, inflows, evaporation rates, and releases from the reservoirs.

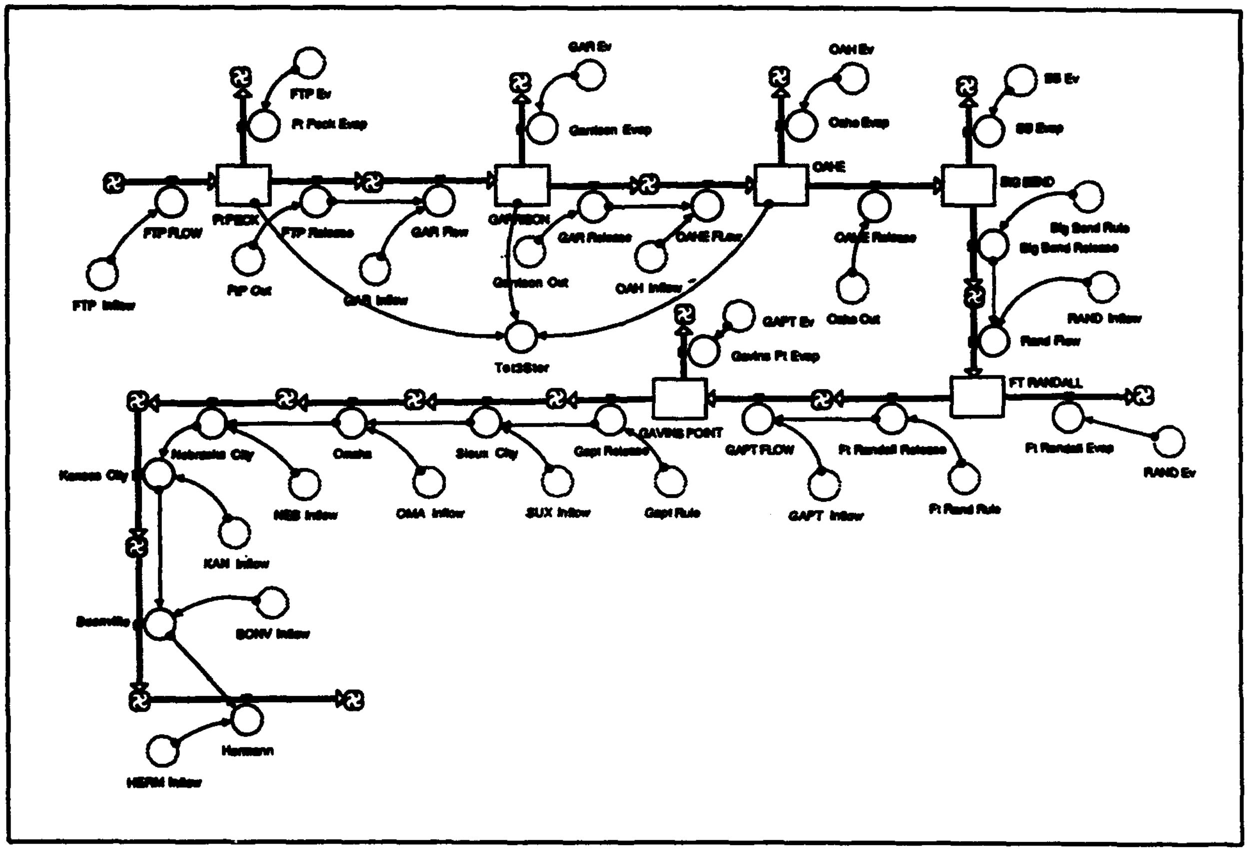


Figure B.1 SiMM Schematic of Main Stem Missouri River System

SiMM is a mass balance model run on a monthly time-step. The governing equation of this model is the continuity equation:

$$S_{t+1} = S_t + I_t - E_t - R_t$$

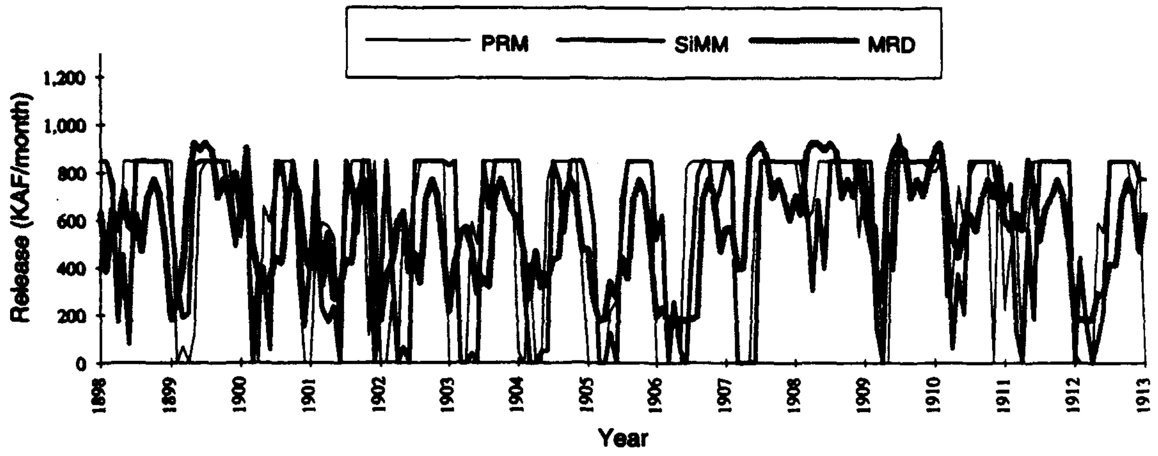
where S represents storage. S is calculated at each time step and is equal to zero for the six downstream nodes. I represents the inflow into each reservoir or downstream node. I is the historical inflow and is input in the model as a time series. E is the evaporation from each reservoir. E is also input as a time series. R represents release from each reservoir or outflow from each downstream node. R is calculated in the model according to the rules derived in Chapter 3. t represents time.

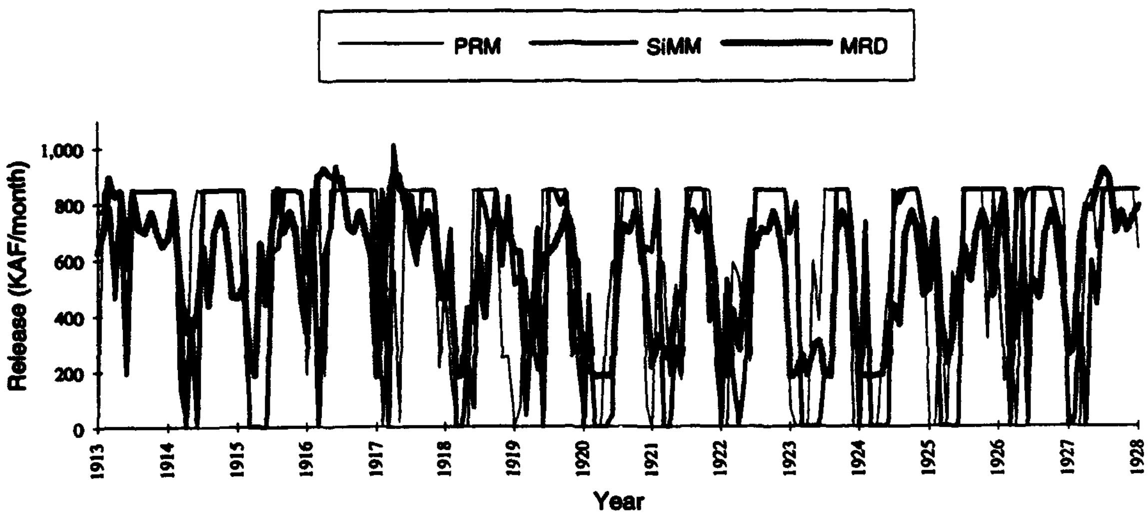
STELLA™ has a number of advantages over other modeling environments:

1. Software is easy to use with models being simple to develop and debug,
2. It is flexible to represent both common and unusual operating rules,
3. Due to its graphical environment STELLA™ is easy to explain and understand,
4. Data can be imported and exported easily from STELLA™.

Appendix C

Time Series Plots of Modeled Reservoir Releases





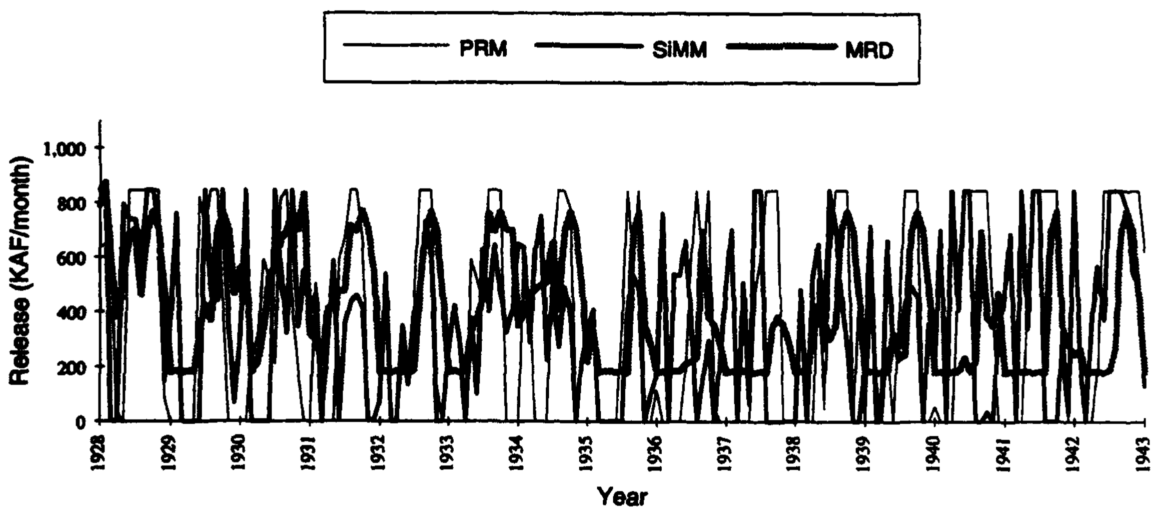


Figure C.1 Full Operation Rules Test: Fort Peck Release 1898-1943

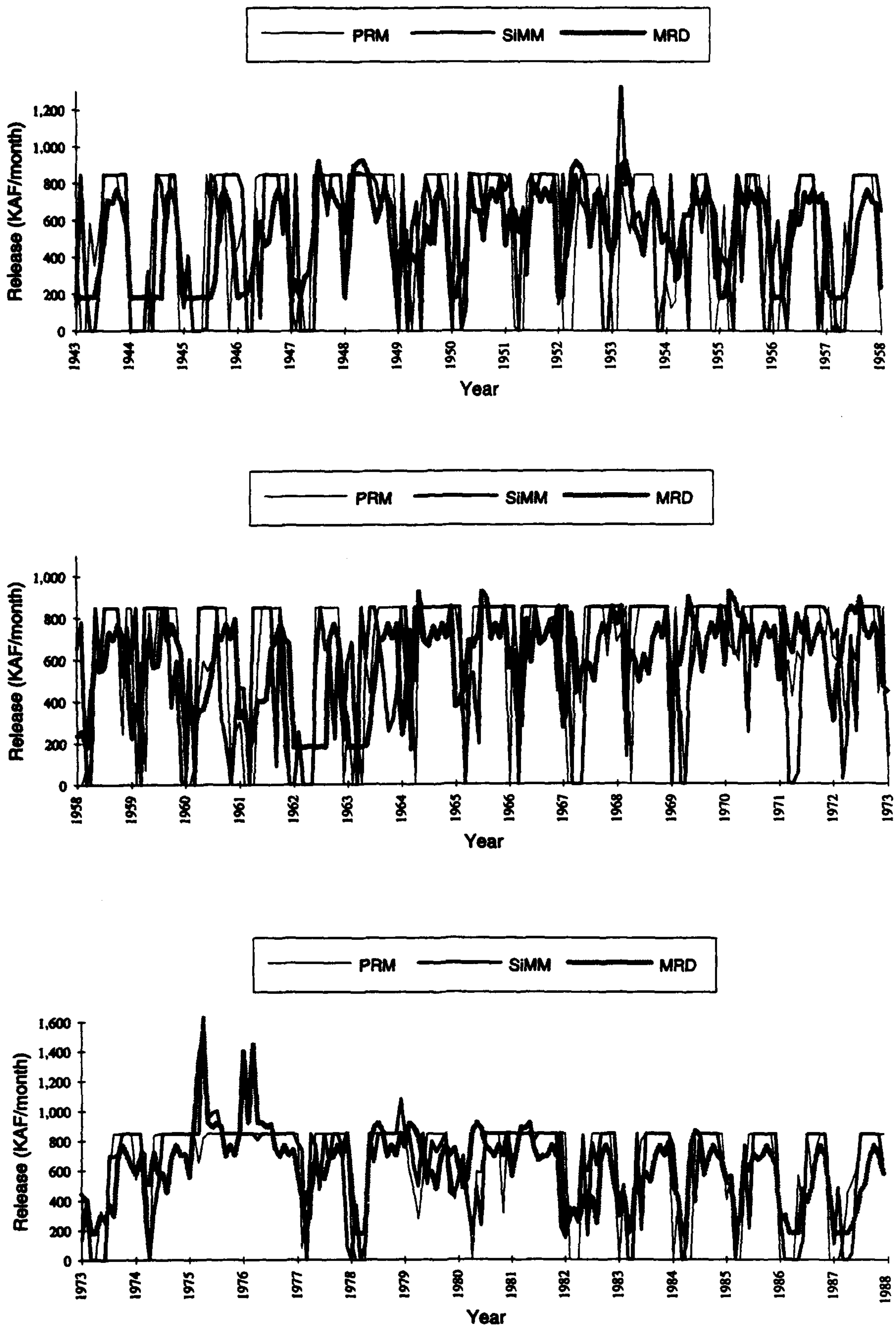


Figure C.2 Full Operation Rules Test: Fort Peck Release 1943-1988

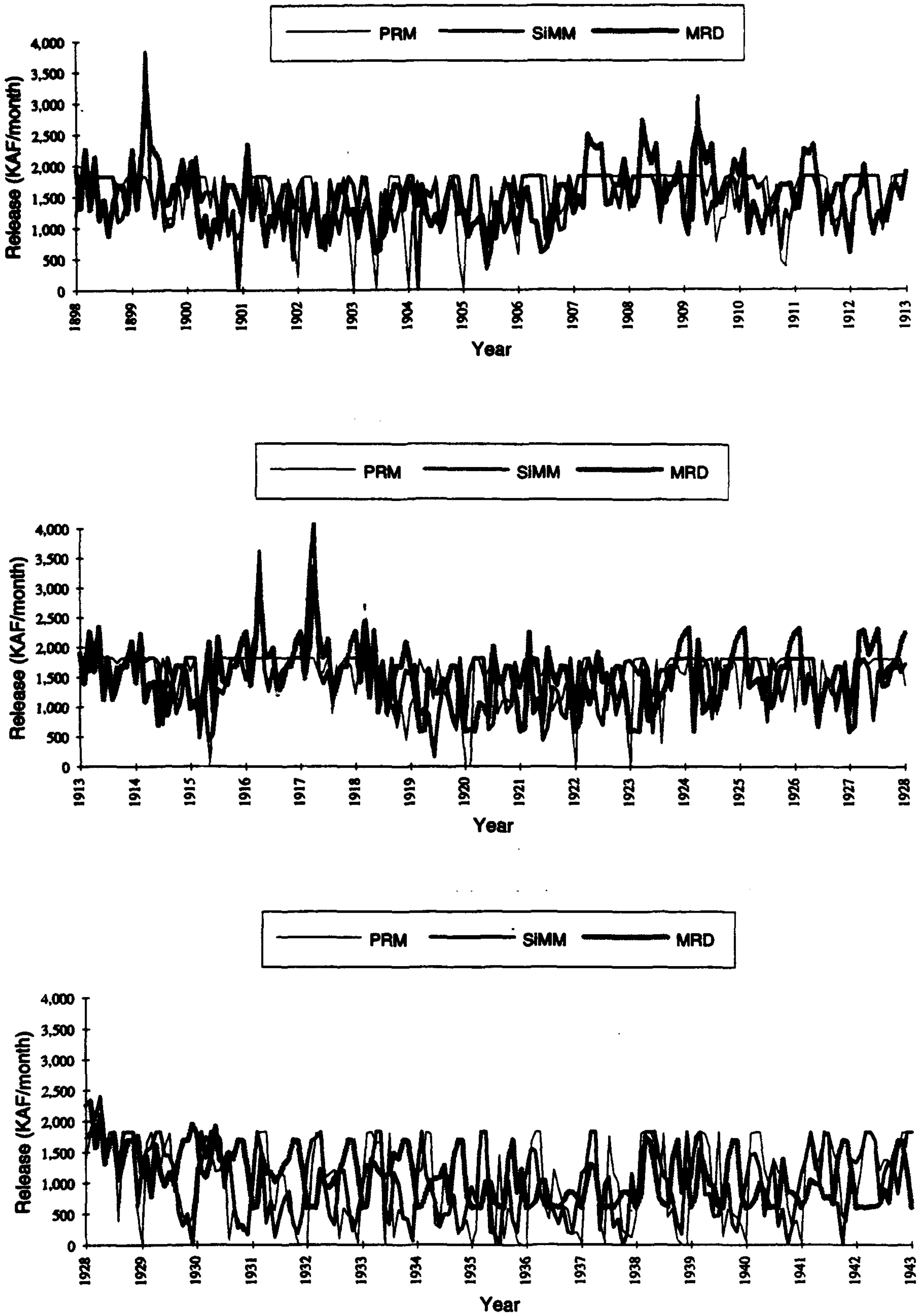


Figure C.3 Full Operation Rules Test: Garrison Release 1898-1943

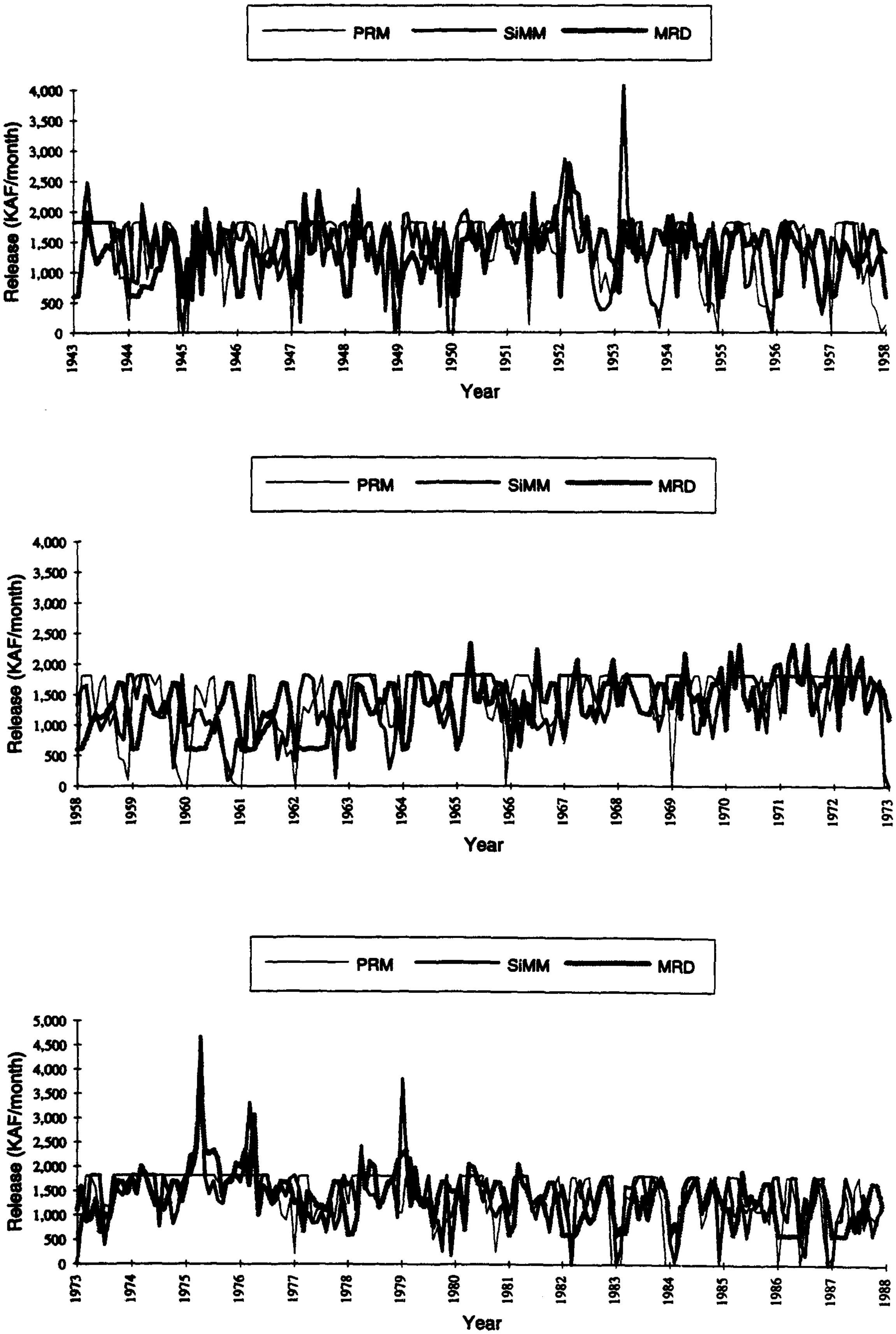
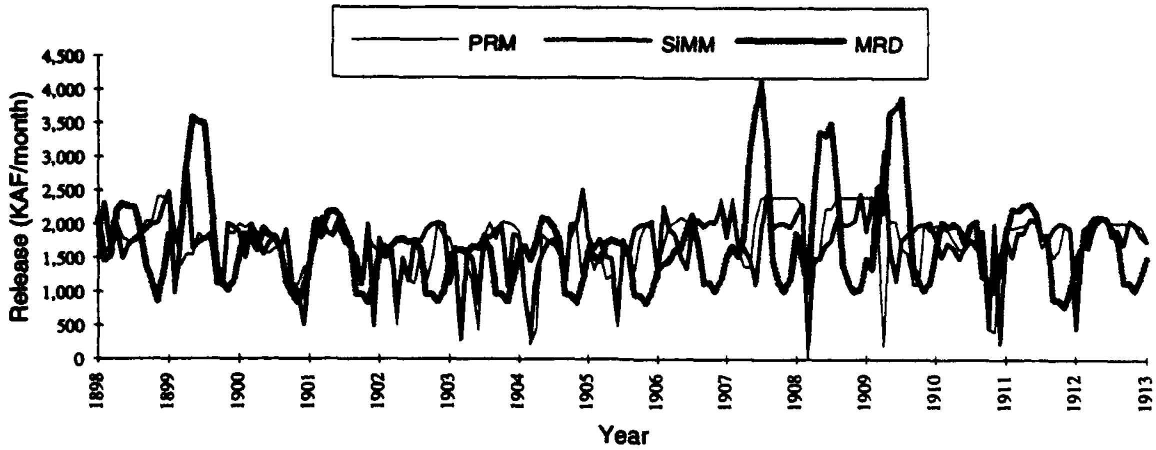
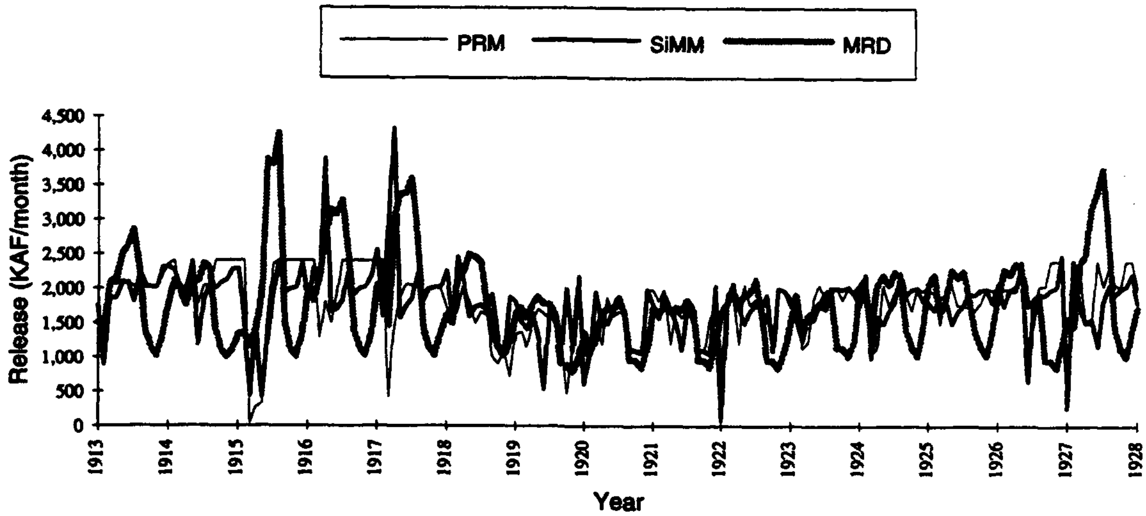


Figure C.4 Full Operation Rules Test: Garrison Release 1943-1988





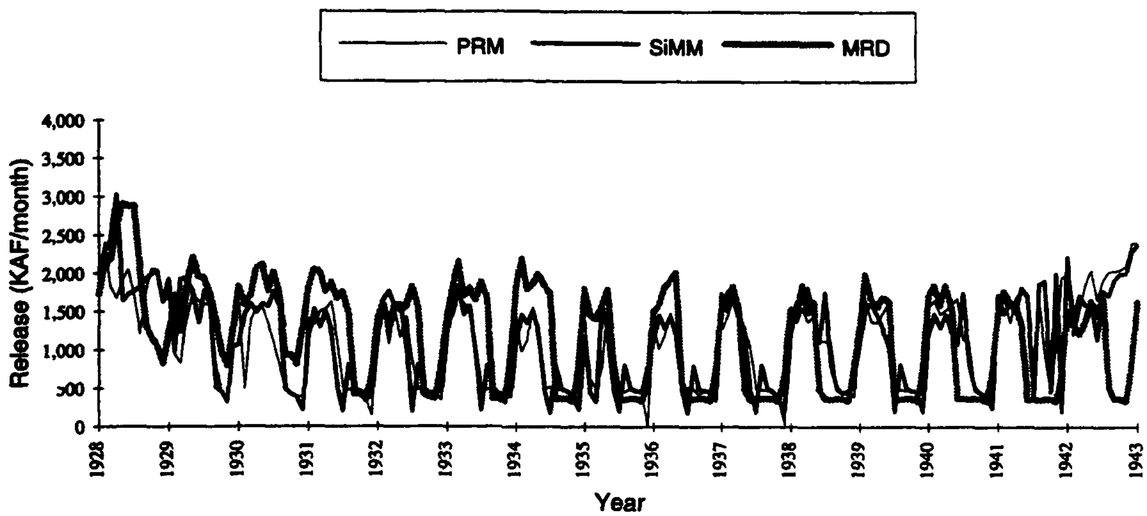
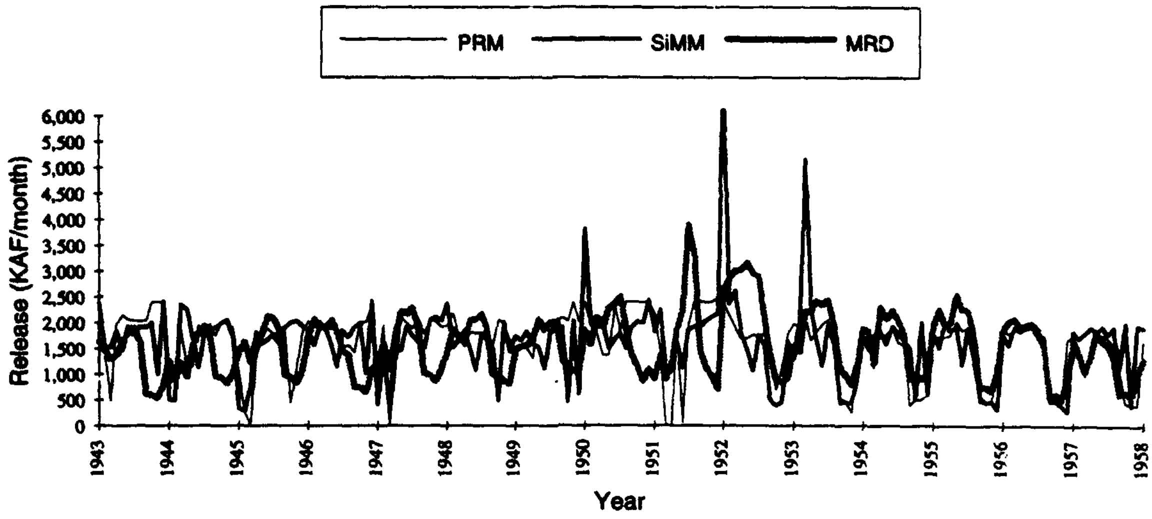
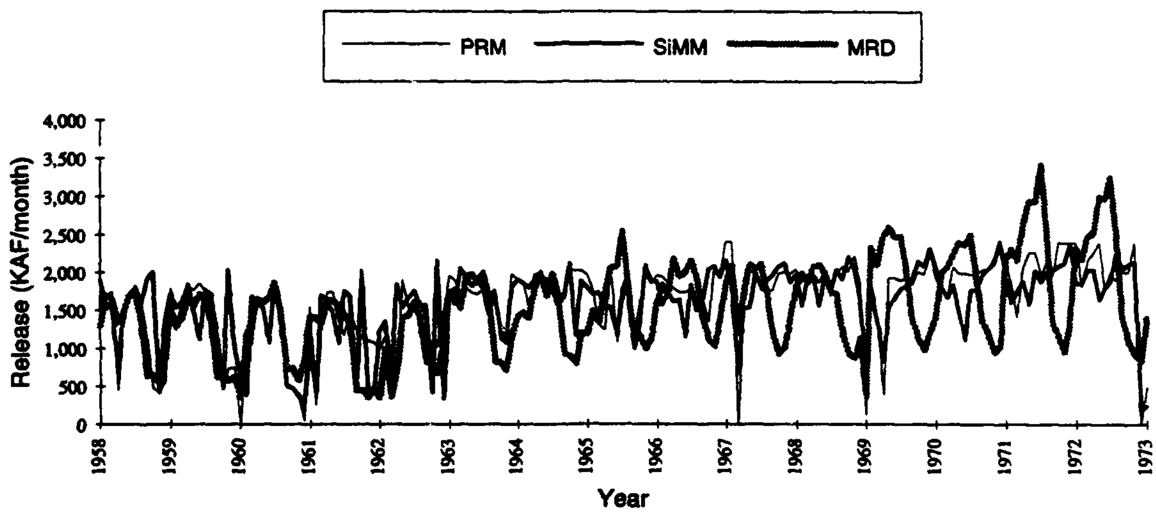


Figure C.5 Full Operation Rules Test: Fort Randall Release 1898-1943





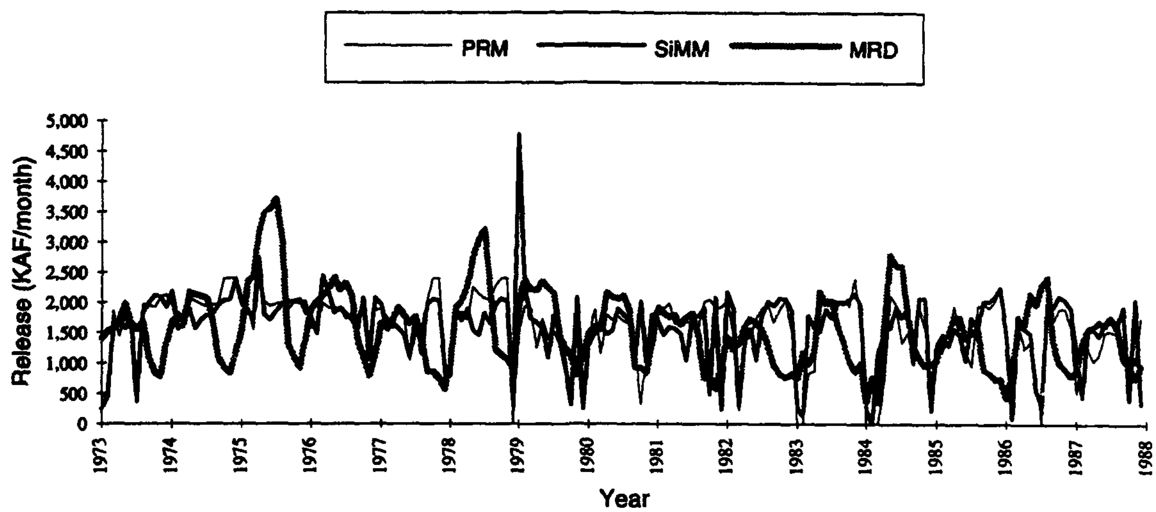
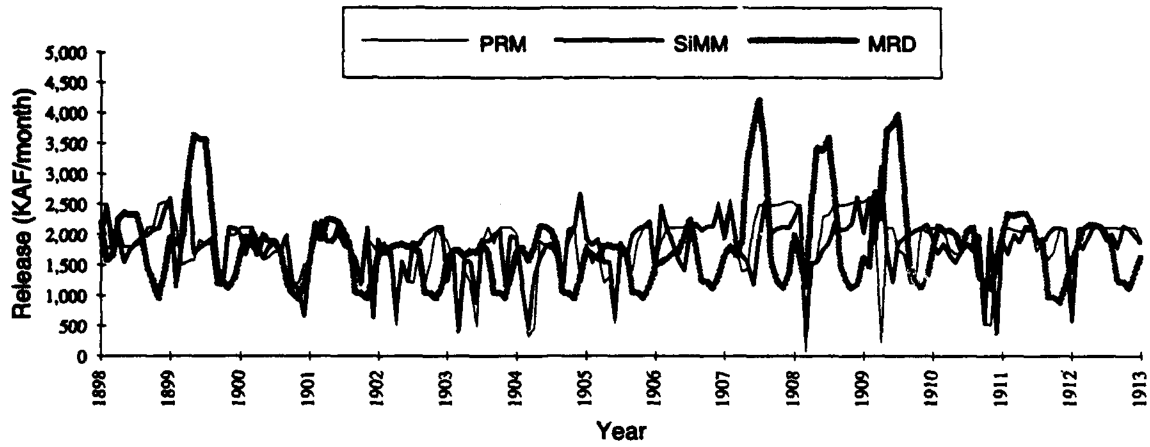
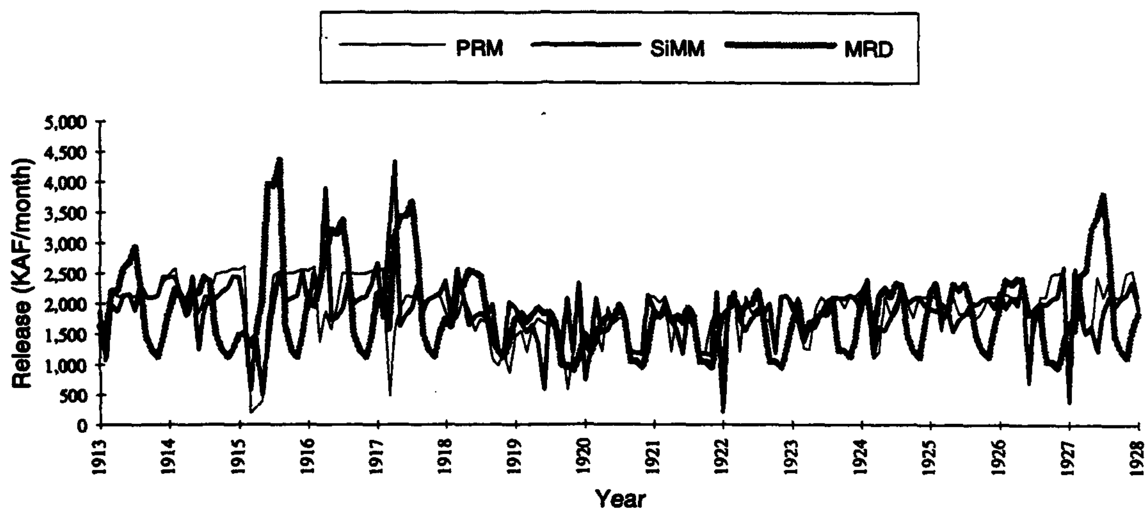


Figure C.6 Full Operation Rules Test: Fort Randall Release 1943-1988





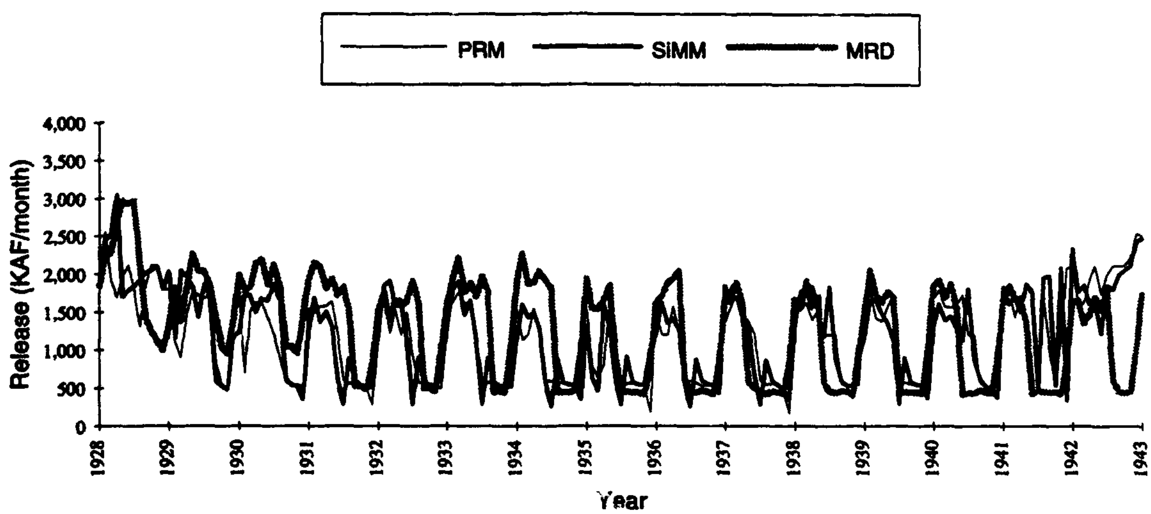
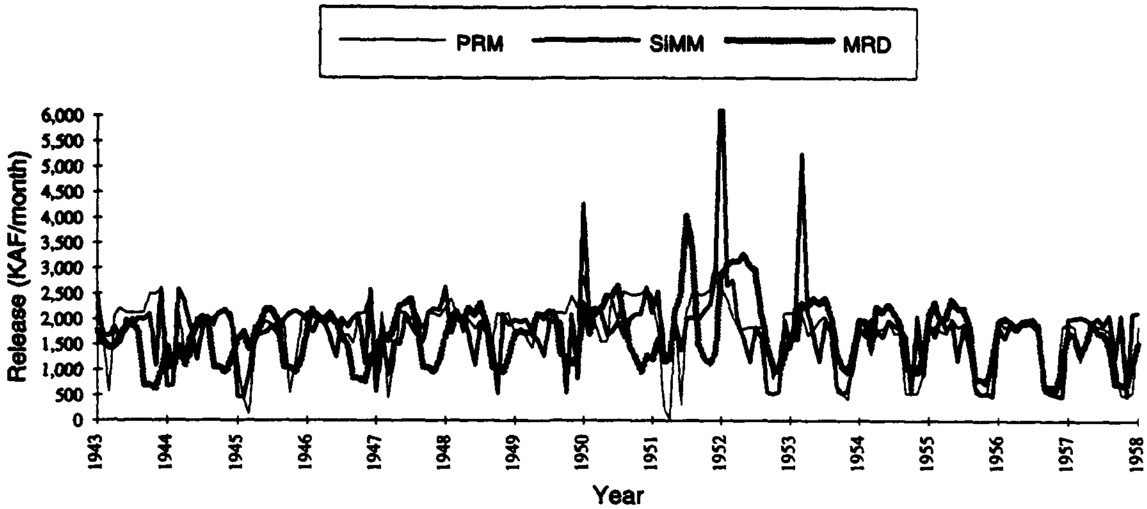
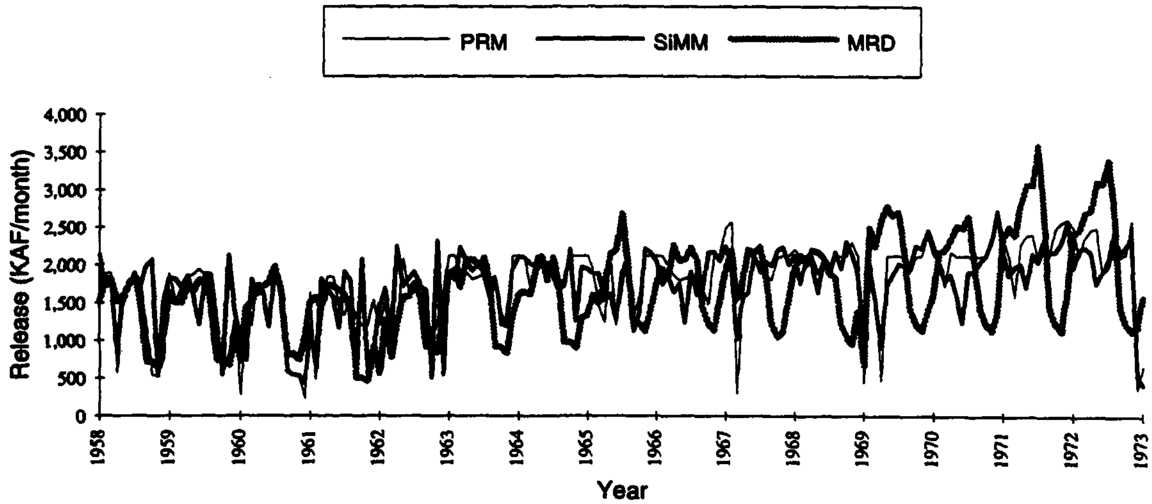


Figure C.7 Full Operation Rules Test: Gavins Point Release 1943-1988





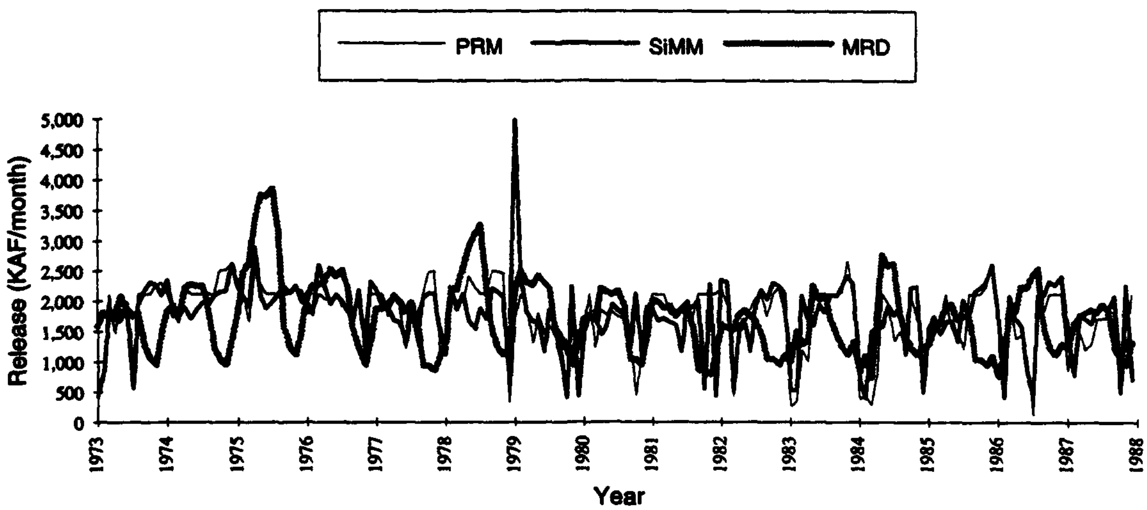


Figure C.8 Full Operation Rules Test: Gavins Point Release 1943-1988

Appendix D

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