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Application of HEC-PRM for Seasonal Reservoir Operation of the Columbia River System

June 1996

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Nicole B. Murk, Hydrologic Engineering Intern

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US ARMY CORPS OF ENGINEERS
HYDROLOGIC ENGINEERING CENTER (HEC)
609 Second Street
Davis, CA 95616-4687

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This report presents the results and conclusions of an application of the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) for seasonal operation of the Columbia River System. A position analysis approach is used to suggest promising seasonal operations for the Columbia River System which can be updated throughout the annual drawdown refill cycle. Such HEC-PRM-based seasonal reservoir operation advice could offer guidance in simulation testing and reduce the number of simulation runs needed to formulate seasonal operation plans.

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Hydrologic Engineering Center
U.S. Army Corps of Engineers
609 Second Street
Davis, CA 95616-4687

(916) 756-1104

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Preface

This report presents the seasonal operation study on the Columbia River system using the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) with the position analysis approach. The North Pacific Division (NPD) Corps of Engineers staff provided data necessary for this study. Jim Barton of NPD directed the data collection and responded promptly to data requests, which allowed this study to progress on schedule.

This study was conducted by the Hydrologic Engineering Center, Davis, California. Nicole Murk, Hydrologic Engineering Intern, prepared the data for model execution, performed the model runs, post-processed the output, analyzed the results and wrote this report. Dr. Jay R. Lund, Associate Professor of Civil and Environmental Engineering at the University of California at Davis, directed this study. Mike Burnham, Chief, Planning Analysis Division, provided study direction and management. Kenneth W. Kirby provided extensive assistance and advice throughout this study, notably developing a program to post-process HEC-PRM results. Loshan Law performed word processing for the final report. Darryl Davis was Director of the Hydrologic Engineering Center during the study.

Executive Summary

Report Summary

This report presents the results and conclusions of an application of the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) for seasonal operation of the Columbia River System. A position analysis approach is used to suggest promising seasonal operations for the Columbia River System which can be updated throughout the annual drawdown refill cycle. Such HEC-PRM-based seasonal reservoir operation advice could offer guidance in simulation testing and reduce the number of simulation runs needed to formulate seasonal operation plans.

HEC-PRM is run using the position analysis approach, a common form of risk analysis designed to examine reservoir operations for seasonal periods (Hirsch, 1978). Position analysis addresses seasonal operation rather than long-term, strategic operation. The procedure uses a simulation or optimization model to conduct separate runs for many (n) scenarios of future seasonal hydrologies. Each model run begins with the same, current reservoir storage. The number of runs (n) is determined by the number of inflow sequences available, based usually on n years of historical record or n alternative forecasts for future inflows.

Although greatly modified in recent years, due to environmental concerns, the Columbia River System traditionally operates on a seasonal basis. The three operating seasons include the fixed drawdown season (August-December), variable drawdown season (January-March), and refill season (April-July). Each year, hundreds of simulation model (HYSSR) runs are conducted to plan seasonal operations. Four HEC-PRM seasonal studies are presented in this report. Each study captures at least one of these three traditional operating seasons.

This project is the first extensive use of HEC-PRM as a seasonal reservoir operation model. Past HEC-PRM studies of the Columbia River System are strategic planning studies (USACE, 1991b, 1993, 1995). The idea of using HEC-PRM as a seasonal model was proposed and encouraged by a preliminary HEC-PRM seasonal study in 1995 (USACE, 1995).

The findings of this report demonstrate that HEC-PRM is potentially useful for seasonal operation studies of the Columbia River System. Overall, for the four studies in this report, the HEC-PRM seasonal operation advice is reasonable and consistent. Simulation should be used to refine and test HEC-PRM seasonal advice to explore its potential for improved operations. The use of HEC-PRM may allow for a considerable focusing of detailed simulation studies.

Background

Columbia River System

The Columbia River System is located in the Pacific Northwest region of the United States (Figure 1). The entire Columbia River System is comprised of over 250 reservoirs and 100 hydroelectric projects. For the HEC-PRM seasonal operation studies in this report, the reservoir system is represented by a selection of key reservoirs only. Figure 2 shows the network developed for HEC-PRM runs. This reservoir network was formulated in previous USACE Columbia River reports (USACE, 1991b, 1993, 1995).

Seven main storage reservoirs are the focus of the seasonal operation study analysis. The seasonal reservoir operations for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs are the operations discussed throughout the four studies in this report.

Inflow Hydrology

Standardized inflow hydrology for the period of 1928 - 1978 is used in each seasonal study (USACE, 1993). Low and high flow patterns are present and critical periods are included. The standardized inflows are adjusted to reflect 1980 depletions and are modified to incorporate inflow forecasts when available.

The forecast modifications made to historical inflows were performed by the U. S. Army Corps of Engineers North Pacific Division (USACE NPD). Inflow forecasts are made at the beginning of the month, for the months of January to June. As a result, the inflow hydrology for the 1994 Drawdown season study, which spans from July to March, is not modified because inflow forecasts are unavailable.

Approach Overview

The approach to seasonal operation studies presented here uses HEC-PRM according to the position analysis technique.

> "Position analysis is a specialized application of risk analysis. Its purpose is to estimate the risks associated with a given plan of operation over a period of a few months...it consists of n separate simulations rather than one continuous simulation of length n years. Each of these simulations is initialized with the same reservoir storage value--that storage actually existing in the reservoir at the beginning of the present month. Thus, it is an analysis of risks evaluated from the present 'position'" (Hirsch, 1978).

Hirsch discusses the use of the position analysis approach for simulation modeling only. Position analysis also can be applied to optimization studies, evidenced by the HEC-PRM seasonal studies using position analysis in this report. The use of position analysis with an

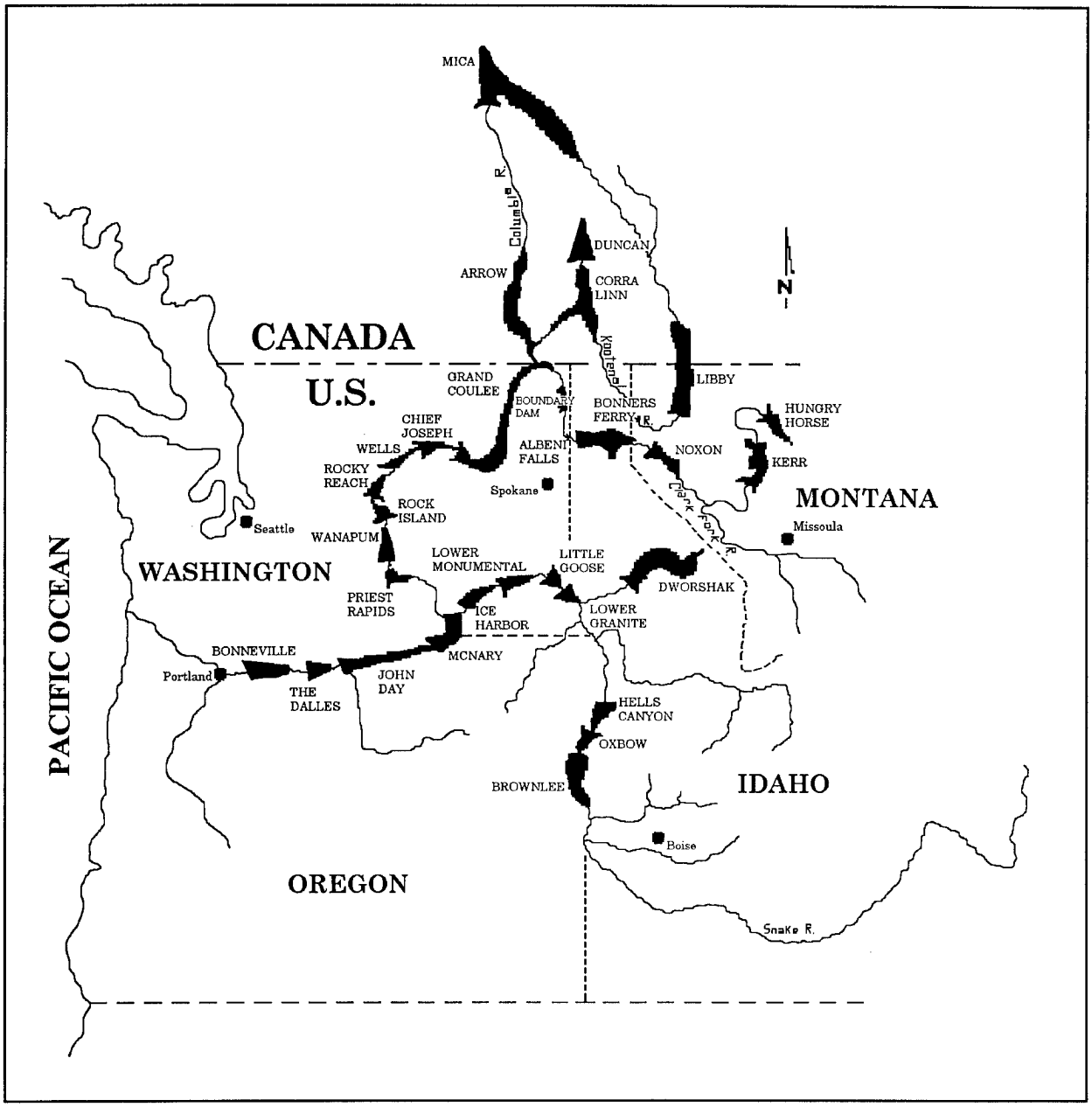


Figure 1 Columbia River System

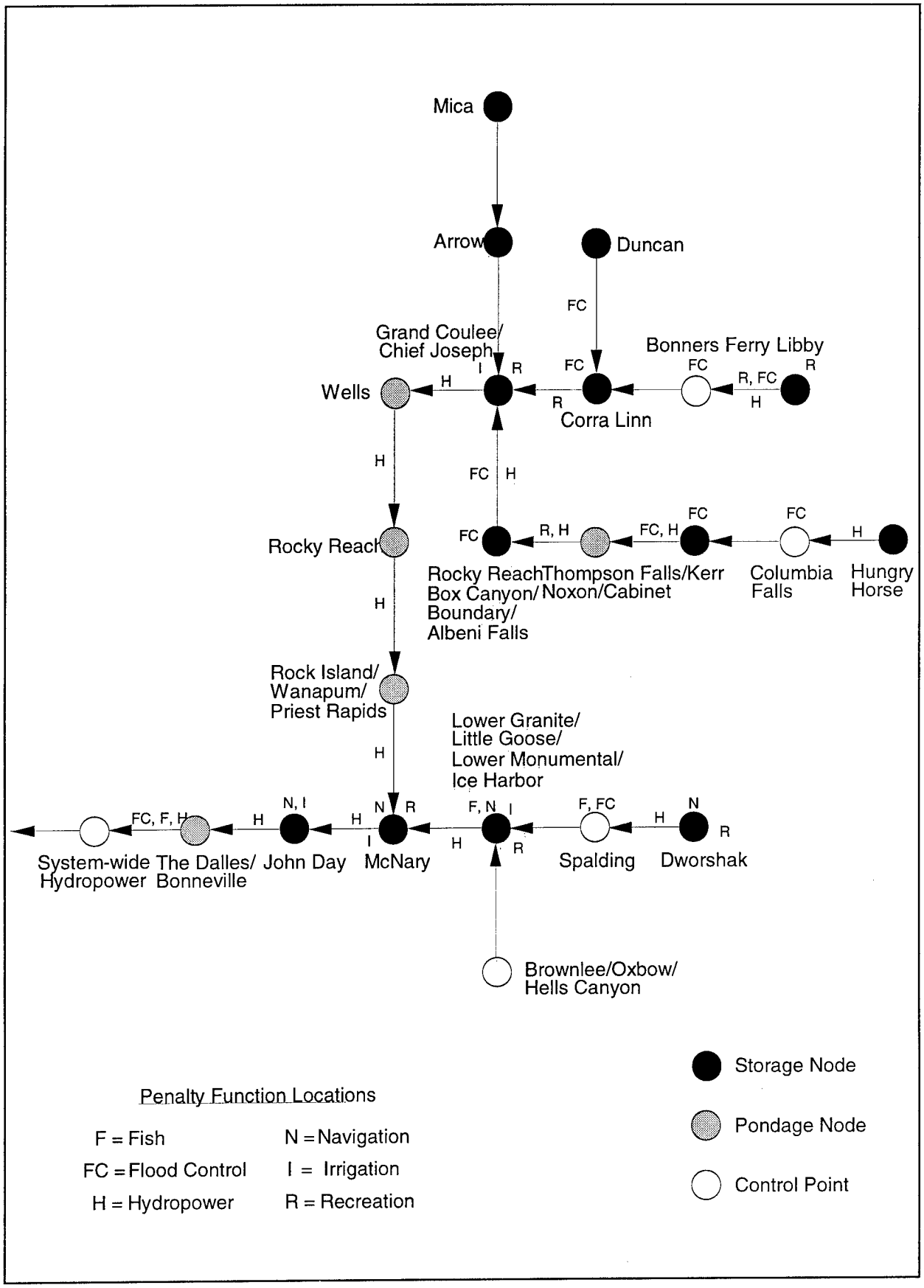


Figure 2 Updated Single-Period Network Model of Columbia River System

optimization model allows for rapid identification of promising short-term operating advice for consideration by system operators and more detailed simulation testing and refinement.

HEC-PRM is a network flow model that optimizes reservoir operations by minimizing flow and storage penalties or costs throughout a reservoir system network. Position analysis, as stated above, is a common study approach that focuses on short-term, seasonal periods, conducting many separate model runs for a range of historically-based future flow scenarios. In its most basic form, n years of historical record are divided to provide data for n shorter runs of a seasonal operations model (Hirsch, 1978).

The number of runs (n) is directly related to the number of inflow sequences available. In this report, the historical streamflow record forms the basis for at least 48 seasonal forecasts of system inflows. These inflow scenarios are then used in at least 48 separate HEC-PRM runs to find the ranges of promising operations for this system. As explained by Hirsch, for each model run, each reservoir begins at a given current initial storage, or "position."

HEC-PRM

HEC-PRM is the model used to suggest seasonal reservoir operations for the four seasonal studies in this report. HEC-PRM is a prescriptive (or optimization) model and, therefore, the model optimizes the allocation of available water in the Columbia River System to find seasonal reservoir operations. HEC-PRM also is a network flow model. As a result, a network of nodes (reservoirs) and links (channels, diversions, etc.) needs to be defined to represent the actual, physical framework of a reservoir system, the Columbia River System in this case (Jensen and Barnes, 1980).

As a prescriptive model, HEC-PRM finds solutions based on predetermined operational objectives. Penalty functions define these operational objectives. The objective function of the network flow problem is the sum of the convex, piecewise-linear approximations of the penalty functions (USACE, 1991b).

The aim of the use of HEC-PRM is to develop storage and release advice for use in more detailed simulation studies and to decrease the number of simulation runs required to formulate seasonal reservoir operation plans. Advantages of using HEC-PRM for this purpose are that the quantity of runs necessary to reach a storage or release target is typically less than for a simulation model and the model is driven explicitly by formally stated system operating purposes, in the form of penalty functions.

A limitation of HEC-PRM is the model's omniscient perspective of future inflows. This allows HEC-PRM perfect foresight into future seasonal inflows, which is unrealistic, and, therefore, subsequent simulation testing is usually required.

Step-by-Step Seasonal Study Procedure

The step-by-step seasonal study procedure using HEC-PRM with the position analysis approach for the Columbia River System is as follows.

1. *Develop a HEC-PRM model of the system.* This includes representing the actual reservoir system as a network of nodes and links. Penalty functions are formulated to drive the optimization process and define the operating objectives of the system, both economic and non-economic. Both the reservoir network and penalty functions were already developed for the Columbia River System when these seasonal studies were begun (USACE, 1991b, 1993, 1995).

2. *Define the operating seasons of the reservoir system.* For the Columbia River System, there are three operating seasons: the fixed drawdown season (August-December), the variable drawdown season (January-March), and the refill season (April-July).

3. *Define the seasonal periods for each optimization study.* More than one season may be included in a seasonal study. Four seasonal studies are presented in this report. Three of the four seasonal studies in this report, the 1994 and 1995 January - July studies and the 1994 Drawdown season study, span two of the three operating seasons in the Columbia River System. The 1994 and 1995 January - July studies incorporate both the variable drawdown season and the refill season. The 1994 Drawdown season study encompasses the fixed drawdown season and the following variable drawdown season. The 1995 April - July seasonal update study covers the refill season only.

4. *Formulate end-of-period storage penalty functions.* End-of-period storage penalty functions manage carryover storage at the end of each study period. For the Columbia River System end-of-period storage penalty functions, the median storage results from a USACE NPD simulation model (HYSSR) study in 1995 were used as storage targets, with penalties for missing this target equal to the value of stored energy (USACE, 1995).

5. *Set current initial storage values for each reservoir.* Here, Actual Energy Regulation (AER) storage values were used in the seasonal studies to represent the initial storages or starting "positions" of each reservoir.

6. *Specify the inflow hydrologies to be used in the seasonal operation study.* Historical flows and forecasted inflows are used throughout the four seasonal studies in this report. The forecasted inflows are historical inflows modified by flow forecasts. The flow forecasts are determined monthly according to snowpack and soil moisture conditions. These forecasts are only available from January to June in the Columbia River System. As a result, forecasted inflows were available for every study in this report except the 1994 Drawdown season study, where historical flows were used.

7. *Run HEC-PRM for each inflow sequence.* For the seasonal studies in this report, the number of years of inflow available for each study ranged from 47 to 50 years. Each reservoir starts at the current initial storage, or "position," and the optimization analysis is run for the length of the season of interest.

8. *Interpret the HEC-PRM storage and release results.* Numerous graphs are used to aid interpretation of results. Position analysis plots show the storage or release results for each run overlaid upon each other; this display clearly shows the band of storage and release results suggested by HEC-PRM given the initial storage and range of inflow hydrologies. Quartile plots are a statistical representation of the position analysis plots; only the minimum, maximum and 25th, 50th and 75th percentile storage or release results are plotted. Exceedance and non-exceedance plots and storage allocation graphs also are used to evaluate the HEC-PRM seasonal reservoir operations. Storage allocation plots are useful to determine basic refill or drawdown operations on a system-wide basis. The intent is to examine the optimization results to find consistent and promising near-term advice for efficient operations.

9. *Test HEC-PRM advice from the study conclusions with simulation.* The HEC-PRM advice should be able to direct the focus of simulation studies and lessen the number of simulation runs required to establish seasonal reservoir operation plans. This part of a seasonal reservoir study was not conducted for the studies in this report.

Seasonal Operation Application with Many Flow Forecasts

This section discusses the HEC-PRM seasonal operations for the Columbia River System for seasons in which flow forecasts are available. Forecasted inflows are available only from January to June. Many flow forecasts are made each month during this period from current snowpack and moisture conditions, allowing for possible modifications to each year of the historical inflow record Three of the four studies discussed in this report have forecasts for the seven reservoirs under study available for use. The 1994 and 1995 January 1 flow forecasts are used in the 1994 and 1995 January - July studies respectively. Similarly, the April 1 inflow forecasts are used in the 1995 April - July seasonal update study. Since the 1994 Drawdown season study begins in July, flow forecasts are unavailable and historical inflows are used for the optimization analysis.

The HEC-PRM results for each of the seasonal studies in this report are analyzed to provide the following six items.

1. The probability of refill or drawdown for each of the seven reservoir is examined because a main goal of optimization and simulation modeling is to suggest how to operate a reservoir system to reach the end-of-period target storage. Analysis is conducted to assess if each reservoir reaches its target storage at the end of the season for all inflow sequences.

2. The HEC-PRM system-wide operation of the reservoirs is compared to the Actual Energy Regulation (AER) operation of the reservoir system. AER storages were used for the initial reservoir storages. The HEC-PRM system reservoir operation should be fairly similar to the operation used for the initial reservoir storages to ensure that HEC-PRM produces realistic seasonal operations.

3. The HEC-PRM system-wide storage allocation is examined to discover HEC-PRM's advice on system-wide drawdown or refill. Storage allocation analysis shows the order of reservoir drawdown or refill desirable for seasonal operations.

4. HEC-PRM and AER storage trends (drawdown, refill or level storage) from month-to-month are compared. Storage trend comparisons show if HEC-PRM operates each reservoir with the same basic trend as the AER operation. For the 1994 Drawdown study, HYSSR storage trends are available for comparison also.

5. Study the storage magnitude difference between HEC-PRM storage values and the AER operation. It is important to know the variation between HEC-PRM storage operation and the established operation, such as AER, for a seasonal period.

6. HEC-PRM specific quantitative storage and release results are determined. Any strong HEC-PRM quantitative advice is potentially useful for input into simulation studies.

Near-Term Period Analysis

Seasonal operation study result analysis typically focuses on the near-term period within each study. The "near-term" here is the first three months in a seasonal study. For instance, in the 1995 January - July study, the majority of the result analysis focuses on the January - March period. Near-term analysis is emphasized because of the potential use of seasonal update studies, conducting new optimization studies every month or every several months, where only the near-term information is valuable. Seasonal update studies are seasonal operation studies re-run within a seasonal period as current storage conditions and inflow forecasts are updated. The 1995 April - July seasonal update study in this report explores this technique.

January - July Season Results (1994 and 1995)

The 1994 and 1995 January - July studies both examine the variable drawdown season and refill season, but with different inflow forecasts and slightly different starting storage conditions. As a result, a comparison can be made between HEC-PRM results for both studies, understanding that initial reservoir storages and forecasted inflow hydrology vary. There is a significant difference between the inflow characteristics of these two studies; the 1994 forecasted inflows are less than those in 1995. Actually, the 1994 water year was drier than the 1995 water year (CRWMG, 1994).

The six key items focused on in the analysis of the HEC-PRM results are compared below for the 1994 and 1995 January - July studies.

1. HEC-PRM refilled more system reservoirs to their target storage for all of the inflow sequences tested in the 1995 study than the 1994 study. Four reservoirs, Mica, Arrow, Grand Coulee and Libby, always stored the target level in July in the 1995 study. Only two reservoirs, Mica and Grand Coulee, always reached their target storages in the 1994 January - July study. These findings are logical since less water was forecasted in 1994.

2. For both January - July season studies, HEC-PRM suggests drawing down the system throughout the near-term period (January, February and March, coincidentally the variable drawdown season). Notably, HEC-PRM suggests storing less water at the end of March in 1995 than 1994; HEC-PRM is aware that the greater 1995 forecasted inflows will refill the system sufficiently.

The 1994 Actual Energy Regulation operations draw down the system much as HEC-PRM did. However, 1995 actual AER operations were not so consistent throughout January - March (Figure 3), beginning refill in February.

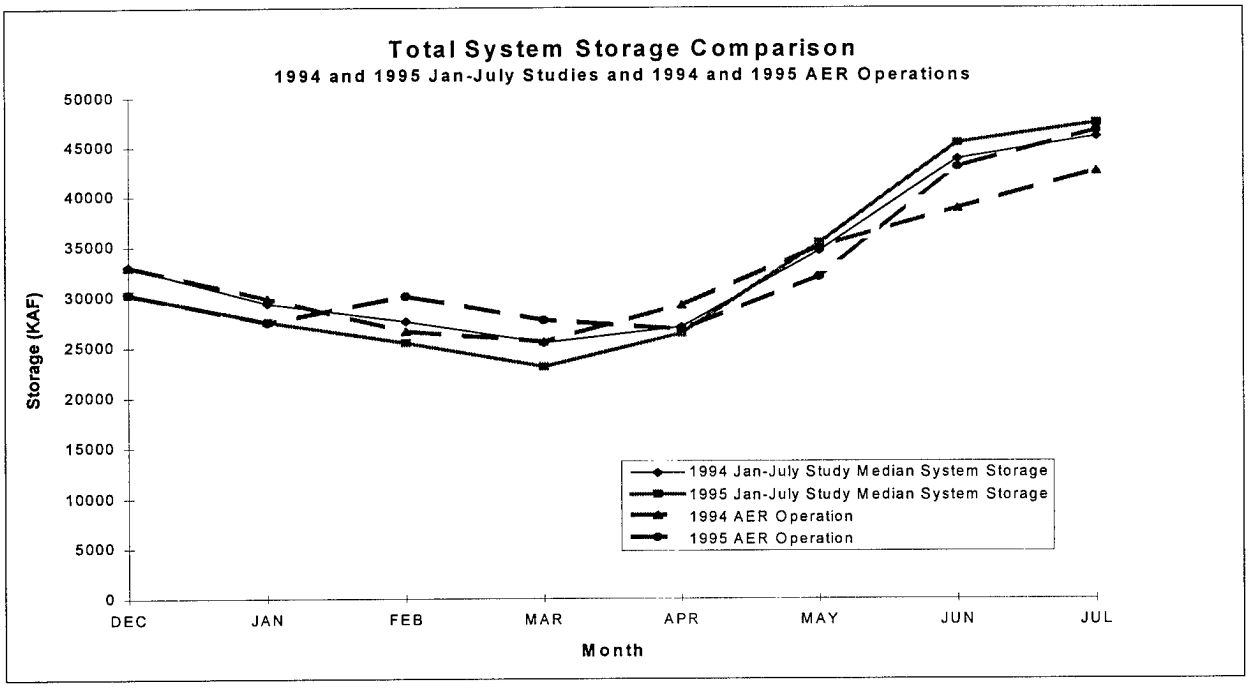


Figure 3 Comparison of Total System Storage for 1994 and 1995 Jan-July Studies and 1994 and 1995 AER Operations

3. HEC-PRM suggests similar system-wide ordering of reservoir drawdowns (storage allocation) for the January - March variable drawdown operation for both 1994 and 1995 studies. Arrow reservoir is drawn down first, followed by either Mica or Dworshak. Grand Coulee is drawn down fourth. In the 1995 January - July study, Libby reservoir is the last reservoir to be drawn down, while both Libby and Hungry Horse draw down last together in the 1994 study.

4. The storage trends of HEC-PRM and AER compare better for the 1994 operations than the 1995 operations. For instance, 13 of 21 possible storage trends match for 1994, while 9 of 21 trends agree between the 1995 HEC-PRM and AER operations. In addition, comparing the HEC-PRM storage trends together, 16 of 21 trends agreed (Table 1).

5. Comparison of the storage magnitude between HEC-PRM results and actual AER operations shows stronger agreement between them in the 1995 variable drawdown season than the 1994 variable drawdown season. Furthermore, given HEC-PRM's tendency to draw down the system more in 1995 (the wetter water year) than in 1994, HEC-PRM also tends to store less water in a number of reservoirs in 1995 than the 1995 AER operation. Conversely, in 1994, HEC-PRM tends to store more water than the AER operation in more reservoirs, responding to lesser forecasted inflows.

6. HEC-PRM specific quantitative storage and release advice is strong for both 1994 and 1995 studies. In both January - July season studies, HEC-PRM suggests releasing 603KAF, the minimum release, from Mica each month of the variable drawdown season. Both HEC-PRM studies store the minimum allowable storage of 227KAF in Arrow monthly from January to March. HEC-PRM suggests the following releases in January, February, and March in both January - July studies: Duncan reservoir at 6KAF (minimum allowable release) per month, Libby releases of 181KAF, the minimum allowable release, each month, Hungry Horse releases of 60KAF monthly and Dworshak releases between 300KAF and 450KAF each month. Additionally, for the 1994 January - July study, Grand Coulee stores 9107KAF (maximum storage).

April - July Season Results (1995)

The 1995 April - July study is a seasonal update study for the 1995 January - July period. Updated inflow forecasts and storage levels of April 1st were used to run the 1995 April - July study for the 1995 refill study. Comparison of the HEC-PRM 1995 refill operations for the 1995 April - July seasonal update study and the 1995 January - July study shows that HEC-PRM refill operations were modified in the seasonal update study.

Specifically, the 1995 April - July study operations follow the AER operation more closely than the 1995 January - July study results. It is encouraging that HEC-PRM offers reservoir operation modifications as new flow and storage information becomes available. Therefore, HEC-PRM seasonal update studies are feasible for continuous improvement of seasonal operations, given new inflow forecasts and storage updates.

Below, the six main findings from the 1995 April - July seasonal update study results are presented.

1. HEC-PRM refilled three of the seven storage reservoirs, Mica, Grand Coulee and Libby reservoirs, to their target storages for all inflow sequences in the 1995 April - July study. The number of reservoirs that HEC-PRM always refilled to their target storages decreased by one from the 1995 January - July study to the 1995 April - July study. HEC-PRM always refilled Arrow reservoir in the 1995 January - July, but, with the updated inflow forecasts and storage

Table 1 Comparison of Storage Trends for 1994 and 1995 Variable Drawdown Seasons

RESERVOIR	1995 Jan - July Study	1994 Jan - July Study
January		
Mica	Drawdown	Drawdown
Arrow	Drawdown	Drawdown
Grand Coulee	Refill	Refill
Duncan	Refill	Refill
Libby	Drawdown	Drawdown
Hungry Horse	Refill	Drawdown
Dworshak	Drawdown	Drawdown
February		
Mica	Drawdown	Drawdown
Arrow	Maintain 227KAF	Drawdown
Grand Coulee	Drawdown	Variable
Duncan	Refill	Refill
Libby	Variable	Drawdown
Hungry Horse	Drawdown	Drawdown
Dworshak	Drawdown	Drawdown
March		
Mica	Drawdown	Drawdown
Arrow	Maintain 227KAF	Maintain 227KAF
Grand Coulee	Drawdown	Drawdown
Duncan	Refill	Refill
Libby	Drawdown	Drawdown
Hungry Horse	Variable	Drawdown
Dworshak	Drawdown	Drawdown

levels of April, HEC-PRM clearly did not have enough water to ensure that Arrow reservoir always would reach its target storage in the 1995 April - July study.

2. The system-wide operations for both HEC-PRM and AER operations are refill in the 1995 April - July study. HEC-PRM's April to June system-wide operation in the 1995 January - July study is the same: consistent refill. Notably, HEC-PRM's system-wide storage is closer to the AER operation for the 1995 seasonal update study than the 1995 January - July study.

3. HEC-PRM allocates storage and orders refill among the seven reservoirs in the 1995 April - July as follows (Figure 4). Grand Coulee reservoir refills first to the 9107KAF level. Arrow and Mica reservoirs significantly refill next. Duncan, Libby, Hungry Horse and Dworshak reservoirs are refilled after Grand Coulee, Arrow and Mica reservoirs begin refilling. The similarities between HEC-PRM's storage allocation for the 1995 January - July study and the 1995 April - July study are few. Mica and Arrow reservoirs refill once Grand Coulee refills to 9107KAF and levels off. A discrepancy between the two studies is that Grand Coulee is first priority for refill in the seasonal update study but Libby refills first in the 1995 January - July study.

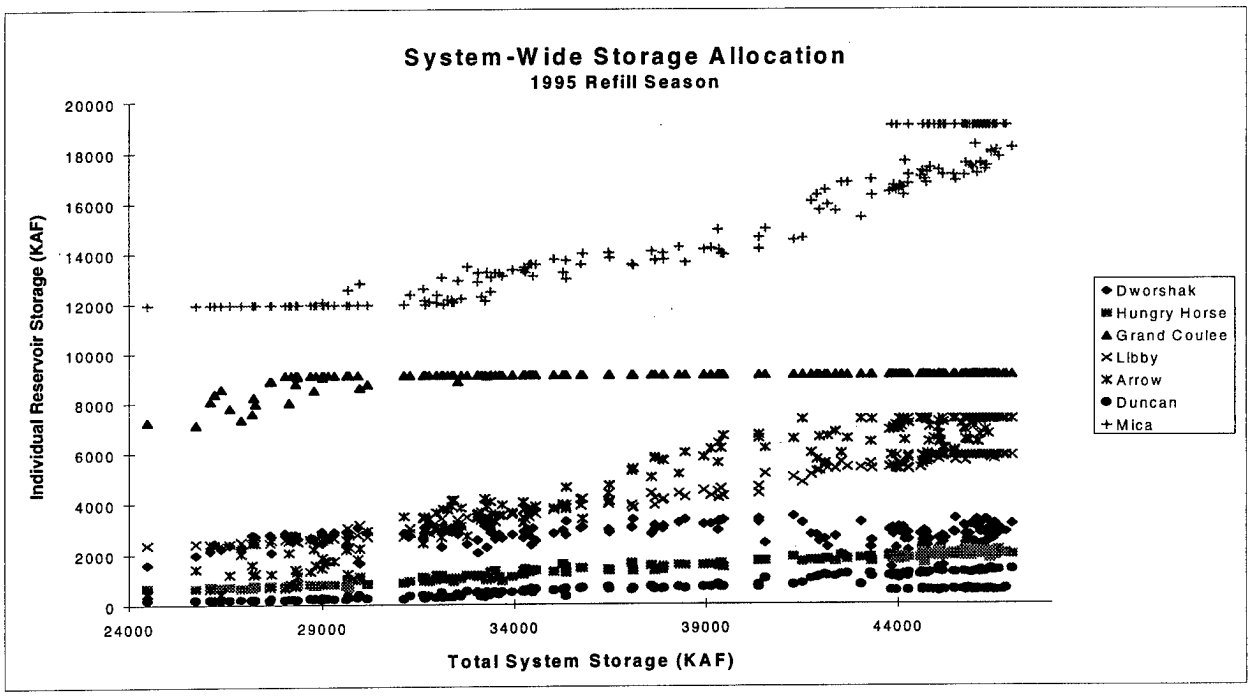


Figure 4 System-Wide Storage Allocation for Refill for HEC-PRM 1995 Apr-July Study

4. HEC-PRM and AER storage trends match for 12 of 21 comparisons for the 1995 seasonal update study.

5. HEC-PRM typically stores more water in Mica, Grand Coulee, Duncan, Libby and Hungry Horse reservoirs in April, May and June than the AER operation in the 1995 April - July study. Similarly, in the 1995 January - July study, HEC-PRM stores more water in the above five reservoirs than the AER operation.

6. HEC-PRM's specific quantitative storage and release advice is strong for the 1995 April - July seasonal update study (Table 2). Grand Coulee should store 9107KAF in April, May and June. Arrow and Duncan releases of 302KAF and 6KAF, respectively, should be made all three months.

Libby and Hungry Horse releases for April, May and June are 181KAF and 60KAF, respectively. Dworshak releases should range from 300KAF to 450KAF each month. The specific quantitative advice from HEC-PRM is the same between the 1995 April - July study and the 1995 January - July study for Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak for all three months.

Seasonal Operation Application without Flow Forecasts

The 1994 Drawdown study is unique because the fixed drawdown season is the only season in the Columbia River System without flow forecasts. Inflow forecasting from snowpack and soil moisture conditions is not available from July to December. As a result, the season from July to December is typically operated according to a fixed drawdown pattern and the 1994 Drawdown season study is run using historical inflow hydrology.

The 1994 Drawdown season study results are analyzed the same ways that the 1994 and 1995 January - July studies and the 1995 April - July study were analyzed. As a result, the six key items described earlier in the "Seasonal Operation Application with Many Flow Forecasts" section were the focus of the result analysis and they are presented below. Notably, the 1994 Drawdown season study results are compared to the AER operation as usual, and HYSSR simulations operations as well. The 1994 Drawdown season study is the only seasonal study in this report for which HYSSR results were available for comparison.

1. HEC-PRM always drew down all seven reservoirs to their respective March target storages.

2. Both HEC-PRM and actual AER operations begin system-wide drawdowns in August, while HYSSR starts system-wide drawdown in September. HEC-PRM typically stores more water in the system than the AER operation. HEC-PRM and HYSSR system-wide storages tend to overlap with a slight tendency for HEC-PRM to store a small amount more water than HYSSR.

3. HEC-PRM allocates storage by drawing down Mica, Duncan and Dworshak reservoirs first. Grand Coulee is kept high and level at 9107KAF as long as possible. Arrow reservoir is drained to 227KAF. Consequently, Grand Coulee is drawn down significantly. Mica, Libby,

Hungry Horse and Dworshak reservoirs draw down also. Duncan stays relatively level after its initial drawdown to 30KAF (minimum allowable storage).

Table 2 Comparison of HEC-PRM Specific Advice (KAF) for Both 1995 Studies

Mica	1995 Apr-July	%	1995 Jan-July	%
April	Store 11950	50	Store 14075	50
May	Release 0	50	Release 0 - 145	25
June	Release 0	75	Release 0 - 150	50
Arrow				
April	Release 302(Min)-771	25	Store 227	50
May	Release 302	75	SAME	50
June	Release 302	25	SAME	50
Grand Coulee				
April	Store 9107(Max)	50	SAME	75
May	Store 9107	75	SAME	100
June	Store 9107	100	SAME	100
Duncan				
April	Release 6(Min)	100	SAME	100
May	Release 6	100	SAME	100
June	Release 6	100	SAME	100
Libby				
April	Release 181(Min)	100	SAME	25
May	Release 181	100	SAME	25
June	Release 181	75	SAME	25
Hungry Horse				
April	Release 60	75	SAME	75
May	Release 60	100	SAME	75
June	Release 60	75	SAME	75
Dworshak				
April	Release 300-450	50	SAME	75
May	Release 300-450	75	SAME	75
June	Release 300-450	75	SAME	50

4. HEC-PRM and AER storage trend operations match for 11 of 21 comparisons. HEC-PRM and HYSSR storage trends agree for 12 of 21 comparisons. All three operations have similar storage trends for 7 of 21 instances.

5. HEC-PRM typically stores more water in Mica reservoir than HYSSR in the near-term, but approximately the same amount as the AER operation (Figure 5). Among the three operations, HEC-PRM stores the least amount of water in Arrow in July, August and September. Grand Coulee is operated at or near 9107KAF by all three operations throughout the near-term period (Figure 6). HEC-PRM stores more water in Duncan, Libby and Hungry Horse than the AER operation; HEC-PRM and HYSSR store approximately the same amount of water in these three reservoirs. For Dworshak reservoir, HEC-PRM tends to store less water than AER and HYSSR in July, August and September.

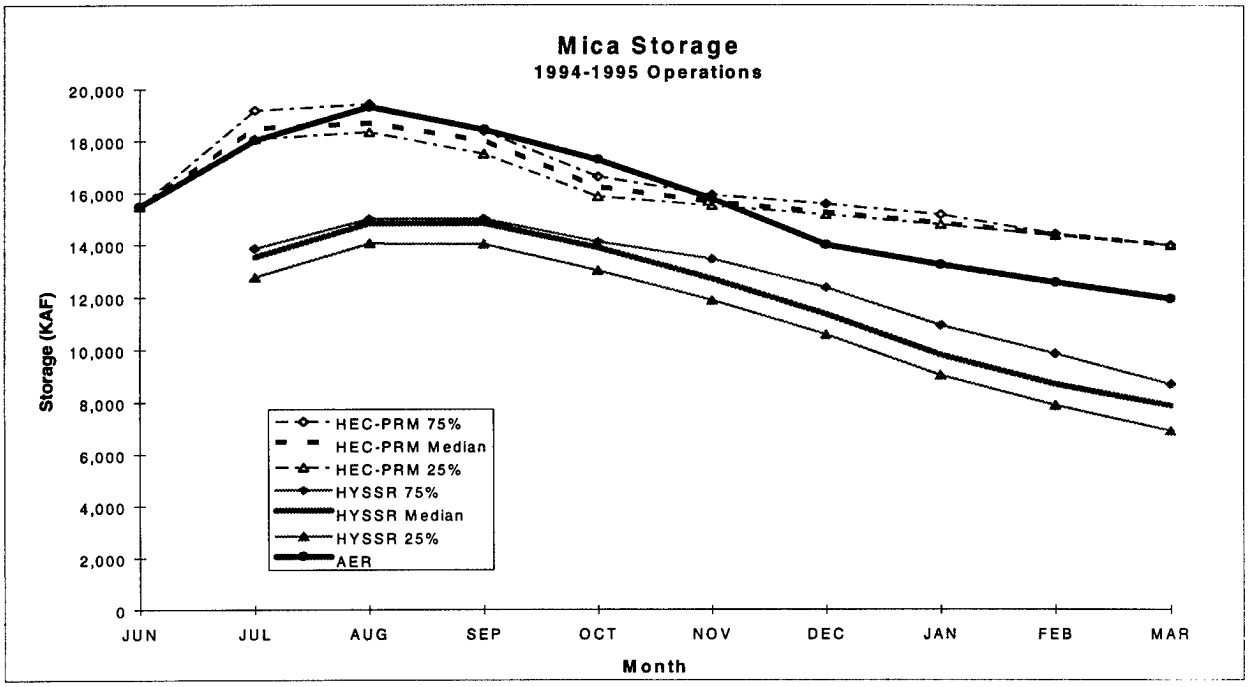


Figure 5 Comparison of Mica Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

6. HEC-PRM's strong, specific quantitative storage and release advice exists for three reservoirs. Grand Coulee always should store 9107KAF in July, August and September. Hungry Horse reservoir should release 60KAF in July, August and September. A release of 6KAF should be made from Duncan each month from July to September.

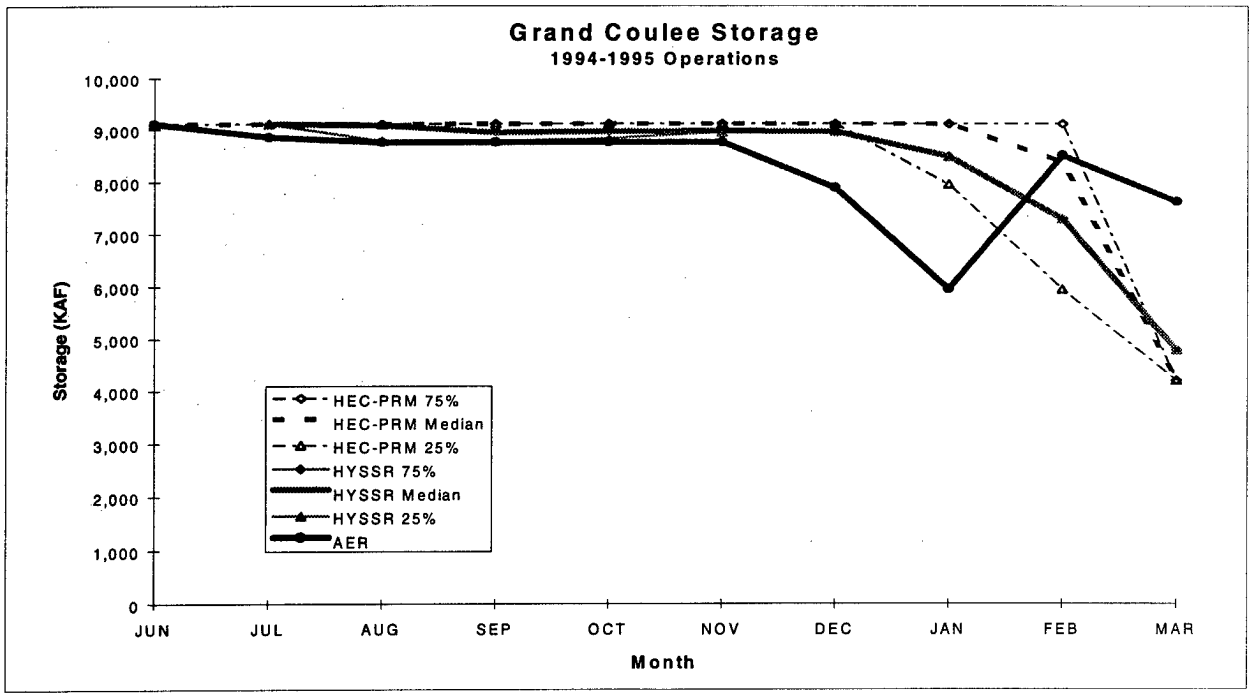


Figure 6 Comparison of Grand Coulee Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

Report Conclusions

1. HEC-PRM appears to be useful as a seasonal reservoir operation model using the position analysis approach, offering promising suggestions for seasonal operations. HEC-PRM operates the Columbia River system reservoirs similarly to the Actual Energy Regulation (AER) operations and suggests consistent advice throughout the four seasonal studies. Here, the AER storages are used as the initial storage values, forming the basis of HEC-PRM's optimization.

2. It is feasible, and useful, to make HEC-PRM runs throughout the season to provide updated operating advice. The 1995 April - July seasonal update study shows that HEC-PRM advice for the 1995 refill season is modified from the original 1995 January - July study. HEC-PRM uses the updated forecasted inflows and initial storages to study the ever-changing seasonal reservoir operations. For instance, the 1995 April - July study operations follow the AER operation more closely than the 1995 January - July study results.

3. HEC-PRM advises realistic operations for reaching reservoir refill target storages in the seasonal studies conducted for the January - July period. Given a limited supply of water to allocate, HEC-PRM typically suggests refilling the reservoirs with the capability to produce the highest energy content. For instance, Mica and Grand Coulee always meet their refill target storage for all inflow sequences for all three refill studies of this report. Also, the reservoirs with the greater inflows typically meet their refill targets more often.

4. HEC-PRM offers seasonal operation advice that both closely follows AER operation and deviates from it. Both types of advice are useful. The HEC-PRM advice that matches AER storages shows that HEC-PRM suggestions are reasonable. HEC-PRM advice that differs from AER operation may offer an improved seasonal operation plan. Such advice should be tested with simulation to explore its usefulness.

5. HEC-PRM advice changes appropriately to reflect changes in inflow hydrology. The forecasted inflows for the 1994 January - July season are smaller than the 1995 January - July forecasted inflows, and HEC-PRM advice for these studies differ as a result. HEC-PRM does not draw down the system as much as for the 1994 January - July study as the 1995 January - July study because HEC-PRM knows that 1994 inflows would not be large enough for adequate refill.

6. HEC-PRM typically allocates water throughout the seven reservoir system similarly for a given season. HEC-PRM draws down the system similarly in the 1994 and 1995 January - July studies. In addition, HEC-PRM's drawdown advice for the variable drawdown period is very close in the 1994 Drawdown study and 1995 January - July study.

7. HEC-PRM consistently encourages storing considerable volumes of water in the system. Mica and Grand Coulee reservoirs typically are kept at the highest storage level possible, likely due to their high energy contents. An exception to this HEC-PRM advice is for Arrow reservoir. HEC-PRM always suggests that Arrow should be drained to its lowest allowable storage in the variable drawdown season. Notably, no penalties are placed on Arrow's operation; therefore, HEC-PRM appears to use Arrow for system-wide benefit.

8. HEC-PRM provides specific quantitative advice consistently across the four seasonal studies. These storage and release suggestions should be tested with simulation to assess their usefulness for seasonal operations.

9. A future HEC-PRM seasonal study of the Columbia River system should be conducted using the observed storages as the basis of the optimization. AER storages form the basis of the four seasonal studies in this report.

10. HEC-PRM may be able to store considerable water in the Columbia River reservoirs because recent fish releases are not incorporated into the HEC-PRM penalty functions. Future modifications made to the penalty functions should include more consideration for fish requirements.

Chapter 1

Introduction

1.1 Purpose

This report describes an application of the Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM) using the position analysis approach to develop seasonal reservoir operation advice for the Columbia River System. The Columbia River System traditionally is operated in three distinct seasonal periods, the fixed drawdown season (August - December), the variable drawdown season (January - March) and the refill season (April - July) (USACE, 1993). The aim of this research study is to assess HEC-PRM's ability to suggest promising seasonal operations for the Columbia River System. Simulation should be used to refine and test HEC-PRM seasonal advice for improved operations. The Hydro System Seasonal Regulation Program (HYSSR) is the simulation model used by the U. S. Army Corps of Engineers North Pacific Division (NPD) to simulate the Columbia River System operations. This study is the first extensive use of HEC-PRM as a seasonal reservoir operation model. Past HEC-PRM studies of the Columbia River System are strategic, long-term planning studies (USACE, 1991b, 1993, 1995).

1.2 Description of the Columbia River System

The Columbia River basin is located in the Pacific Northwest region of the United States (Figure 1.1). The entire river basin spans Washington, Oregon, Idaho, Montana, Wyoming, Nevada and Utah in the USA, and British Columbia in Canada, for a total of 259,000 square miles (USACE, 1995). There are over 250 reservoirs and 100 hydroelectric projects distributed on the Columbia, Snake, Kootenai, Clearwater, and Pend Oreille Rivers and their tributaries. The Columbia River System is comprised of more than 120 of the above projects. This coordinated system is operated by the U.S. Army Corps of Engineers (Corps) and the U.S. Bureau of Reclamation for power generation, flood control, anadromous fish protection, navigation, and irrigation. Additional reservoir operations include water supply, recreation and fish and wildlife. The hydropower from this system is sold by the Bonneville Power Administration.

The Columbia River System is represented with the network model shown in Figure 1.2. The objectives for each reservoir node also are given in this figure. For study purposes, only the results for the main seven storage reservoirs, Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak, are discussed in detail. The formulation of this network model is presented in previous Columbia River reports (USACE, 1991b, 1993, 1995).

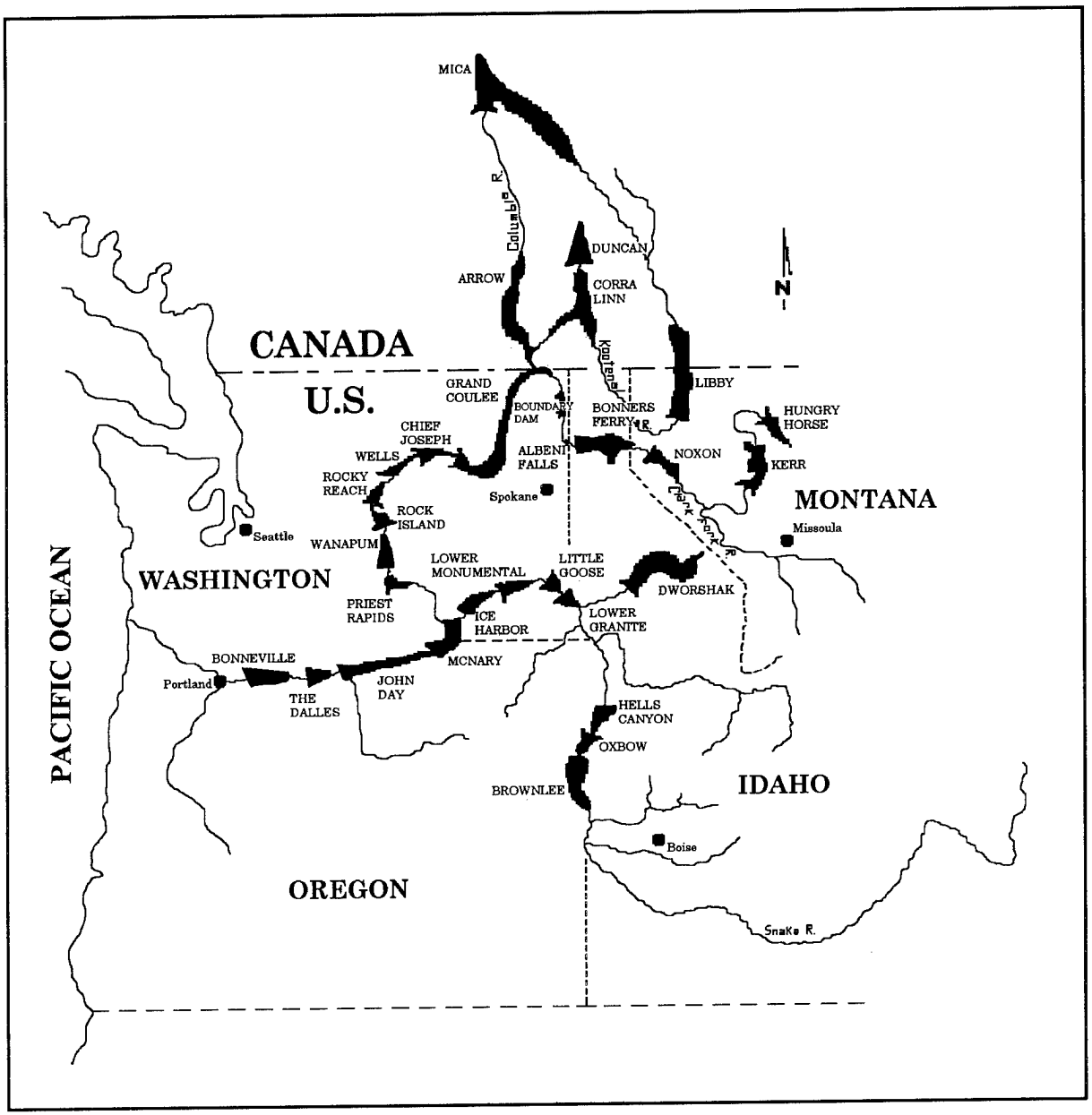


Figure 1.1 Columbia River System

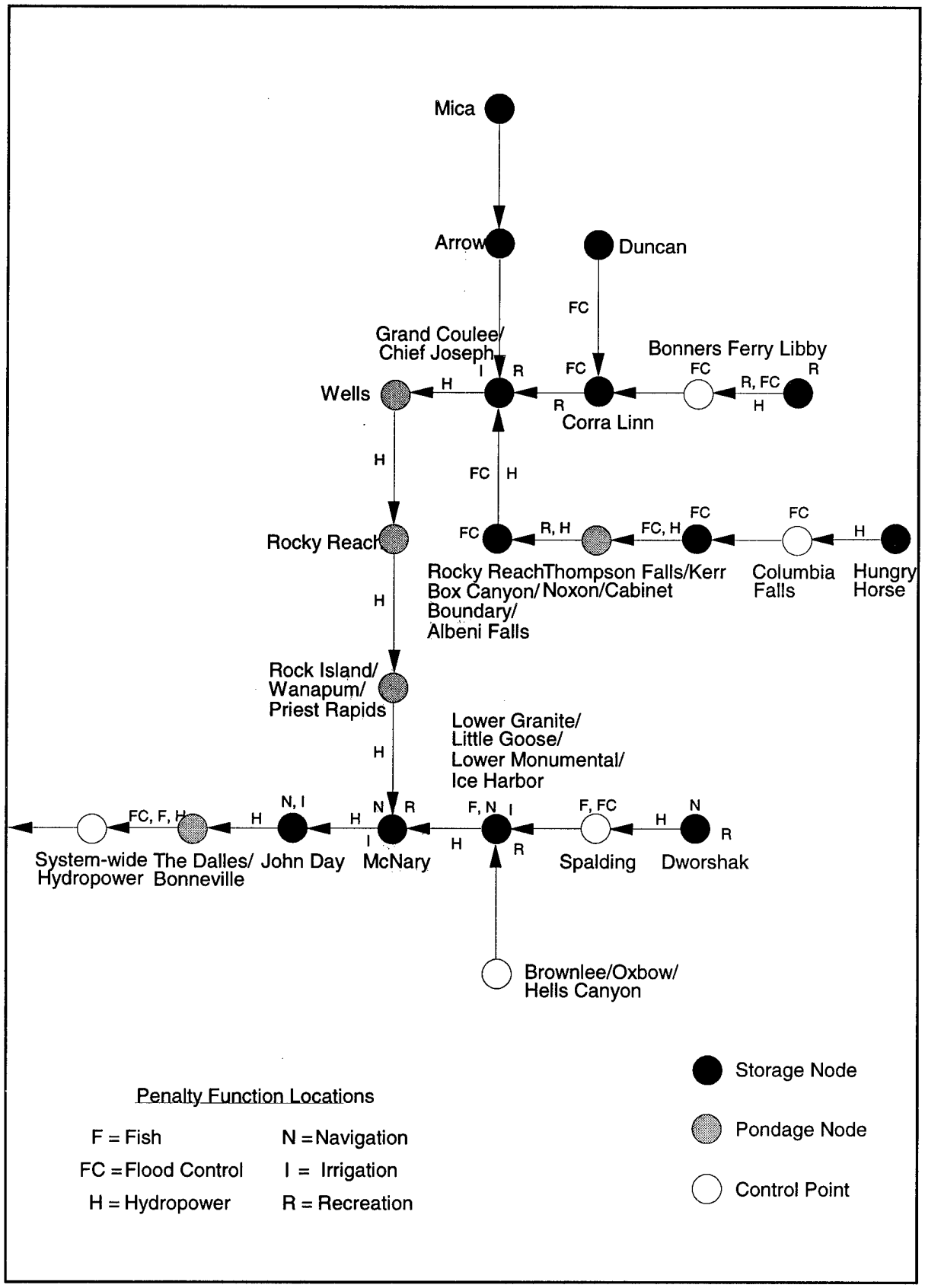


Figure 1.2 Updated Single-Period Network Model of Columbia River System

1.3 Method of Approach

Problem Statement

Each year the Columbia River System must be operated for changes in seasonal inflows and forecasts of future inflows based on snowpack and soil moisture information. The inflow forecasts are available monthly from January to June. Currently, these forecasts are used as inputs for seasonal simulation models, such as HYSSR, to aid in the formulation of near-term releases and seasonal storage targets for system operating purposes.

Study Approach

This report presents a preliminary application of a prescriptive model, HEC-PRM, for the development of seasonal operation of the Columbia River System using the position analysis approach. Prescriptive reservoir operation models suggest desirable release and storage values, given the reservoir system configuration, the inflow hydrology, and a quantified set of operating purposes. HEC-PRM seasonal reservoir operation studies are intended to optimize water allocation for near-term operation. Similar short-term reservoir operation optimization applications have been performed in practice and studied in academia (Crawley and Dandy, 1993; Palmer and Tull, 1987; Palmer and Holmes, 1988; Croley, 1974). These HEC-PRM seasonal reservoir operation optimization studies extend previous efforts in simulation modeling that explored seasonal reservoir operation (Hirsch, 1978, 1981a and 1981b).

HEC-PRM

HEC-PRM suggests seasonal reservoir operations for the four seasonal studies in this report. HEC-PRM, as a prescriptive (or optimization) model, optimizes the allocation of available water in the Columbia River System to find seasonal reservoir operations. HEC-PRM also is a network flow model and, as a result, a network of nodes (reservoirs) and links (channels, diversions, etc.) must be defined to represent the actual, physical framework of a reservoir system, the Columbia River System in this case (Jensen and Barnes, 1980).

As a prescriptive model, HEC-PRM finds solutions based on predetermined operational objectives. The penalty functions define these operational objectives and the objective function of the network flow problem is the sum of the convex, piecewise-linear approximations of the penalty functions (USACE, 1991b).

The goal of the use of HEC-PRM is to develop storage and release advice for use in more detailed simulation studies, and decrease the number of simulation runs required to formulate seasonal reservoir operation plans. An advantage of using HEC-PRM for this purpose is that the quantity of runs necessary to reach a storage or release target is typically less than for a simulation model due to the explicit driving of the model by formally stated system operating purposes, in the form of penalty functions.

A prescriptive, or optimization, model also has limitations relative to a simulation model. For HEC-PRM, limitations include the simplification of the reservoir system and the operating

objectives. In addition, HEC-PRM has perfect foresight into future seasonal inflows, which is unrealistic. These limitations support the continued need of simulation models, such as HYSSR. Despite the limitations of prescriptive models, simulation studies should be more focused and converge more quickly given the optimization model results as inputs for the simulation processes.

Position Analysis Approach Overview

To better represent the operation of the system and limit the impact of model foresight, the use of HEC-PRM in this study follows the application of position analysis, common in simulation modeling (Hirsch, 1978). Position analysis is designed to optimize or simulate reservoir operation for a seasonal period. The optimization or simulation starts from the current "position," the initial storage, of a reservoir and extends throughout the seasonal period under study. The optimization or simulation runs are repeated for the seasonal period for all applicable inflow sequences.

> "Position analysis is a specialized application of risk analysis. Its purpose is to estimate the risks associated with a given plan of operation over a period of a few months...it consists of n separate simulations rather than one continuous simulation of length n years. Each of these simulations is initialized with the same reservoir storage value--that storage actually existing in the reservoir at the beginning of the present month. Thus, it is an analysis of risks evaluated from the present 'position' " (Hirsch, 1978).

Hirsch discusses the use of the position analysis approach for simulation modeling only. Position analysis also can be applied to optimization studies, as shown with the HEC-PRM seasonal studies in this report. The use of position analysis with an optimization model allows for rapid identification of promising short-term operating advice for consideration by system operators and more detailed simulation testing and refinement.

Position analysis focuses on short-term, seasonal periods, conducting many separate model runs for a range of historically-based future flow scenarios. In its most basic form, n years of historical record are divided to provide data for n shorter runs of a seasonal operations model (Hirsch, 1978).

The number of runs (n) is directly related to the number of inflow sequences available. In this report, the historical streamflow record forms the basis for at least 48 seasonal forecasts of system inflows. These inflow scenarios are then used in at least 48 separate HEC-PRM runs to find ranges of promising operations for this system. As explained by Hirsch, for each model run, each reservoir begins at a given current initial storage, or "position."

Step-by-Step Seasonal Study Procedure

The step-by-step application of the position analysis technique to the Columbia River System is given below.

1. Represent the actual reservoir system as a suitable network of nodes and links for HEC-PRM. Formulate the relevant penalty functions to define the operation objectives of the system. The reservoir network and set of penalty functions were available from past HEC-PRM studies performed on the Columbia River System (USACE, 1991b, 1993, 1995).

2. Establish the operating seasons of the system. The Columbia River System has three seasons of operation, the fixed drawdown season (August - December), the variable drawdown season (January - March) and the refill season (April - July).

3. Determine the seasonal study periods for the HEC-PRM seasonal runs. In this report, there are four HEC-PRM seasonal studies. The 1995 January - July study, the 1995 April - July seasonal update study, the 1994 January - July study and the 1994 Drawdown season study were conducted.

4. Establish end-of-period storage penalty functions to encourage HEC-PRM to operate the reservoirs at their target storage at the end of each operating season. The target storage values used in the four HEC-PRM seasonal studies in this report are the median HYSSR values from the past HYSSR study (USACE, 1995).

5. Determine the current initial storage values for each reservoir in the reservoir network. For instance, the initial storages for the 1995 January - July study were the Actual Energy Regulation (AER) storages for January 1st.

6. Establish the inflow hydrology for a HEC-PRM seasonal study. Typically, historical inflows for the system are used. As for the Columbia River System, inflow forecasts can be used to modify historical inflows when available. The HEC-PRM seasonal studies that focus on the variable drawdown season or refill season have inflow forecasts available for such modifications.

7. Run HEC-PRM for each inflow hydrology sequence. Forty-eight to fifty years of inflow hydrology are used in each of the four HEC-PRM seasonal studies.

8. Analyze the storage and release results. Position analysis plots, quartile plots, exceedance and non-exceedance probability plots and storage allocation plots are among the graphs used to display the HEC-PRM results.

9. Test the HEC-PRM seasonal operation advice with simulation. Simulation testing has not been conducted for the seasonal studies in this report. In addition, HEC-PRM advice could be used to focus simulation studies and lessen the number of simulation runs.

1.4 Discussion of HEC-PRM Seasonal Studies

A brief description of the four HEC-PRM seasonal studies in this report is given in this section. The seasonal study analysis procedure is outlined. The concepts of HEC-PRM seasonal update runs and near-term period analysis are presented. In addition, the inflow hydrology, Actual Energy Regulation (AER) storages, HEC-PRM penalty functions and end-of-month storages used in these studies are discussed.

Description of HEC-PRM Seasonal Studies

Four HEC-PRM seasonal studies were conducted. The 1995 January - July study incorporates both the 1995 variable drawdown and refill seasons. The 1995 April - July study is a seasonal update run; only HEC-PRM's seasonal advice for the 1995 refill season is updated. The 1994 January - July study captures the variable drawdown and refill seasons for 1994. Lastly, the 1994 Drawdown season study includes the 1994 fixed drawdown season and the 1995 variable drawdown season. All four studies cover the three main operating seasons in the Columbia River System: fixed drawdown, variable drawdown and refill seasons. Table 1.1 lists the four studies, the corresponding analysis seasons and inflow types.

Table 1.1 Description of Seasonal Studies

Chapter	Study	Season Start	Season End	Seven Reservoir System Inflows
3	1995 Jan- July	January 1, 1995	July 31, 1995	Forecasted
4	1995 Apr - July	April 1, 1995	July 31, 1995	Forecasted
5	1994 Jan - July	January 1, 1994	July 31, 1994	Forecasted
6	1994 Drawdown	July 1, 1994	Mar 31, 1995	Historical

Seasonal Study Analysis

The HEC-PRM results for each of the seasonal studies in this report are analyzed to provide the following six items.

1. The probability of refill or drawdown for each reservoir is studied because a main goal of optimization and simulation modeling is to suggest how to operate a reservoir system to reach the end-of-period target storage. Analysis is conducted to determine if each reservoir reaches its target storage at the end of the season for all inflow sequences.

2. The HEC-PRM system-wide operation of the reservoirs is compared to the AER operation of the reservoir system since AER storages formed the basis of the optimization as the initial reservoir storages. The HEC-PRM system reservoir operation should be fairly similar to

the operation used for the initial reservoir storages to ensure that HEC-PRM produces realistic seasonal operations.

3. HEC-PRM system-wide storage allocation is examined to discover HEC-PRM's advice on system-wide drawdown or refill. Storage allocation analysis shows the order of reservoir drawdown or refill desirable for seasonal operations.

4. HEC-PRM and AER storage trends (drawdown, refill or level storage) from month-to-month are compared. HYSSR storage trends are considered in the 1994 Drawdown season study. Storage trend comparisons show if HEC-PRM operates each reservoir with the same basic trend as the AER operation, or HYSSR operation (when applicable).

5. Study the storage magnitude difference between HEC-PRM storage values and the AER operation. It is important to know the variation between HEC-PRM storage operation and the established operation, such as AER, or the simulated operation from HYSSR, for a seasonal period.

6. Specific HEC-PRM quantitative storage and release results are determined. Any strong HEC-PRM quantitative advice is potentially useful for input into simulation studies.

HEC-PRM Seasonal Update Runs

HEC-PRM seasonal update studies are useful to keep seasonal operation advice current. To ensure that HEC-PRM near-term seasonal operation advice is up-to-date, HEC-PRM seasonal studies should be run more than once in a given season, using current forecasted inflows and storage. The 1995 April - July study is a seasonal update run for the 1995 January - July study period. The April 1 initial storage conditions and inflow forecasts were used to formulate a seasonal operation update study on the April to July period (refill season). Comparison of the HEC-PRM seasonal advice for the April to July period from the 1995 January - July season study and the 1995 April - July season study shows that HEC-PRM's advice was modified between the 1995 January - July study and the 1995 April - July study.

Near-Term Period Analysis

The analysis of seasonal operation study results typically focuses on the near-term period within each study. The "near-term" here is the first three months in a seasonal study. For instance, in the 1995 January - July study, the majority of the result analysis focuses on the January - March period. Near-term analysis is emphasized because of the potential use of seasonal update studies and conducting new optimization studies every month or every several months.

Inflow Record

Each HEC-PRM seasonal study in this report uses inflow hydrology from the standardized inflow period of 1928 - 1978 (USACE, 1993). These fifty years of standardized inflow include low and high flow periods to represent the system inflow sufficiently (USACE,

1993). The critical periods of 1928 - 1932, 1943 - 1945 and 1977 are included (USACE, 1993).

The standardized inflows are adjusted and modified before they are used in HEC-PRM. The modified inflows used in the four HEC-PRM seasonal studies in this report are the 1980 level modified flows, reflecting 1980 depletions (USACE, 1993). For the 1994 and 1995 January - July studies and the 1995 April - July seasonal update study, inflow forecasts on January 1st and April 1st for the seven reservoirs under study were used to update the inflow record further. NPD updated the 1980 level modified flows with the seasonal inflow forecasts for these three HEC-PRM seasonal studies. The 1994 Drawdown study used the 1980 level modified streamflows directly since inflow forecasts are unavailable in July.

Actual Energy Regulation (AER) Storage Values

Actual Energy Regulation (AER) storage values are used as the initial storages in the four HEC-PRM seasonal studies described in this report. The AER storages formed the basis of the HEC-PRM storages rather than the observed storages, as the North Pacific Division provided HEC with the AER storage information. AER storage is defined as the legal or proportional drafting limit of a reservoir (U.S. Dept of Energy (USDOE), 1991). Typically, AER storage values are the lowest draft levels of a reservoir, in winter and spring, because AER allows for the production of non-firm energy (USDOE, 1991). Detailed comparisons between the HEC-PRM seasonal advice and the AER storages are presented for all four HEC-PRM seasonal studies.

HEC-PRM Penalty Functions

The penalty functions in the four HEC-PRM seasonal studies are those used in the earlier, trial HEC-PRM seasonal study for the Columbia River System in 1995 (USACE, 1995). The development of these penalty functions are described in detail in the previous Columbia River reports (USACE, 1991b, 1993, 1995). Very important penalties for the HEC-PRM seasonal studies are the end-of-period target storage penalty functions (USACE, 1995). Since the HEC-PRM seasonal runs extend for months, rather than years, the HEC-PRM operation throughout the season is influenced greatly by the end-of-period targets, therefore, they need to be chosen wisely.

For the 1995 January - July study, the 1995 April - July study and the 1994 January - July study, the July end-of-period storage penalty function already established for the preliminary HEC-PRM seasonal study was used. An additional penalty function was developed for the 1994 Drawdown season study. The March end-of-period penalty function, designed to guide HEC-PRM to the variable drawdown season target storage, was needed. The median HYSSR storage results from a past HYSSR study were used as the end-of-period storage targets (USACE, 1995).

End-of-Month Storage

Unless otherwise specified, monthly storage values discussed throughout this report represent end of the month storages. A June storage on a graph, labeled "JUN", describes the reservoir storage on June 30th. For consistency, storages on the 1st of the month, such as HEC-PRM study initial storages, are represented as the end of the month storage for the preceding

month. For instance, January 1 initial storages for the 1995 January - July study are described as "DEC" on plots.

HEC-PRM Storage and Release Values

The HEC-PRM storage and release results in this report are recorded to the nearest 10KAF unless the results are the minimum or maximum allowable storage or release values. Only the minimum or maximum HEC-PRM values can be stated precisely. (The AER storages are stated exactly as received from NPD, and the HYSSR results used for end-of-period target storages are not estimated either.)

1.5 Report Organization

Chapter 2 presents the background on the existing seasonal operations in the Columbia River System, and describes additional HEC-PRM studies conducted for the Columbia River, Missouri River and other locations.

Chapters 3 - 6 discuss the HEC-PRM results and seasonal advice for the four seasonal studies: the 1995 January - July study, the 1995 April - July study, the 1994 January - July study and the 1994 Drawdown season study. The results for each study are compared to the AER operations. HYSSR results are available for comparison for the 1994 Drawdown season study only.

Chapter 3 describes the HEC-PRM results and advice for the 1995 January - July study.

Chapter 4 presents the HEC-PRM seasonal results and advice for the 1995 April - July study and a detailed comparison of the HEC-PRM results for the April - July (refill) period for both 1995 studies.

Chapter 5 discusses the HEC-PRM seasonal results and advice for the 1994 January - July study. A seasonal update run was not conducted for this period. The HEC-PRM results are compared to the 1995 January - July variable drawdown results.

Chapter 6 describes the 1994 Drawdown season study, which extends from July 1994 to March 1995. The HEC-PRM results for this study are compared to the 1995 variable drawdown season study results. The 1994 Drawdown season study is the only study which has HYSSR results available for comparison.

Chapter 7 presents the overall conclusions of the seasonal reservoir operation studies for the Columbia River System, and discusses the advantages and limitations of HEC-PRM as a seasonal operation model.

Appendix A lists the references used in this report. Appendix B provides a description of the model, HEC-PRM.

Chapter 2

Background

2.1 Existing Operations of the Columbia River System

The Columbia River System traditionally has been operated seasonally. Three seasons, the fixed drawdown season, the variable drawdown season and the refill season, define the different periods of reservoir operation for the system (USACE, 1993). The fixed drawdown season is from August to December when reservoirs are drawn down according to fixed rule curves. Variable drawdown operations begin in January, when runoff forecasts become available, and this season extends until March. The refill season starts in April and continues through July, with peak inflows reaching the reservoirs during this period. The HEC-PRM seasonal studies presented here are modeled after these three seasons.

Specific operation objectives for the Columbia River System exist each season (USACE, 1993). In the fixed drawdown season, flood control and power generation are the main operational goals. The objectives in the variable drawdown season are basically the same as for the fixed drawdown season, flood control and power generation. In addition, a sufficient storage level should be kept for a greater probability of refill in July, and to store enough water for required spring fish flow releases. During the refill season, fish releases should be made to assist fish migration to the Pacific Ocean. At the same time, reservoirs should store the peak inflows and fill. Similar to the operation objectives in both drawdown seasons, flood control and hydropower generation should continue in the refill period.

2.2 Seasonal Use of HEC-PRM for the Columbia River System

There is a demand for a seasonal operation model to aid the reservoir operation planning of the Columbia River System because the Columbia River System traditionally is operated on a distinct seasonal basis. The Columbia River System experiences definite seasons of drawdown and refill annually. Since the reservoirs are drawn down in the fall and winter, and refilled in the spring, storage space must be created to accommodate the runoff due in the following spring during the fall and winter. As snowpack melts in the spring, the large amounts of runoff enter the Columbia River basin and the reservoirs must store this water.

This cycle occurs every year and dependable reservoir operations are necessary because the storage capacity of the system is only about one-third of the mean annual flow through the basin (USACE, 1995). As a result, it may be advantageous to have additional advice, provided by a prescriptive (objective driven) model such as HEC-PRM, for the Columbia River System operation. HEC-PRM has the potential to offer insight and possible improvements to the Columbia River System's seasonal reservoir operation.

The HEC-PRM seasonal reservoir operation studies are modeled after the three operating seasons in the Columbia River System. The 1994 and 1995 January - July studies incorporate both the variable drawdown and refill seasons. The 1995 April - July study describes the 1995 refill season only. The 1994 Drawdown study covers both the 1994 fixed drawdown season and the 1995 variable drawdown season.

2.3 Previous HEC-PRM Studies

HEC-PRM typically has been used to find desirable strategic reservoir operation plans. The use of HEC-PRM as seasonal reservoir operation model is a recent proposal. A preliminary HEC-PRM seasonal study was conducted in 1995, studying the Columbia River System (USACE, 1995). The conclusions encouraged the further study described in this report. The previous HEC-PRM studies include the Missouri River system, the Columbia River System, and the Alamo Reservoir system.

Missouri River Reservoir System

HEC-PRM originally was developed to study the Missouri River reservoir system. The Missouri River system operation policy review in 1990 motivated the development of an analysis tool to assist in the project. As a result, the prescriptive reservoir optimization model, HEC-PRM, was designed and constructed (USACE, 1992a). In Phase I of the Missouri River study, HEC-PRM was tested to validate its usefulness as an analysis tool for the system operation policy review (USACE, 1991a). As a result of successful testing, HEC-PRM was applied to the Missouri River system, and preliminary critical period studies were conducted (USACE, 1991a).

Based on the results of the Phase I HEC-PRM application to the Missouri River system, using the 93-year historical record, strategic operating rules were inferred and compared with then-current operations (USACE, 1992b). These rules were refined and successfully tested using a simulation model (USACE, 1994). The HEC-PRM operation plans for the Missouri River system are long-term, strategic plans; seasonal operations were not considered in the Missouri River study.

Phase II of the Missouri River reservoir system continued the HEC-PRM reservoir operation analysis (USACE, 1992a). Model modifications and improvements were made. For instance, the portion of the Missouri River system under study was expanded, the penalty functions were refined and HEC-PRM's user interface was improved.

Columbia River System

HEC-PRM was applied to the Columbia River System in several studies, beginning in 1991. Phase I of the Columbia River study involved the investigation, and subsequent verification, of HEC-PRM as an analysis model for the Columbia River System (USACE, 1991b). HEC-PRM was applied to the Columbia River's July 1928 - February 1932 critical flow period to conduct a preliminary study on the system. The conclusion was that HEC-PRM's operations were favorable.

In Phase II, model modifications and improvements were made to HEC-PRM, and additional HEC-PRM applications were run for the Columbia River System (USACE, 1993). The changes to HEC-PRM included the expansion of the Columbia River System network in the model, penalty function refinement and software improvements. The HEC-PRM operations from both Phase I and II are strategic planning operations, including the use of HEC-PRM as a screening model to evaluate different planning alternatives.

The third phase of the study presented preliminary operating rules for the Columbia River System (USACE, 1995). HEC-PRM strategic advice was found to be reasonable. HEC-PRM results tended to be similar to the operation strategy to HYSSR, but suggested several refinements.

The proposal to use HEC-PRM as a seasonal model originated during Phase III of the Columbia River application. As a result, the first HEC-PRM seasonal run was conducted to test the feasibility of using HEC-PRM as a seasonal model. HEC-PRM's potential as a seasonal model appeared promising, and inspired this current, more extensive HEC-PRM seasonal study.

Alamo Reservoir

HEC-PRM was applied to Alamo Lake, Arizona in 1994 (Kirby, 1994). HEC-PRM, in conjunction with a simulation model, was tested as an analysis tool to help resolve the conflict over the US Army Corps of Engineers operation of Alamo reservoir. The Alamo HEC-PRM study is a strategic planning study. Seasonal operation was not considered in this effort. The conflict existed because the agencies involved in Alamo Lake's management had different operational objectives. Unique to the Alamo Lake HEC-PRM project are environmental objectives, such as the protection of the endangered species, the Southern Bald Eagle. As a result, a new method for the development of HEC-PRM penalty functions was proposed, the Relative Unit Cost method (RUC).

The RUC method compares operation objectives on a non-monetary basis to avoid the controversy over measuring environmental objectives economically. First, the "ideal", "acceptable" and "adverse" storage and release ranges must be defined for each of the given reservoir operation objectives. Then, the relative unit penalty slopes are assigned for the ideal, acceptable and adverse ranges. For example, let a zero slope be assigned when the reservoir operates in the ideal range. Define a slope magnitude of 0.5 to the acceptable range and a slope magnitude of 1 to the adverse range. These slopes should be used for all objectives; the actual ranges of ideal, acceptable and adverse storage and releases differentiate the operation preferences between objectives.

Other Applications of HEC-PRM

There are additional applications of HEC-PRM. None of these HEC-PRM studies are seasonal operation studies. HEC-PRM was used to study the Highland Lakes system in Texas (Martin, 1992). HEC-PRM was used to discover possible operation improvements for the Highland Lakes system during drought periods.

HEC-PRM also is being applied at the University of California, Davis to the Carson-Truckee system in Nevada and California (Israel, 1996). The Carson-Truckee study uses HEC-PRM to explore water distribution, given that the Carson-Truckee system operates on a priority-based water use program.

The use of HEC-PRM to study the Alamo Reservoir continues with funding from the Corps Los Angeles District. Currently, multi-objective analysis is being used to discover possible solutions to the operation conflicts (Kirby, 1996a). There is an additional proposal to study Alamo Reservoir operations to determine beneficial operations for the Southern Bald Eagle.

Lastly, HEC-PRM is being used to study the South Florida system with support from the Corps Jacksonville District (Kirby, 1996b). The purpose of the South Florida study is to explore water conservation operations for Lake Okeechobee.

Chapter 3

1995 January - July Season Study

The 1995 January - July study period spans two traditional operating seasons for the Columbia River System, the variable drawdown season (January-March) and the refill season (April-July). HEC-PRM reservoir operation results for these two seasons are described in this section. The 1995 January - July study is based on January 1, 1995 inflow forecasts. The initial storage values (Actual Energy Regulation (AER) values) are listed. The probability of refill in July is analyzed. HEC-PRM's overall system-wide operations are presented. In addition, HEC-PRM's near-term operations are compared to the AER operation. HEC-PRM's near-term advice is given, both for the seven reservoir system and for each reservoir individually. Lastly, the conclusions of the study are discussed.

3.1 Initial Storage and Forecasted Inflows

January Initial Storage Values

Table 3.1 lists the January 1 initial storage values used in the 1995 January - July season study. The initial storages reflect the drafting limit given by the Actual Energy Regulation (AER). The AER storage values allow for the production of non-firm energy generation (USDOE, 1991). The U.S. Army Corps of Engineers North Pacific Division provided the AER values for the HEC-PRM study of the Columbia River System.

Table 3.1 January 1, 1995 Initial Storages (AER Values)

Reservoir	January 1 Initial Storage (KAF)
Mica	14008
Arrow	3451
Grand Coulee	7883
Duncan	36
Libby	2432
Hungry Horse	465
Dworshak	2023

Forecasted Inflows

The 1995 January - July study is run on forecasted inflow sequences based on standardized flows from the years 1929 - 1976. These forty-eight annual sequences are modified from the historic inflows with the January 1 inflow forecasts where available. Forecasted inflows are available for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs. Historical inflows have been used for the inflow points where forecasts are unavailable.

3.2 Probability of Refill in 1995

A primary goal of seasonal reservoir operation is to reach the target storage at the end of the season. HEC-PRM's seasonal reservoir operation advice for the Columbia River System is useful when the reservoirs meet their refill targets.

For the 1995 January - July refill season, the seven reservoirs have storage targets for the end of July. Here, the storage targets were selected as the median July storage values of a HYSSR historical record simulation study (USACE, 1995). Table 3.2 lists the July storage targets, HEC-PRM's success reaching the target storage levels for each reservoir, the July 1995 median HEC-PRM storage, and the July 1995 AER storage.

Table 3.2 July 1995 Target Storage Analysis for 1995 January - July Study

Reservoir	July 1995 Target Storage (KAF)	Percentage of Years Target Storage Met (%)	July 1995 Median HEC-PRM Storage (KAF)	July 1995 AER Storage (KAF)
Mica	19045	100	19045	18088
Arrow	7327	100	7327(Max)	6965
Grand Coulee	9107	100	9107(Max)	9107
Duncan	1399	0	670	1423
Libby	5869	100	5869(Max)	5869
Hungry Horse	3072	0	2240	1977
Dworshak	3468	4	3170	3246

HEC-PRM always reached the target storages set for July 1995 for four of the seven reservoirs. Mica, Arrow, Grand Coulee, and Libby's July storages always meet the targets (Figures 3.1, 3.2, 3.3 and 3.5). For these four reservoirs, HEC-PRM's seasonal operations reached the target storage for all 48 inflow sequences. None of the storage targets are exceeded

for any of the seven reservoirs.

HEC-PRM operates only four reservoirs at their target storages in July because water is unavailable to refill all seven reservoirs for all inflow sequences. HEC-PRM's optimal operation, given water shortages, is for Mica, Arrow, Grand Coulee and Libby reservoirs always to receive sufficient water to meet their targets. Grand Coulee is probably included because the hydropower production is best generated with a high head. In addition, the largest median inflows in the system occur at Mica, Arrow, Grand Coulee and Libby reservoirs (Figure 3.8).

Figure 3.9 shows how close the HEC-PRM operations for Duncan, Hungry Horse and Dworshak reservoirs operate near the July storage targets. Though Dworshak reservoir only meets its July target storage for two of forty-eight inflow sequences, the remaining results are reasonable, typically within 80% of target storage (Figure 3.9). Duncan drastically draws down in July and ends up far below the target storage (Figure 3.4). Hungry Horse's July storage is significantly less than the target also (Figure 3.6). Though Hungry Horse refills, it is unable to reach its target storage.

HEC-PRM appears to draw down Duncan and Dworshak to allow Libby to always meet its target and to continue filling Hungry Horse. Duncan reservoir may not be drawing down to supply Grand Coulee with water because Arrow is full in July. HEC-PRM typically uses Arrow to supply water downstream at Grand Coulee.

Duncan reservoir draws down much more than Dworshak reservoir in July. The reason appears to be because Duncan's operation objectives are for flood control only. Therefore, drawing down Duncan in July is reasonable given the Duncan penalty functions.

Hungry Horse never reaches its July target. Possibly, a combination of a low initial storage on January 1st and hydropower objectives may explain why HEC-PRM does not refill Hungry Horse to its July target. A consistent release of 60KAF each month and the low January 1 storage of 465KAF together may make it impractical for Hungry Horse to refill (Figures 3.6 and 3.10).

3.3 HEC-PRM System Operations for January - July 1995

1995 Variable Drawdown Period

The 1995 variable drawdown season for the Columbia River System extends from January to March. Typically, the system reaches its lowest storage levels in March. HEC-PRM storage results for this period show an overall trend to draw down Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs. Figure 3.11 shows HEC-PRM system-wide storage results from the January - July study.

The storage allocation plots show the order in which HEC-PRM draws down the seven reservoirs (Figures 3.12 - 3.14). The individual reservoir storage results are plotted against the

total system storage values for each monthly result. The storage allocation plot is typically analyzed by studying the graph from one end to the other. For a drawdown season analysis, read the graph from the largest total storage value to the smallest value, emulating the basic drawdown pattern. This provides an idea of HEC-PRM's preferred order of drawdown, assuming that the system is full and is to be drawn down.

For example, Figure 3.12 describes the storage allocation for Grand Coulee, Libby, Hungry Horse and Dworshak reservoirs. Starting at the largest total storage of 15000KAF, Dworshak reservoir is partially drawn down first. Once the total system storage decreases to ~13500KAF, Grand Coulee is drawn down dramatically to its minimum allowable storage of 3879KAF. With a low total system storage of ~8000KAF, HEC-PRM draws down Libby last. Throughout the variable drawdown season, Hungry Horse is kept fairly constant relative to the changes in storage in the other three reservoirs.

For the variable drawdown season, HEC-PRM draws down Arrow reservoir first, Dworshak second and Mica next (Figure 3.13). Grand Coulee experiences the most drawdown of any of the seven reservoirs, and HEC-PRM draws it down fourth. Libby is the last reservoir to be drawn down. Duncan and Hungry Horse have relatively level storages, beginning and remaining rather low. Figures 3.12 and 3.14 each focus on four of the seven reservoirs. Grand Coulee and Arrow reservoirs experience the largest changes in storage among the seven reservoirs (Figure 3.14).

1995 Refill Period

The refill season is from April to July, coinciding with the peak runoff season. The basic trend of the HEC-PRM results for the seven major storage reservoirs of the Columbia River System for the 1995 refill season is to fill the reservoirs. Figure 3.11 shows the system refill.

HEC-PRM always refills Mica, Arrow, Grand Coulee and Libby reservoirs to their target storages in July 1995. HEC-PRM clearly could not operate all seven reservoirs at their targets due to limited water supplies and the desirability of meeting other release-based objectives throughout the year.

The HEC-PRM storage allocation results for the 1995 refill period provide HEC-PRM's order of reservoir refills. Libby reservoir fills a small amount first, and Grand Coulee refills second. Duncan, Hungry Horse and Dworshak reservoirs refill gradually throughout the period (Figure 3.15). Arrow reservoir is fairly constant until Grand Coulee refills to its maximum allowable storage of 9107KAF (Figure 3.16). Subsequently, Arrow refills dramatically and Mica begins to refill a significant amount (Figure 3.16). Duncan, Libby, Hungry Horse and Dworshak reservoirs continue to refill slightly (Figure 3.15). When Mica, Arrow, Grand Coulee and Libby reservoirs reach their maximum storage levels, Hungry Horse continues to fill, but Duncan and Dworshak reservoirs draw down (Figures 3.15).

3.4 Comparison of HEC-PRM with AER Operation for January - March

The near-term HEC-PRM results for the 1995 January - July season study are compared to the 1995 AER operation. The near-term period is, coincidentally, the 1995 variable drawdown season. The HEC-PRM results and the AER operation are compared on the basis of storage trends and storage magnitudes.

Near-Term Storage Trend Comparison

HEC-PRM's storage trends and the AER operation for the 1995 variable drawdown period are given in Table 3.3. Of the twenty-one instances in the table, HEC- PRM matches 1995 AER operation nine times.

January

Both HEC-PRM and AER draw down a majority of reservoirs in January. The storage trends of HEC-PRM and AER matched for four of the seven reservoirs. Mica, Arrow and Libby were drawn down and Duncan was refilled by both HEC-PRM and AER operations.

February

The HEC-PRM and AER operations match twice in February. Mica is drawn down, and Duncan is refilled. Otherwise, HEC-PRM encourages drawdown among the system, while the AER operation promotes refilling a majority of the reservoirs.

March

In the last month of the variable drawdown season, HEC-PRM still encourages drawdown in the majority of the reservoirs. The AER operation refills four of the seven reservoirs, and draws down only three. The HEC-PRM and AER operations for Mica, Grand Coulee and Duncan reservoirs are similar. Mica and Grand Coulee reservoirs draw down, and Duncan refills.

Near-Term Storage Magnitude Comparison

HEC-PRM's usefulness lies in its ability to provide seasonal reservoir operation advice that has a formal economic derivation and is reasonable compared to the AER operation. For the HEC-PRM advice to be considered reasonable, the storage magnitudes should compare well to the AER operation. Figures 3.17 - 3.23 include the AER operation and HEC-PRM quartile storage curves for the January to March 1995 period.

Table 3.3 Near-Term Comparison of Storage Trends for HEC-PRM 1995 January - July Study and 1995 AER Operation

RESERVOIR	HEC-PRM	1995 AER
January		
Mica	Drawdown	Drawdown
Arrow	Drawdown	Drawdown
Grand Coulee	Refill	Drawdown
Duncan	Refill	Refill
Libby	Drawdown	Drawdown
Hungry Horse	Refill	Drawdown
Dworshak	Drawdown	Refill
February		
Mica	Drawdown	Drawdown
Arrow	Maintain 227KAF (Min)	Refill
Grand Coulee	Drawdown	Refill
Duncan	Refill	Refill
Libby	Variable	Drawdown
Hungry Horse	Drawdown	Refill
Dworshak	Drawdown	Refill
March		
Mica	Drawdown	Drawdown
Arrow	Maintain 227KAF (Min)	Drawdown
Grand Coulee	Drawdown	Drawdown
Duncan	Refill	Refill
Libby	Drawdown	Refill
Hungry Horse	Variable	Refill
Dworshak	Drawdown	Refill

The differences between storage magnitudes of the HEC-PRM and AER reservoir operations are studied two ways. The magnitude difference between HEC-PRM's median storage value is directly measured against the AER storage. This measured storage difference is compared to the total storage capacity for the given reservoir.

System-Wide

Overall, AER system storage in the variable drawdown season is greater than the majority of the HEC-PRM system storages. HEC-PRM encourages consistent system drawdown in the variable drawdown season, while the AER system operation experiences a variable operation of drawdown and refill (Figure 3.11).

In January, the HEC-PRM median storage for the system essentially matched the AER storage. A large difference in magnitudes occurred in February and March, due to a large jump in the AER operation in February. This abrupt change is due to a large increase in storage in Grand Coulee in February (Figure 3.19). Possibly, hydropower objectives encouraged a sudden refill of Grand Coulee in February. The AER storage values for February and March are ~4MAF greater than the median HEC-PRM storage for the system.

HEC-PRM's operation compares well with the AER storages for four of the seven reservoirs in the system, Mica, Duncan, Libby and Hungry Horse (Figures 3.17, 3.20, 3.21 and 3.22). The difference in magnitude between HEC-PRM and AER operation for Mica is small, but HEC-PRM always stores more water in Mica reservoir. For the three remaining reservoirs, Arrow, Grand Coulee and Dworshak, the differences in storage magnitudes are great, and HEC-PRM typically stores less water than the AER operation.

Mica Reservoir

HEC-PRM typically stores more water in Mica than the AER operation, throughout the entire variable drawdown season (Figure 3.17). In January, the median HEC-PRM storage is ~400KAF greater than the AER storage. The difference between the AER operation and the HEC-PRM median value increased in February and March. The AER operation stored ~1000KAF less than the HEC-PRM median value in February, and ~1200KAF less in March. These differences do not exceed 6% of Mica's total storage capacity. As a result, the differences are small in comparison to Mica storage capacity.

One reason that HEC-PRM stores more water in Mica reservoir during the variable drawdown period appears to be that HEC-PRM makes use of Arrow's storage. Arrow is operated ~2 - 3MAF lower than the AER operation in January, February and March. Arrow reservoir is drained to its minimum allowable storage to supply water downstream which permits Mica to store more water, and contribute less to downstream demands.

In addition, HEC-PRM has perfect knowledge of future inflows, therefore, HEC-PRM can store more water without the threat of flooding. Also, fish releases as mandated by recent biological opinions are not included in the HEC-PRM penalty functions. As a result, any water released for fish requirements in the AER operations may be stored in Mica by HEC-PRM.

Arrow Reservoir

During the variable drawdown season, HEC-PRM stores more water in Arrow reservoir than the AER operation (Figure 3.18). In January and February, an average of 3.3MAF more water is stored in Arrow by the AER operation. The difference between the median HEC-PRM storage and the AER operation decreases in March. The AER storage is ~2MAF greater than the HEC-PRM storage. These differences are significant, between 27% and 45% of Arrow's storage capacity.

The differences are great because HEC-PRM operates Arrow at its minimum allowable storage throughout the variable drawdown season. The lack of penalties on the Arrow reservoir operation makes this drawdown possible. This new operation procedure should be considered with future simulation testing. As mentioned for Mica reservoir, HEC-PRM appears to be suggesting Arrow's use to facilitate Mica and downstream uses.

Grand Coulee Reservoir

HEC-PRM typically stores more water in Grand Coulee than the AER operation in January, and less in February and March (Figure 3.19). The change in operation in February is a result of the large jump in AER storage. From January to February, the AER storage increased by ~2.5MAF. The cause for this sudden increase in AER storage is unknown. Possibly, there was a need for additional head for hydropower.

Specific to January, most HEC-PRM scenarios store ~ 3.2MAF more water in Grand Coulee than the AER operation. In February and March, over 75% of the HEC-PRM storage values are less than the AER storage. The median HEC-PRM storage in February is ~1.2MAF less than the AER value. In March, over 2.2MAF more water is held in Grand Coulee by the AER operation than the median HEC-PRM storage operation. These storage magnitude differences range between 13% and 35% of Grand Coulee's storage capacity, a significant amount.

The large difference in operations between HEC-PRM and AER are a consequence of the early, dramatic AER drawdown in January, and the immediate, drastic increase in AER storage in February. The exact cause of this operation is not clear. Perhaps, Grand Coulee hydropower demands greatly increased in February, and a large increase in head was required.

Duncan Reservoir

The HEC-PRM and AER operations for Duncan are the same in storage magnitude and trend (Figure 3.20). The median HEC-PRM storage operation and the AER operation have essentially the same magnitude throughout the variable drawdown season. In addition, HEC-PRM and AER operations follow the same storage trajectory in January, February and March. HEC-PRM matched the AER operation for Duncan reservoir very well.

Libby Reservoir

Throughout the variable drawdown season, HEC-PRM operates Libby reservoir similar to the AER operation (Figure 3.21). The median HEC-PRM storage is within 125KAF of the AER storage all three months of the variable drawdown season. This difference is a only 2% of Libby's storage capacity, an insignificant amount.

Hungry Horse Reservoir

HEC-PRM stores more water in Hungry Horse in January than the AER operation, but typically less in February and March (Figure 3.22). Throughout the variable drawdown season, the storage trajectories of HEC-PRM and AER are very similar. The magnitude difference between the HEC-PRM and AER operations is small.

The AER storage is ~100KAF less than the HEC-PRM median storage in January, only ~3% of Hungry Horse's total storage capacity. In February, the difference between the median HEC-PRM storage and the AER operation decreased to ~60KAF, less than 2% of the capacity of Hungry Horse. Lastly, in March, AER stores ~200KAF more water than the median HEC-PRM storage, an increase to 6.5% of Hungry Horse's total storage. Therefore, in the variable drawdown season, HEC-PRM operations compare well to the AER storages.

Dworshak Reservoir

HEC-PRM typically stores less water in Dworshak reservoir in the variable drawdown season than the AER operation (Figure 3.23). In January, over 75% of HEC-PRM's storage values are less than the AER storage. The AER operation stores ~375KAF more water in Dworshak in January than the median HEC-PRM storage, ~11% of Dworshak's total storage capacity.

In February and March, all of HEC-PRM's storage values are less than the AER operation. The AER storage for February is greater than the HEC-PRM median storage by ~900KAF, which is 26% of Dworshak's total capacity. Lastly, in March, the difference between the AER operation and the median HEC-PRM storage increases to ~1375KAF, nearly 40% of the reservoir's total storage capacity. The magnitude differences arise because HEC-PRM draws down Dworshak in the variable drawdown season, while the AER operation refills the reservoir.

3.5 HEC-PRM Near-Term Advice for 1995 January - July Study

HEC-PRM advice is found for the near-term period of the 1995 January - July season study, which coincides with the 1995 variable drawdown period. Although only the HEC-PRM results for the first three months of 1995 January - July season study are analyzed in detail, the entire January - July period was included in the run to ensure that the refill target storages are considered in the HEC-PRM optimization process. HEC-PRM advice is given for the seven reservoir system as a whole, and for each reservoir individually. General trends and specific advice are discussed.

Near-Term HEC-PRM System-Wide Operation Advice

The HEC-PRM system-wide storage advice for the 1995 variable drawdown season is to draw down the system in January, February, and March (Figure 3.11). This HEC-PRM operation is different than the AER operation of the reservoirs in the variable drawdown season. Both operations draw down the system in January, but the drastic refill in the February AER operation disrupts the similarity in HEC-PRM and AER system-wide operations. By March, the AER operation draws down again, like the HEC-PRM operation, but the AER total storage in the system is much greater than the HEC-PRM total storage. HEC-PRM advises drawing the system down lower than the system storage levels of the AER operation. HEC-PRM knows that the forecasted inflows in the refill season are large, therefore, the system can be drawn down considerably during the variable drawdown season.

Evidenced by the storage allocation plots for all seven reservoirs in the 1995 variable drawdown season, HEC-PRM suggests that Arrow reservoir draw down first among the seven reservoirs (Figure 3.13). Dworshak, Mica and Grand Coulee reservoirs should be drawn down next, in that order. HEC-PRM's advice for Grand Coulee reservoir is distinctive; draw down the reservoir over its complete range, from its maximum allowable storage (9107KAF) to its minimum allowable storage (3879KAF). Libby reservoir should be drawn down last, to continue system drawdown once the other six reservoirs are at their minimum allowable storage levels. HEC-PRM does not use Duncan and Hungry Horse for dramatic drawdown contributions because both reservoirs begin with little storage on January 1st.

HEC-PRM advises the use of Arrow and Grand Coulee for large drawdown during the 1995 January - March variable drawdown season. Arrow reservoir is encouraged to draw down to its minimum allowable storage. There are no HEC-PRM penalties associated with the Arrow reservoir operation. Grand Coulee reservoir experiences a large decrease in storage in the HEC-PRM variable drawdown study. Grand Coulee should draw down to make room for large spring inflows.

Near-Term HEC-PRM Individual Reservoir Storage Trend and Magnitude Advice

Mica Reservoir

HEC-PRM's advice for Mica reservoir is to draw down consistently throughout the variable drawdown season, but store more water than the AER operation (Figure 3.17). HEC-PRM holds between ~0.4MAF and 1.2MAF more water in Mica than the AER operation. This HEC-PRM operation allows Mica to always reach its target storage in July, whereas the AER operation does not reach the HEC-PRM July target storage.

HEC-PRM may store the additional water in Mica because fish requirements are not included in the Mica penalty functions, and HEC-PRM drains Arrow reservoir to supply water downstream. In addition, a main objective of Mica reservoir operation is hydropower; a high head is advantageous.

Arrow Reservoir

HEC-PRM advises drawing down Arrow reservoir to the minimum allowable storage of 227KAF in January and maintaining this level throughout the variable drawdown season (Figure 3.18). The AER storages are between ~2MAF and 3.5MAF more than the HEC-PRM operation, during this period. HEC-PRM proposes a new operation for Arrow reservoir that should be considered with simulation testing.

Arrow reservoir is drained because no penalties are associated with any fluctuation in storage. The advantage is that HEC-PRM can allocate Arrow's storage to other reservoirs, like Grand Coulee, for greater system benefit. Arrow reservoir is drawn down to its minimum allowable storage and still reaches its maximum allowable storage in July, likely because the January 1, 1995 forecasted inflows are large. Therefore, this HEC-PRM advice seems most feasible when the water year is expected to be relatively wet.

Grand Coulee Reservoir

The HEC-PRM advice for Grand Coulee reservoir is to keep the reservoir full, near 9107KAF in January, and then draw it down in February and March, after Mica and Arrow begin to draw down (Figure 3.19). The HEC-PRM operation allows Grand Coulee reservoir to refill to the target storage. Grand Coulee storage can decrease considerably during the variable drawdown season and reach the target by July because 1995 forecasted inflows are large.

Duncan Reservoir

HEC-PRM advises refilling Duncan reservoir during the variable drawdown season (Figure 3.20). In addition, HEC-PRM dramatically draws down Duncan in July. This operation is feasible because flood control is Duncan's sole operating objective in HEC-PRM.

HEC-PRM probably made the huge releases from Duncan in July because the water is more beneficial to the system at a downstream location. Though the HEC-PRM operation of Duncan reservoir does meet the target in July, HEC-PRM may be offering a new, useful operation, given the inflow sequences used in the 1995 January - July study. HEC-PRM may trade-off Duncan's inability to refill in July to keep Mica, Arrow, Grand Coulee and Libby reservoirs fuller instead.

Libby Reservoir

Typically, Libby should be drawing down slightly by the end of the variable drawdown season (Figure 3.21). The July storage target is met with this HEC-PRM operation. Libby operation objectives include hydropower, which might encourage HEC-PRM to refill the reservoir in July for all inflow sequences.

Hungry Horse Reservoir

HEC-PRM's advice for the Hungry Horse operation is to maintain a relatively steady

storage near its lowest allowable storage level (Figure 3.22). The HEC-PRM operation does not reach the July target storage. One possible cause is HEC-PRM's low initial storage on January 1st. The consistent release of 60KAF may be another reason Hungry Horse never reaches its target storage. Lastly, the median Hungry Horse inflows are among the smallest inflows of the system (Figure 3.8).

Dworshak Reservoir

HEC-PRM advises drawing down Dworshak throughout the 1995 variable drawdown season (Figure 3.23). HEC-PRM suggests storing less water in Dworshak reservoir than the AER operation in January, February and March. Dworshak does not meet its July target storage, but Dworshak draws down in July, similar to Duncan. This HEC-PRM advice to draw down Dworshak in July likely contributes more benefits to the system. Dworshak's July releases must be more useful downstream.

Near-Term HEC-PRM Individual Reservoir Specific Storage and Release Advice

The HEC-PRM results have been examined to identify specific, quantitative storage operation advice. Among the forty-eight inflow sequences studied, HEC-PRM suggests the same value or close ranges of storages and releases for reservoir operation. HEC-PRM results are defined as specific advice when HEC-PRM operates a reservoir similarly for 25% or more of the inflow sequences. Table 3.4 lists the specific advice, and the corresponding percentage of results that provide the advice.

Mica Reservoir

Mica reservoir should release 603KAF (minimum allowable release) per month in January, February and March and continually draw down throughout the variable drawdown season (Figure 3.24). Fifty percent of the HEC-PRM results in January and March suggest this outflow. For February, 25% of the release results are 603KAF. An additional suggestion for Mica reservoir in March is to operate the reservoir at 13075KAF, as indicated by 50% of the storage results.

Arrow Reservoir

Arrow reservoir should store the minimum, 227KAF, in January, February and March (Figure 3.18). Seventy-five percent of the HEC-PRM results for January and February equal 227KAF. HEC-PRM always stores 227KAF in March.

Grand Coulee Reservoir

Fifty percent of the HEC-PRM storage results suggest that Grand Coulee reservoir should be filled to 9107KAF (maximum storage) in January (Figure 3.19). Grand Coulee begins drawdown in February; 50% of the results fall within 6390KAF and 8200KAF. Further drawdown in March decreases the Grand Coulee storage. Fifty percent of the March storage values range from 3879KAF, Grand Coulee's minimum storage, and 5350KAF.

Table 3.4 HEC-PRM Specific Quantitative Advice for 1995 Variable Drawdown Season of 1995 January - July Study

Reservoir	Month	Operation	HEC-PRM Advice (KAF)	Percentage of Results (%)
Mica	January	Release	603 (Min)	50
	February	Release	603	25
	March	Release	603	50
	March	Storage	13075 (Min)	50
Arrow	January	Storage	227 (Min)	75
	February	Storage	227	75
	March	Storage	227	100
Grand Coulee	January	Storage	9107 (Max)	50
	February	Storage	6390-8200	50
	March	Storage	3879(Min)-5350	50
Duncan	January	Release	6 (Min)	75
	February	Release	6	75
	March	Release	6	75
Libby	January	Release	181 (Min)	75
	February	Release	181	75
	March	Release	181-230	25
Hungry Horse	January	Release	60	25
	February	Release	60	75
	March	Release	60	50
Dworshak	January	Release	300-450	50
	February	Release	300-450	75
	March	Release	250-450	75
		Storage	1452 (Min)	50

Duncan Reservoir

Seventy-five percent of the HEC-PRM release results for Duncan reservoir for January, February and March suggest a release of 6KAF, the minimum allowed (Figure 3.25). HEC-PRM advises continuous refill as 6KAF is released.

Libby Reservoir

In January and February, 75% of the HEC-PRM results suggests a Libby release of 181KAF (minimum allowable release) (Figure 3.26). For March, the tightest range of results for Libby reservoir incorporates 25% of the results, and falls within 181KAF and 230KAF. Typically, Libby's operation should be slight drawdown throughout the 1995 variable drawdown

season.

Hungry Horse Reservoir

HEC-PRM suggests a release of 60KAF in January, February and March (Figure 3.10). In January, 25% of the releases equaled 60KAF. This percentage increased in February and March to 75% and 50%, respectively. Hungry Horse should refill concurrently throughout the variable drawdown season.

Dworshak Reservoir

Dworshak reservoir results show that 300 - 450KAF is released for 50% of the inflow sequences in January (Figure 3.27). Seventy-five percent of results for February range from 300 - 450KAF. In March, releases between 250 - 450KAF are suggested by 75% of the results. The storage results are strong; 50% of the storages suggested equal 1452KAF (Figure 3.23). Dworshak should drawdown as these releases are met.

3.6 Conclusions for 1995 January - July Study

1. HEC-PRM operations for the 1995 January - July study have a high probability of reservoir refill. HEC-PRM also offers strong, specific operation advice for the 1995 variable drawdown season. These quantitative pieces of advice should be explored with simulation testing. In addition, HEC-PRM presents new, potentially useful trend operations that should be studied further. Overall, HEC-PRM and the observed operation compare moderately well, both on a system-wide, and individual reservoir, basis.

2. The HEC-PRM advice always met the reservoir target storages for July 1995 for four of the seven reservoirs, Mica, Arrow, Grand Coulee and Libby reservoirs. Duncan and Dworshak reservoirs fail to meet their July storage targets; their drawdown probably allows Libby and Hungry Horse to fill. Duncan reservoir can draw down so dramatically in July because flood control is the only operating objective that HEC-PRM needs to be satisfied. Hungry Horse never reaches its target storage possibly because the initial storage is very low on January 1st.

3. The dominant system-wide storage trend for HEC-PRM is to draw down the reservoir system during the 1995 variable drawdown season. The AER system-wide operation is drawdown in January and March only; a strong refill occurs in February. Grand Coulee's significant refill in February is the primary cause for the system-wide storage increase. HEC-PRM may draw down the system in March because the model knows spring inflows will fill Mica, Arrow, Grand Coulee and Libby to their targets.

4. Evident in the storage allocation plots, HEC-PRM advises drawing down Arrow first, Dworshak second, and Mica and Grand Coulee third and fourth, respectively, in the 1995 variable drawdown season. Libby reservoir is the last reservoir to drawdown. Hungry Horse and Duncan reservoirs are fairly steady in the variable drawdown season.

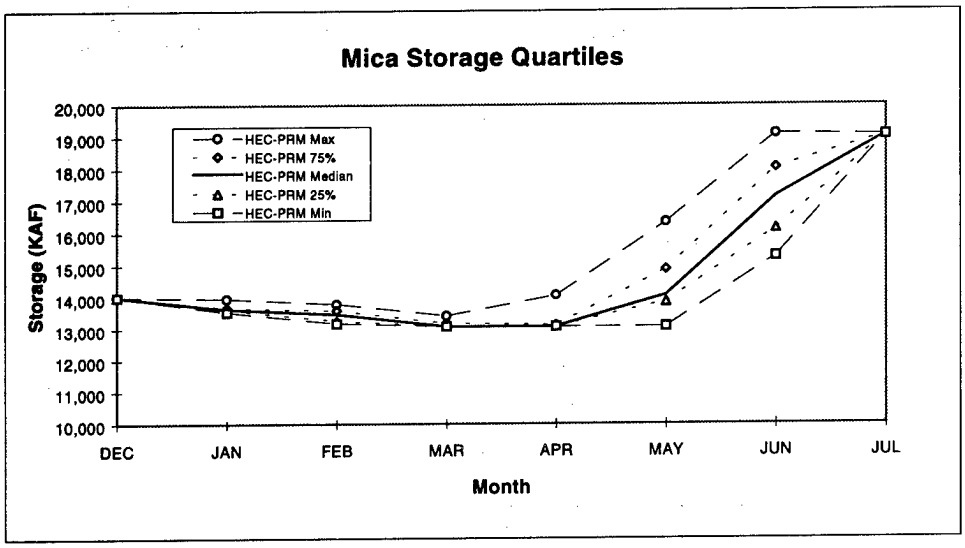
5. HEC-PRM uses Arrow and Grand Coulee reservoirs for the greatest drawdown in system storage. Arrow is ideal for these large changes in storage because there are no penalties placed on its operation. Grand Coulee reservoir can make large drawdown because the reservoir is likely to refill since the reservoir receives Mica, Arrow, Duncan, Libby, Hungry Horse and Dworshak releases.

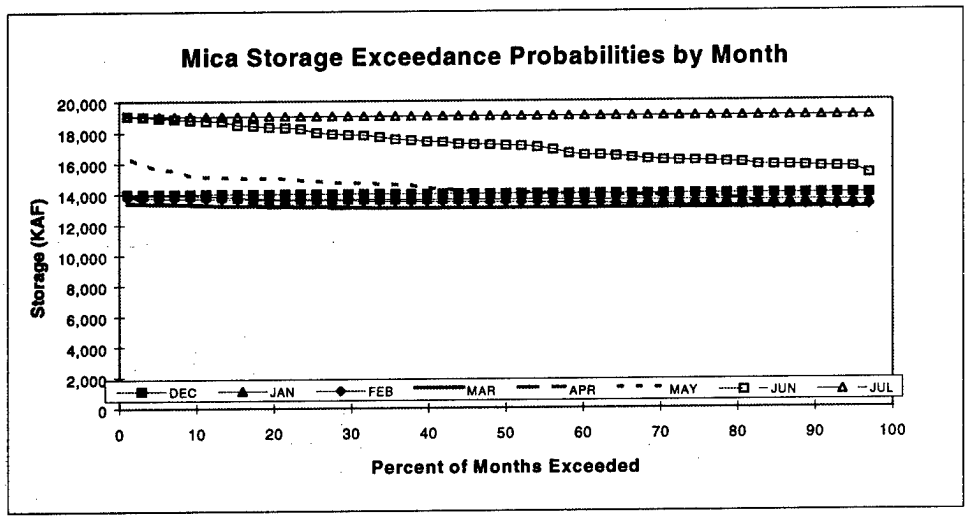
6. HEC-PRM's storage trend advice to draw down Mica reservoir is matched by the AER operations for all three months of the 1995 variable drawdown season. Similarly, both HEC-PRM and AER storage trend operations refill Duncan in January, February and March 1995. HEC-PRM's storage trend advice matched the AER operations in nine of twenty-one instances.

7. The storage magnitudes of HEC-PRM and AER compare well for four of the seven reservoirs, Mica, Duncan, Libby and Hungry Horse. There is a greater difference between the HEC-PRM and AER operations for Arrow, Grand Coulee and Dworshak reservoirs. Though the difference between HEC-PRM and AER operations for Mica reservoir is not very significant, HEC-PRM stores more water in Mica throughout the variable drawdown season. Typically, HEC-PRM stores less water in Arrow, Grand Coulee and Dworshak reservoirs than the AER operation.

8. HEC-PRM provides strong specific operational advice in the 1995 variable drawdown season. The ability of HEC-PRM to offer accurate and specific quantitative advice is encouraging. Mica reservoir should release 603KAF (minimum allowable) each month of the 1995 variable drawdown season. Arrow storage should equal the minimum storage of 227KAF per month, while Duncan releases should be 6KAF/month, the minimum allowable release.

In addition, Libby releases should equal the minimum, 181KAF, in January, February and March, and Hungry Horse should release 60KAF per month. Grand Coulee should fill to the maximum storage of 9107KAF in January and drawdown from this level until March. Dworshak releases should range between ~250KAF and 450KAF each month. All specific advice should be tested by simulation to determine if worthwhile operations are suggested.





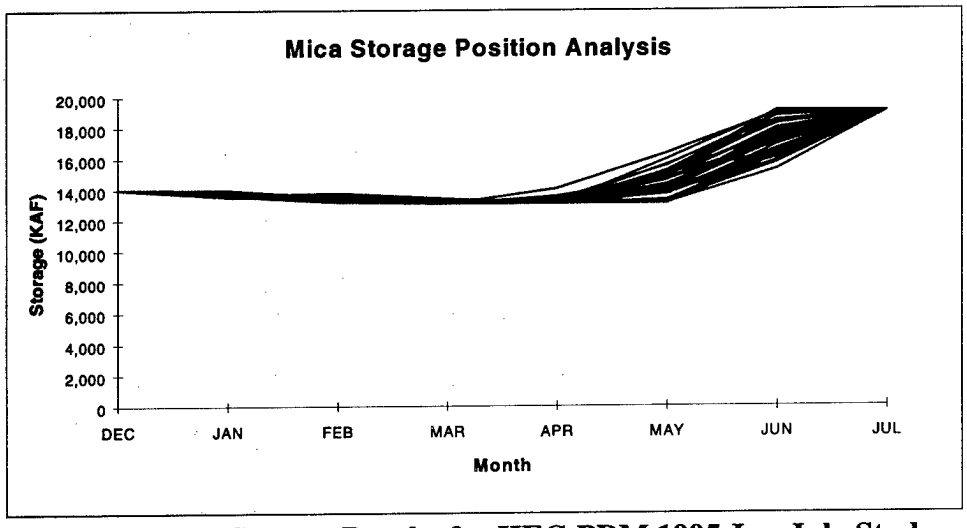
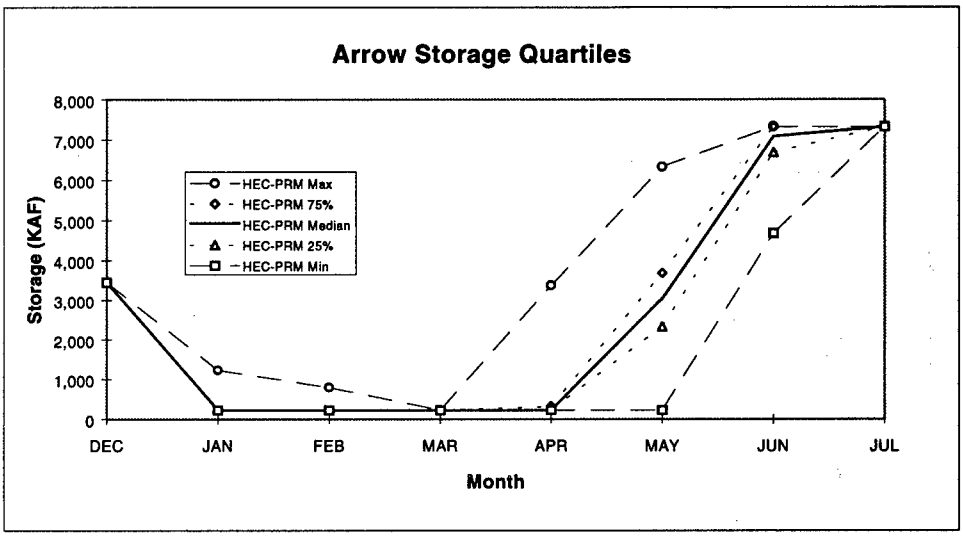
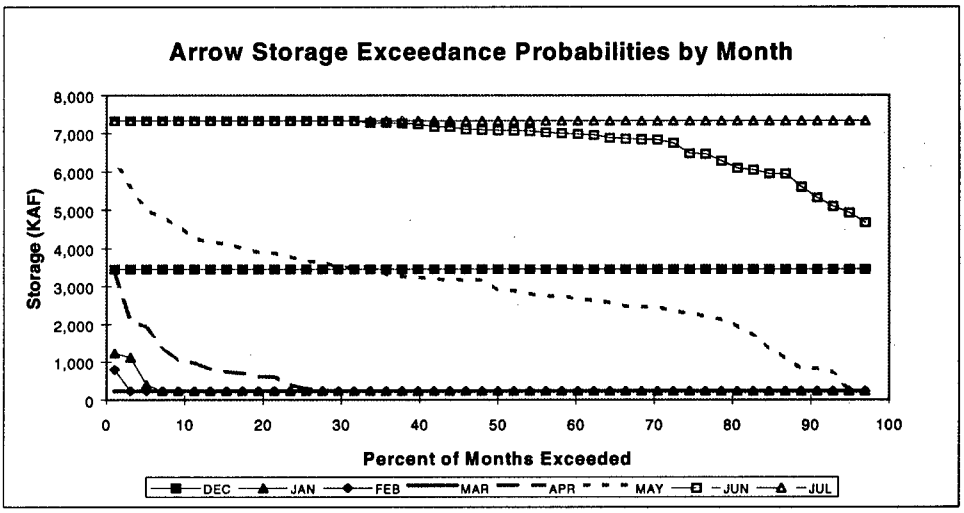


Figure 3.1 Mica Storage Results for HEC-PRM 1995 Jan-July Study





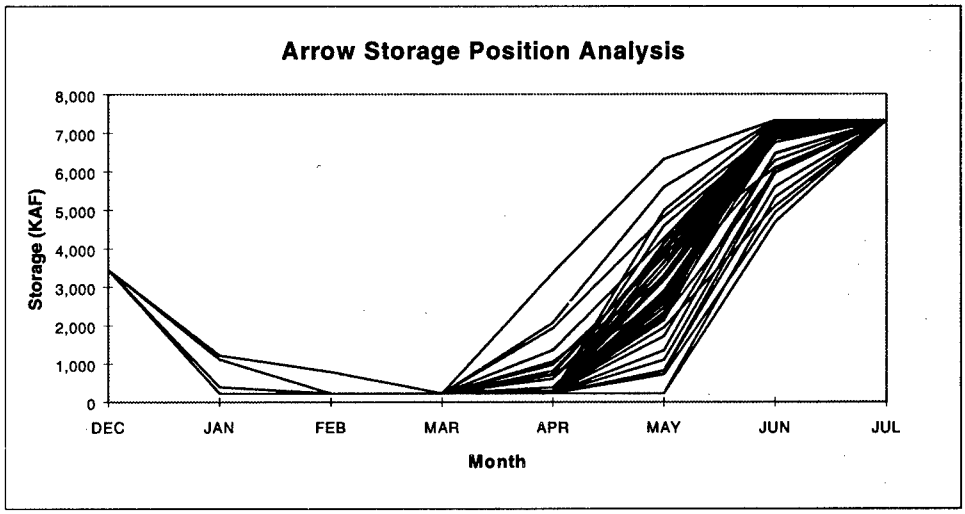
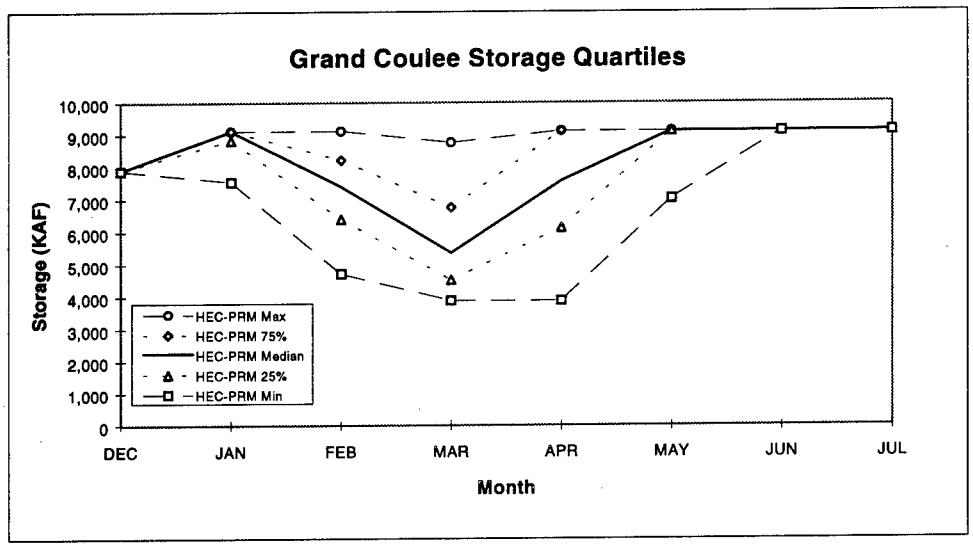
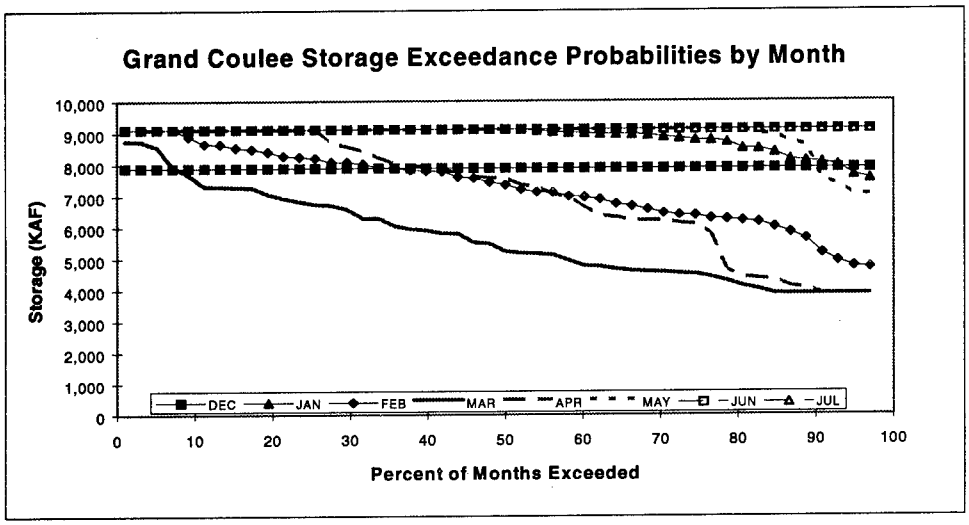


Figure 3.2 Arrow Storage Results for HEC-PRM 1995 Jan-July Study





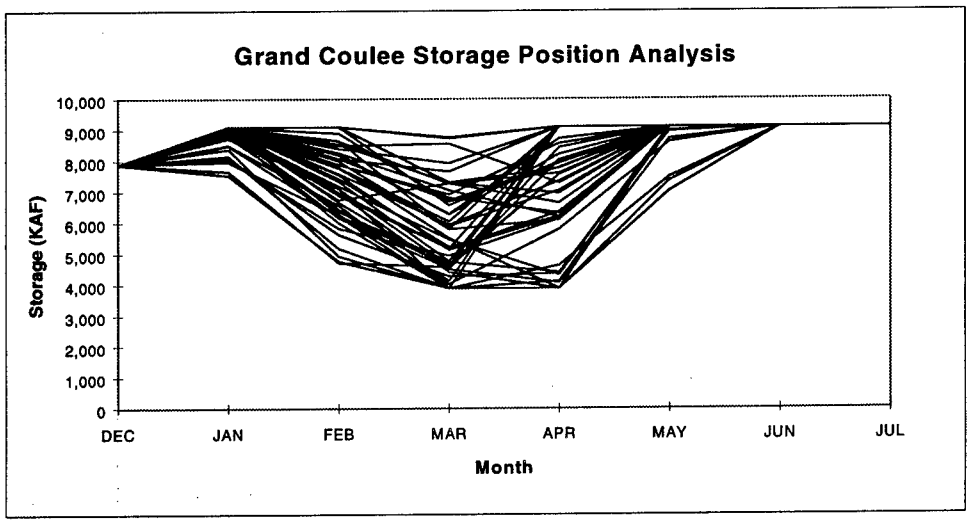
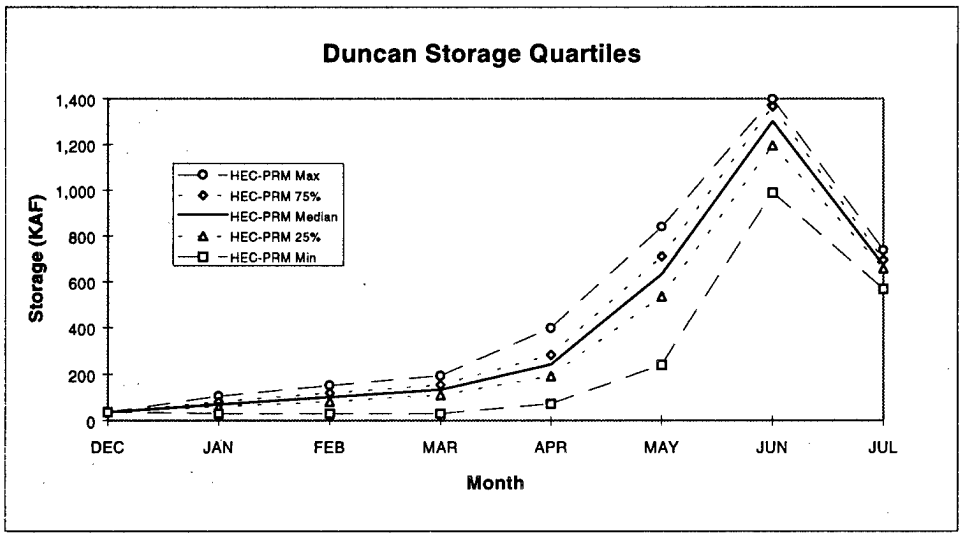
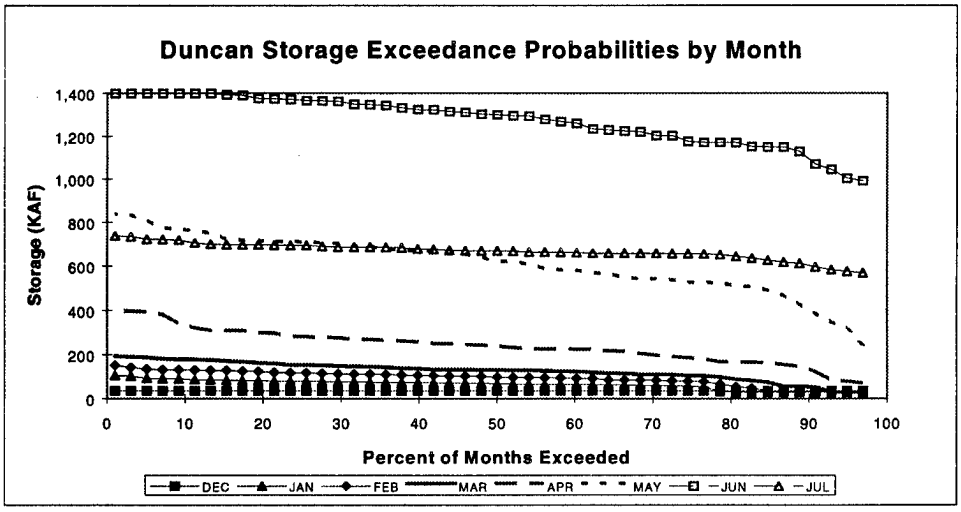


Figure 3.3 Grand Coulee Storage Results for HEC-PRM 1995 Jan-July Study





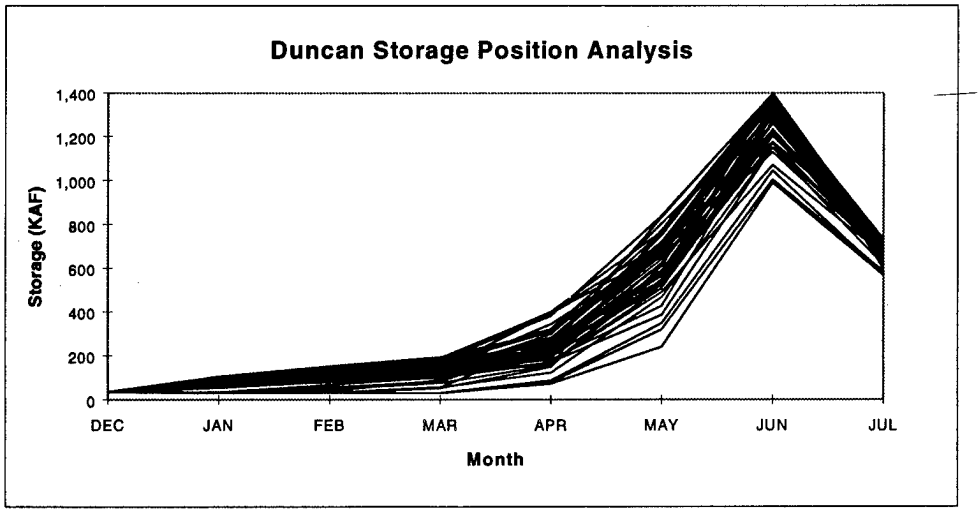
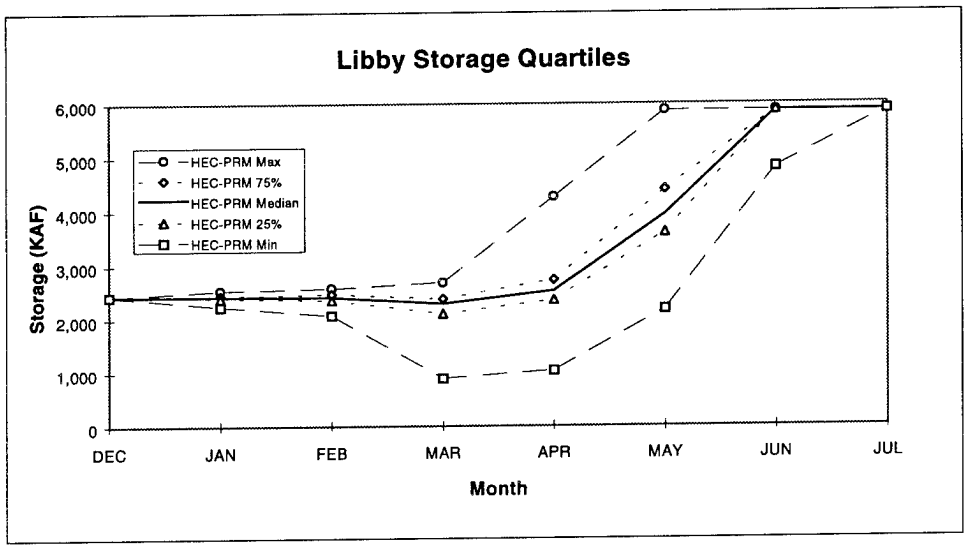
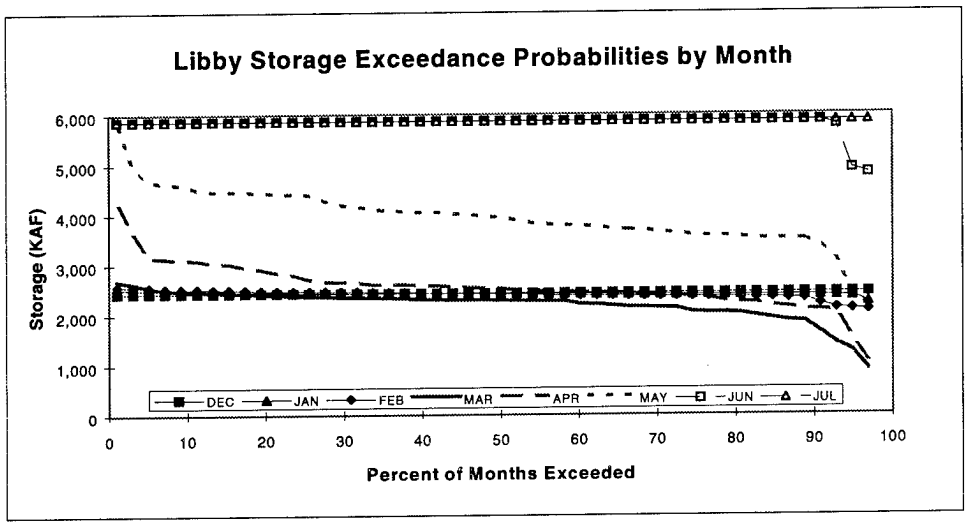


Figure 3.4 Duncan Storage Results for HEC-PRM 1995 Jan-July Study





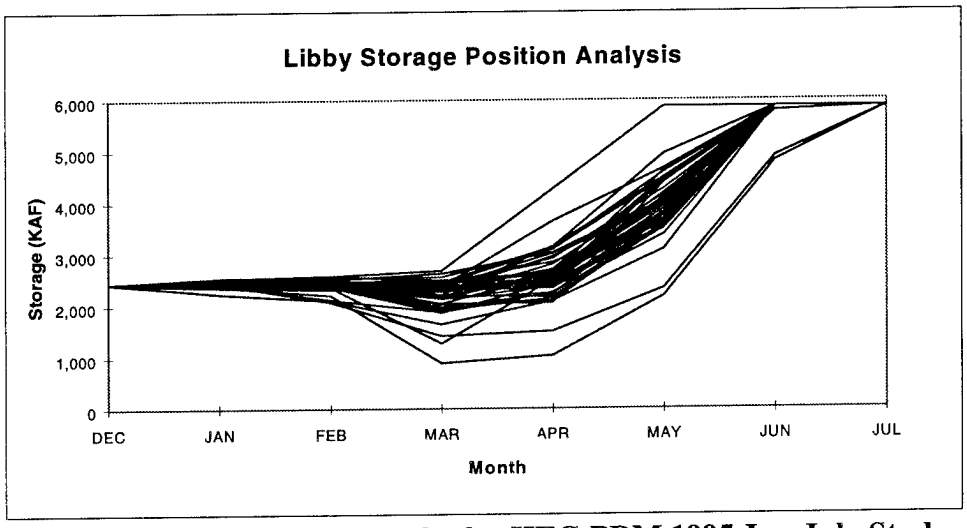
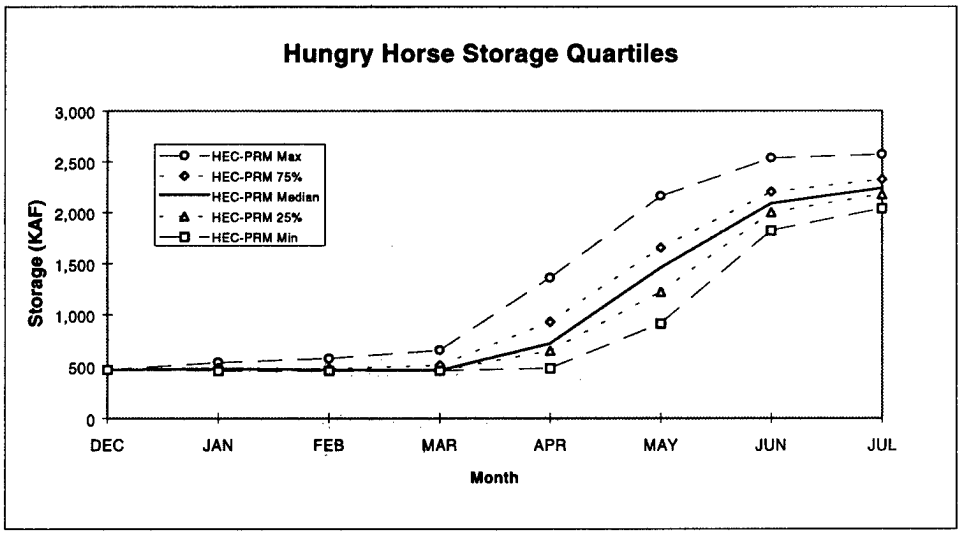
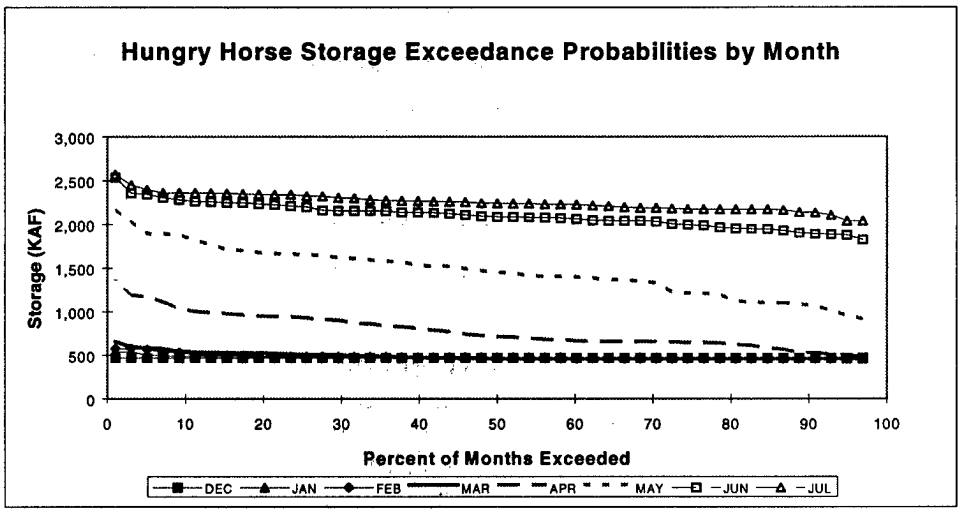


Figure 3.5 Libby Storage Results for HEC-PRM 1995 Jan-July Study





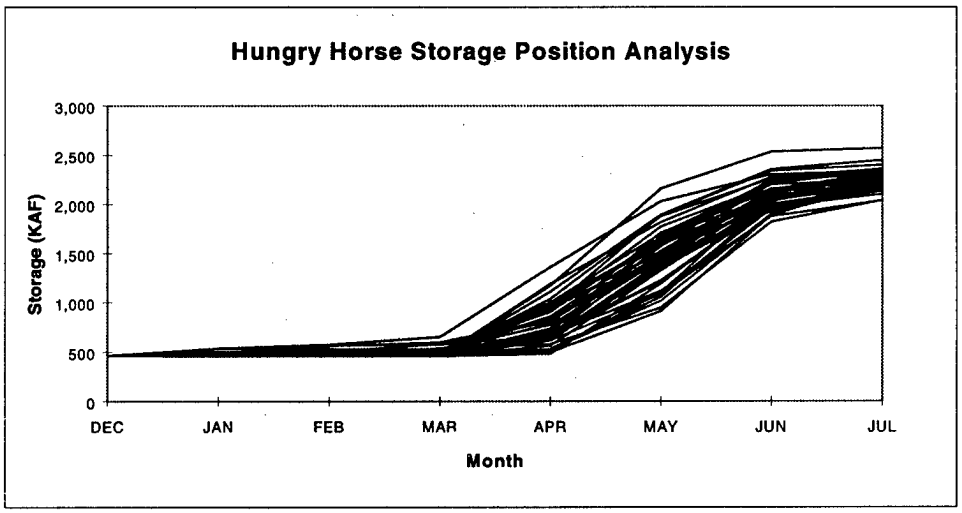
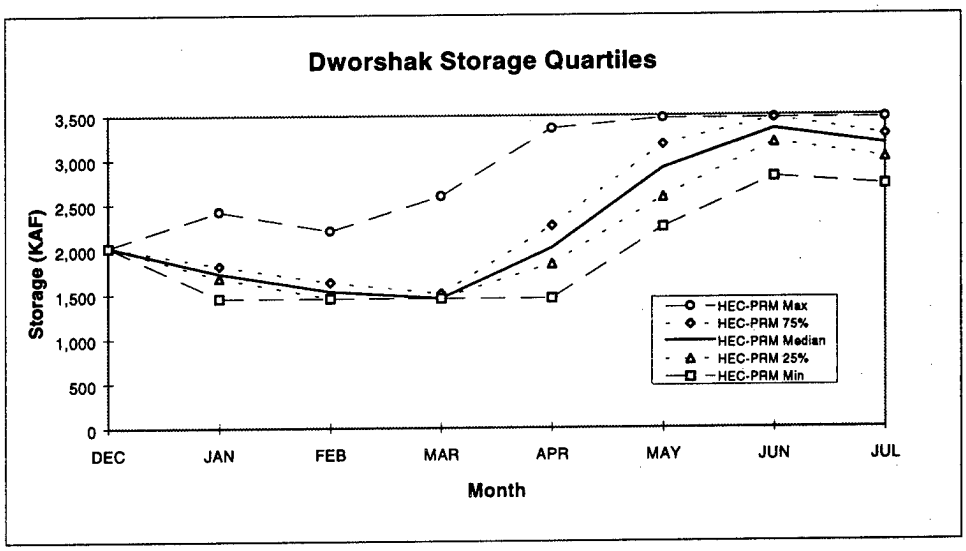
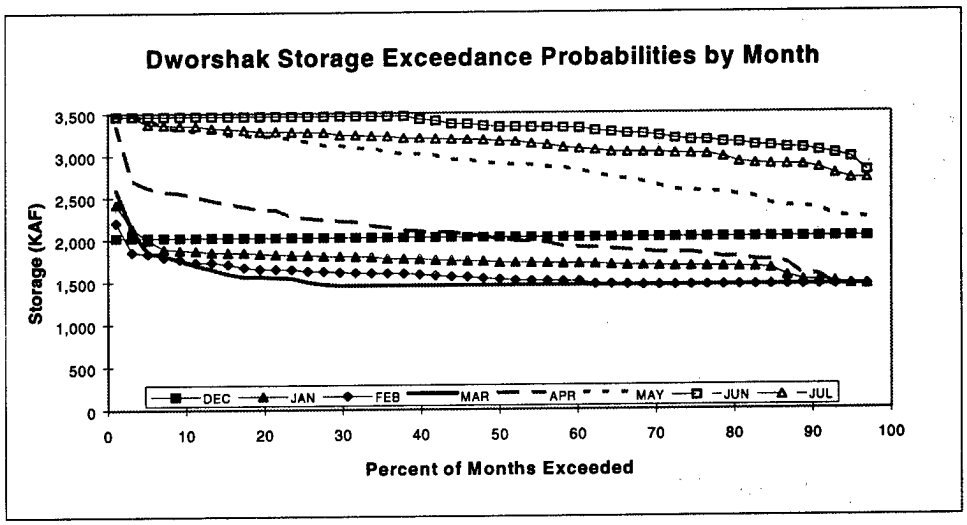


Figure 3.6 Hungry Horse Storage Results for HEC-PRM 1995 Jan-July Study





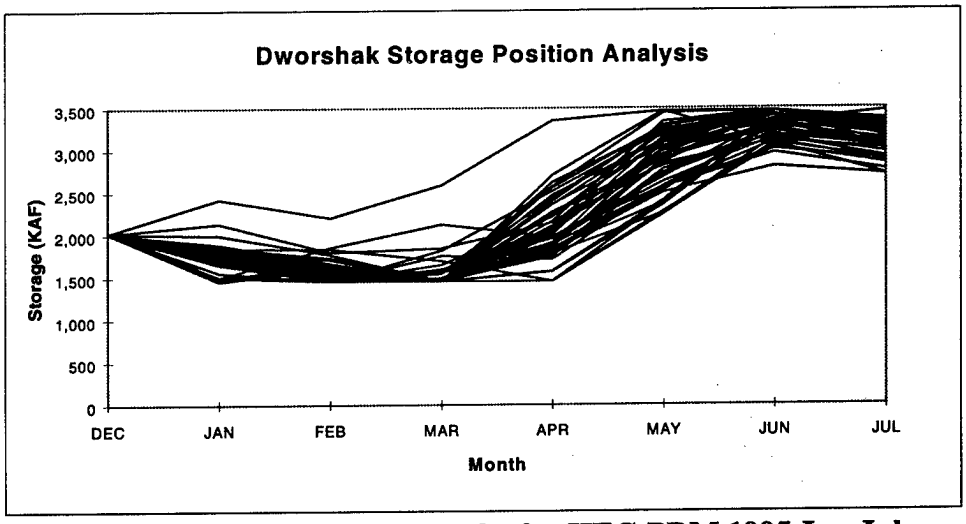


Figure 3.7 Dworshak Storage Results for HEC-PRM 1995 Jan-July Study

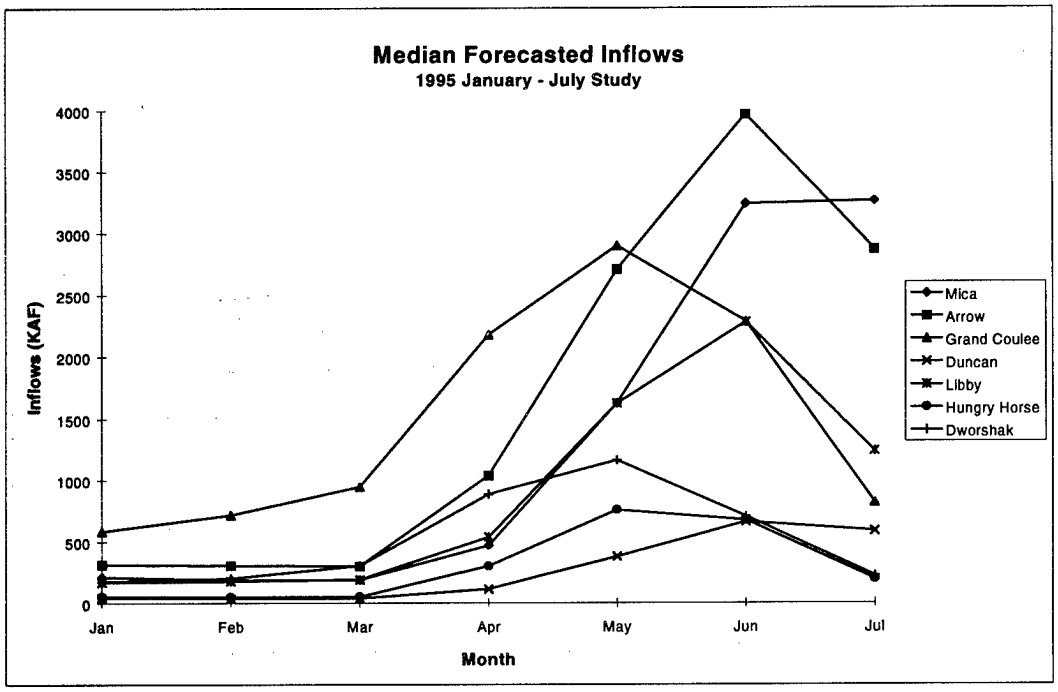


Figure 3.8 1995 Median Forecasted Inflows for System Reservoirs for HEC-PRM 1995 Jan-July Study

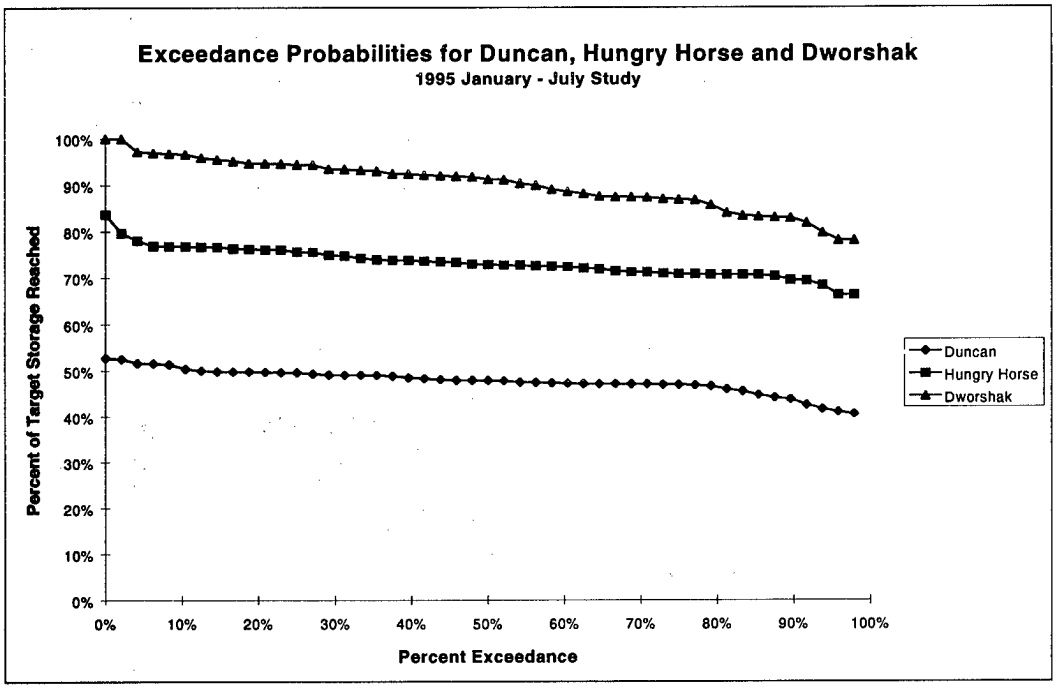


Figure 3.9 Exceedance Probabilities of Percent of Target Storage Reached for Duncan, Hungry Horse and Dworshak for 1995 Jan-July Study

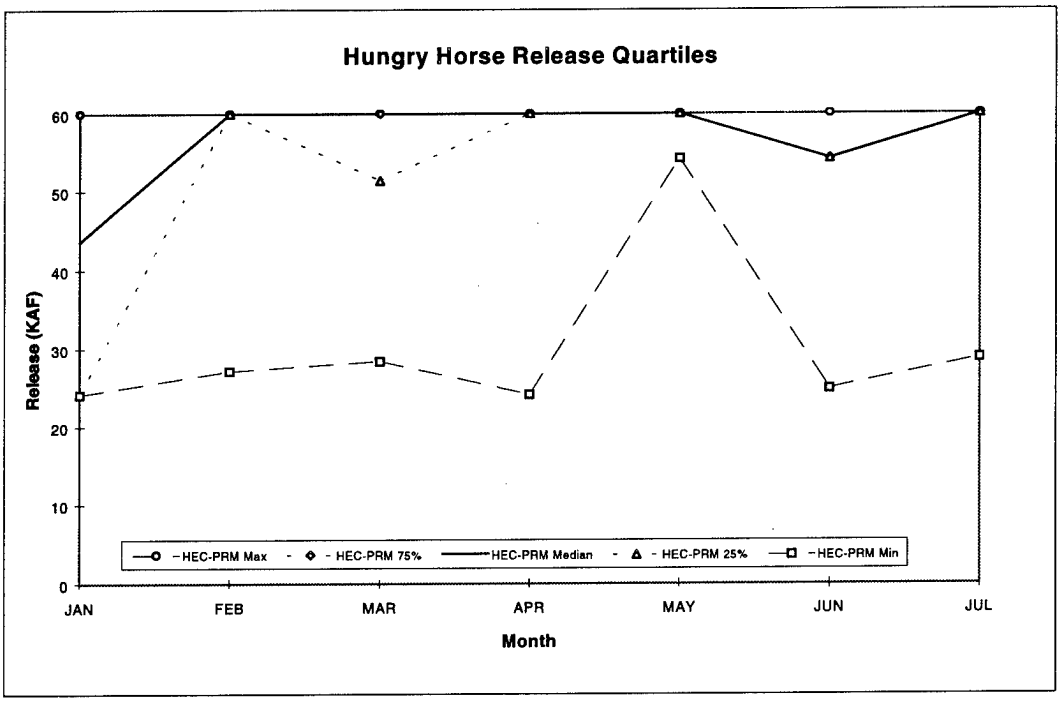


Figure 3.10 Hungry Horse Release Quartiles for HEC-PRM 1995 Jan-July Study

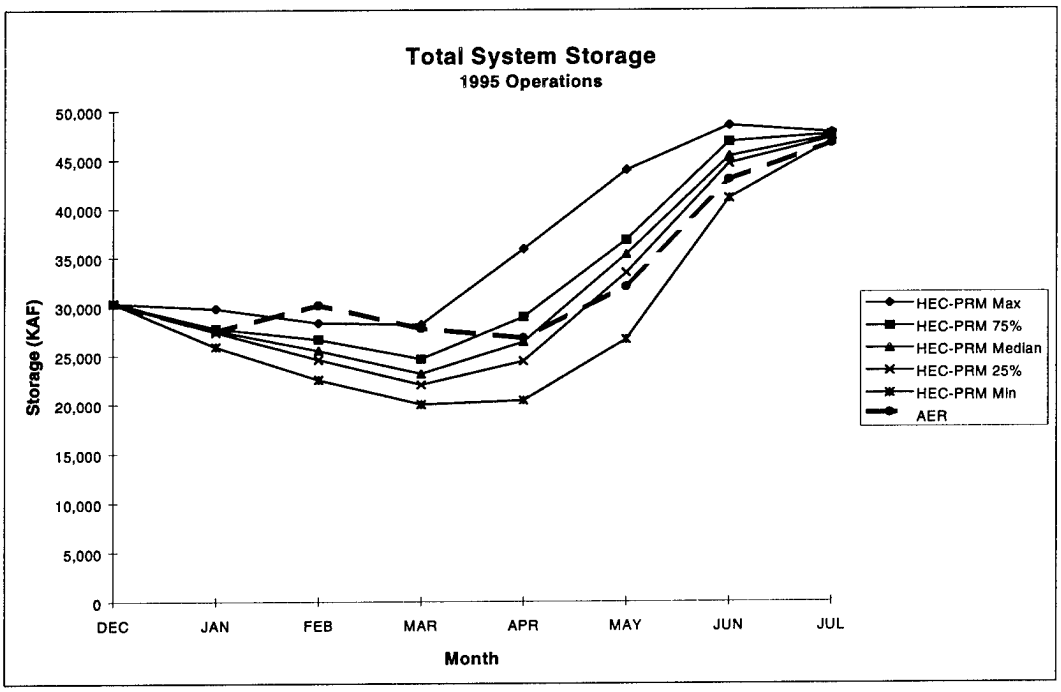


Figure 3.11 Comparison of Total System Storage For HEC-PRM 1995 Jan-July Study and 1995 AER Operation

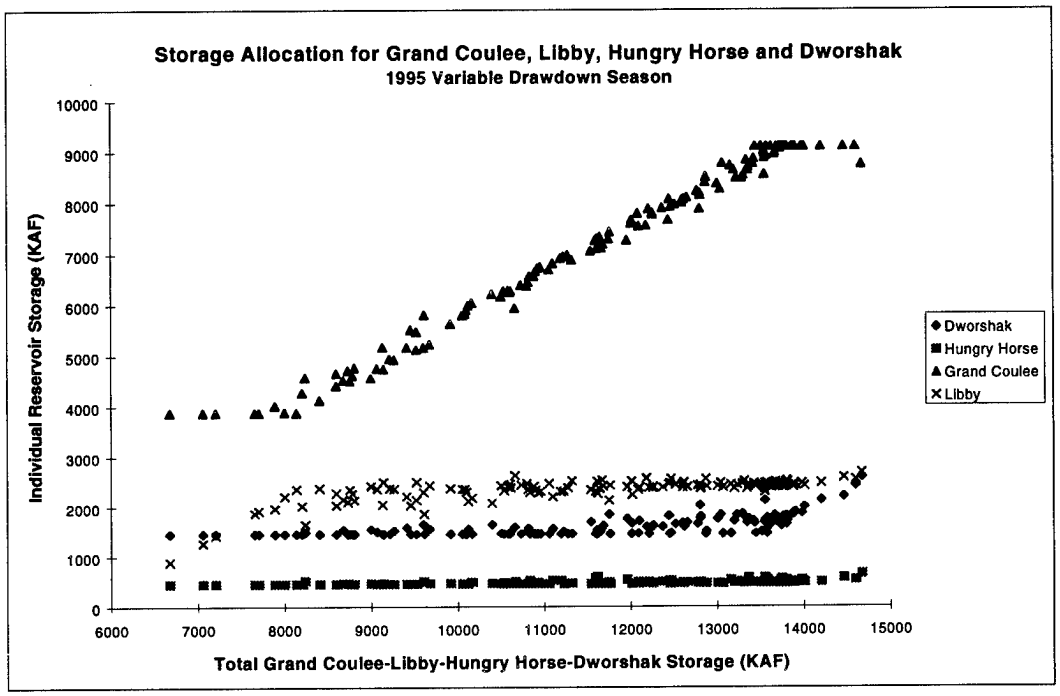


Figure 3.12 Storage Allocation for Grand Coulee, Libby, Hungry Horse and Dworshak for Variable Drawdown for 1995 Jan-July Study

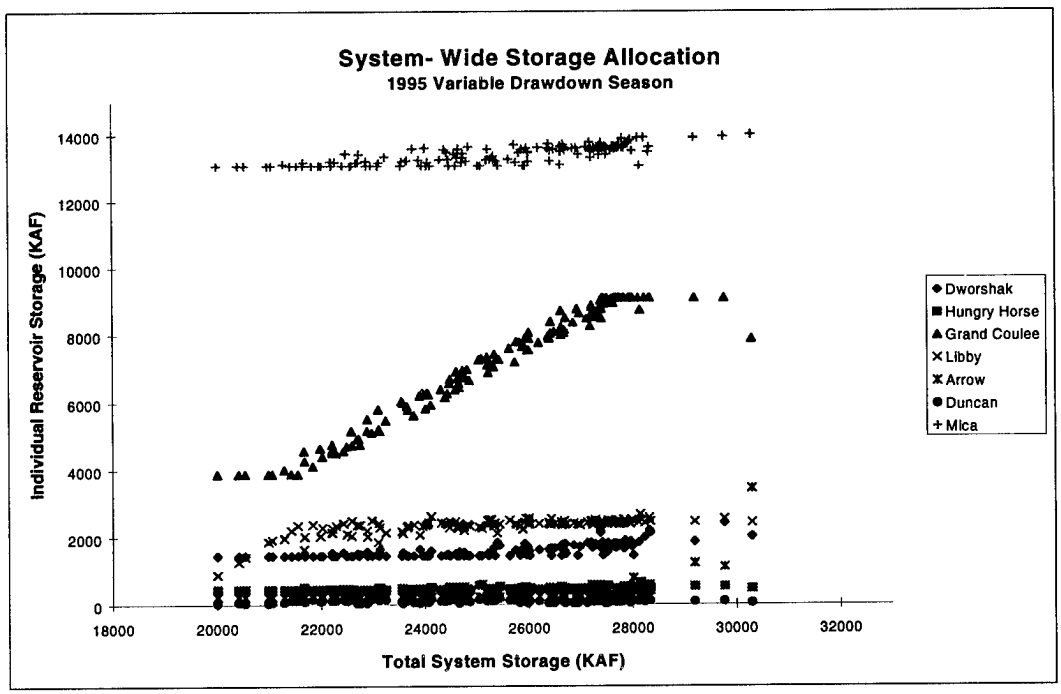


Figure 3.13 System-Wide Storage Allocation for Variable Drawdown for HEC-PRM 1995 Jan-July Study

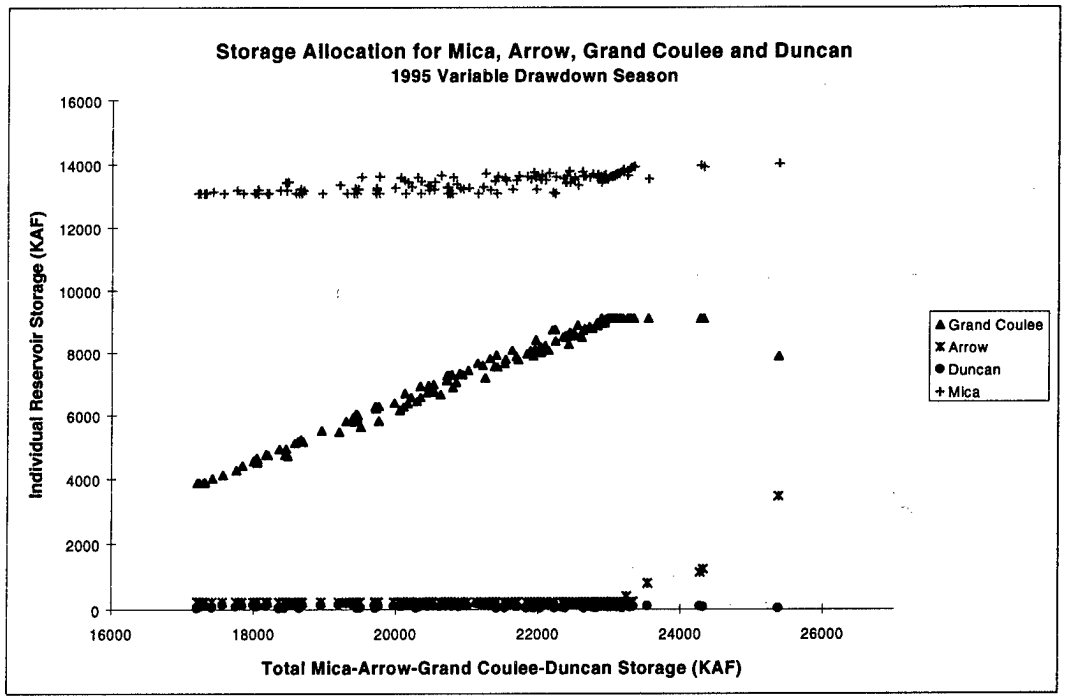


Figure 3.14 Storage Allocation for Mica, Arrow, Grand Coulee and Duncan for Variable Drawdown for HEC-PRM 1995 Jan-July Study

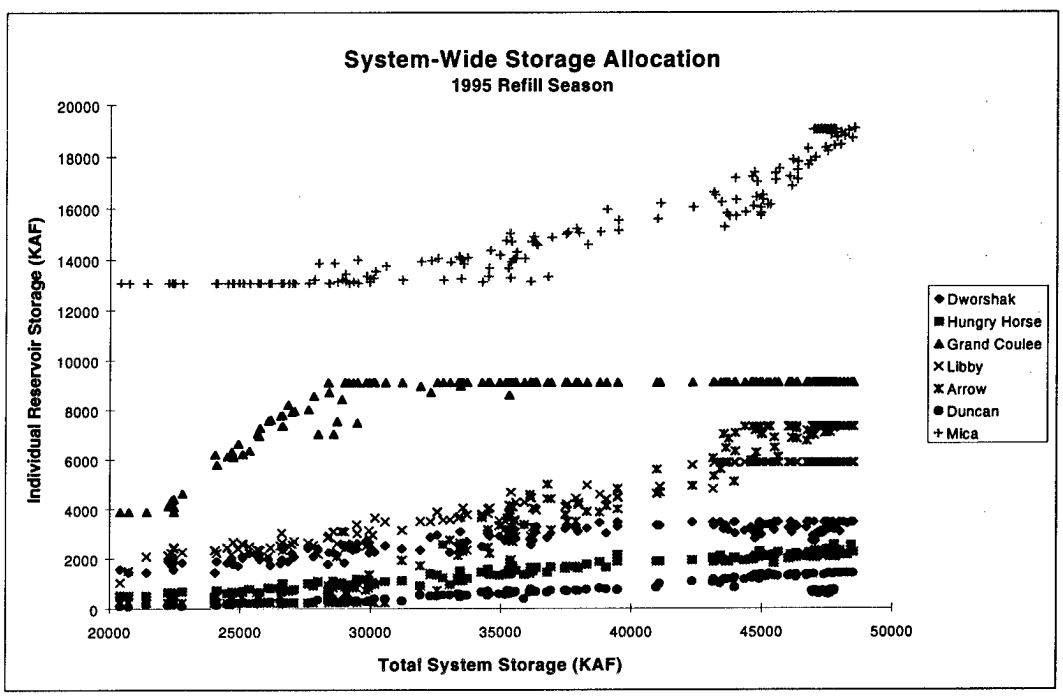


Figure 3.15 System-Wide Storage Allocation for Refill Season for HEC-PRM 1995 Jan-July Study

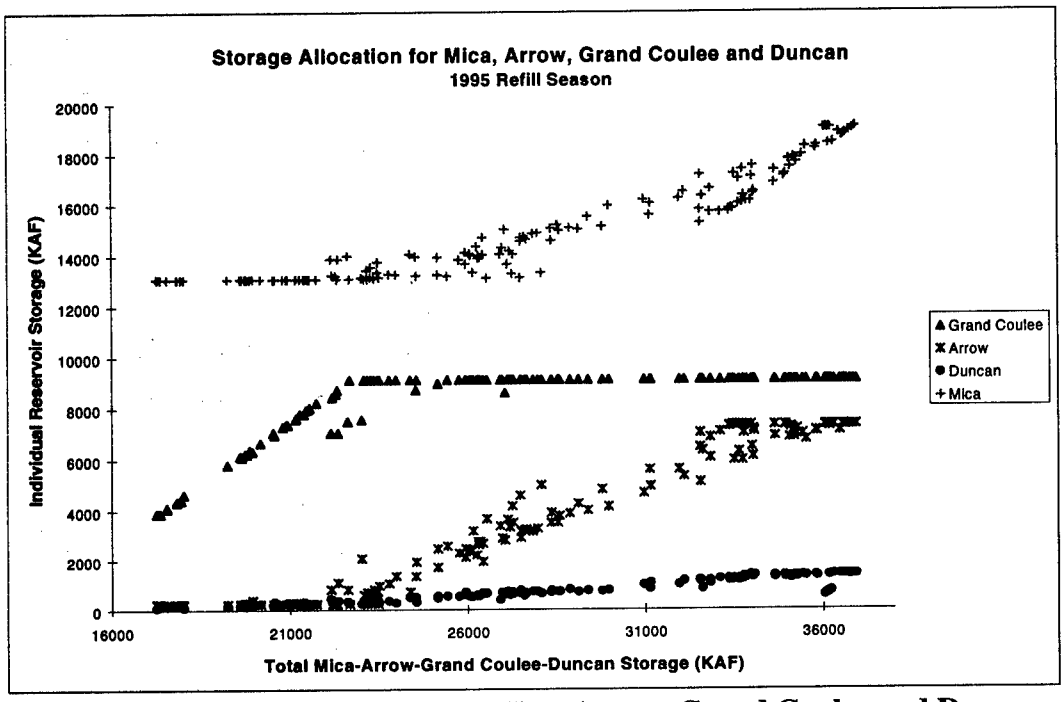


Figure 3.16 Storage Allocation for Mica, Arrow, Grand Coulee and Duncan for Refill for HEC-PRM 1995 Jan-July Study

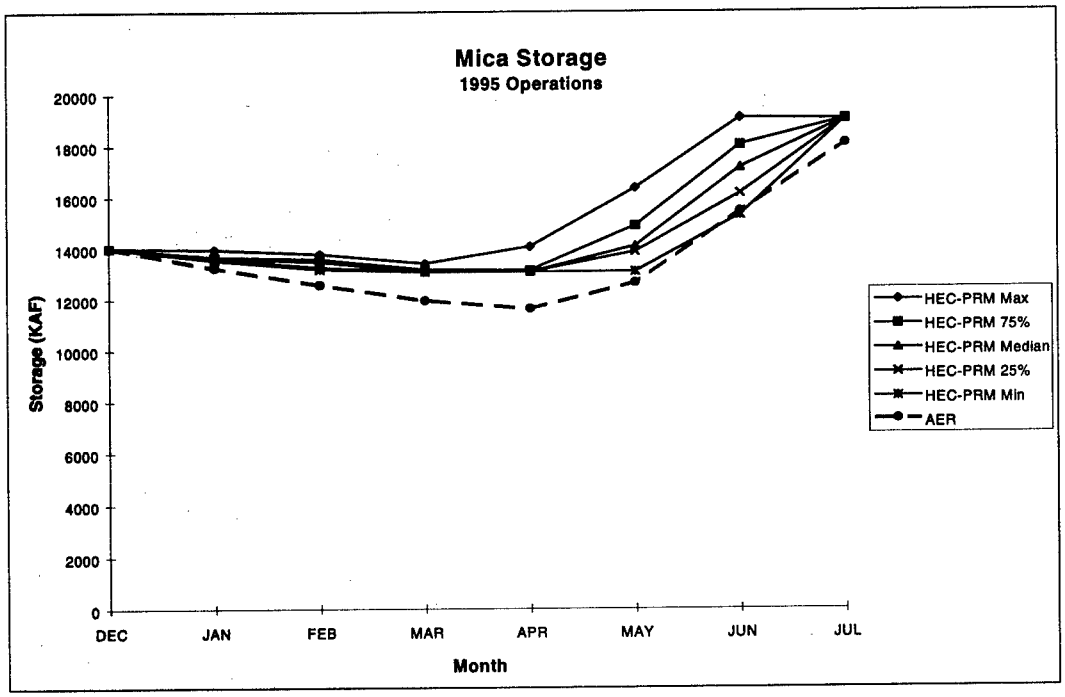


Figure 3.17 Comparison for Mica Storage for HEC-PRM 1995 Jan-July Study and 1995 AER Operation

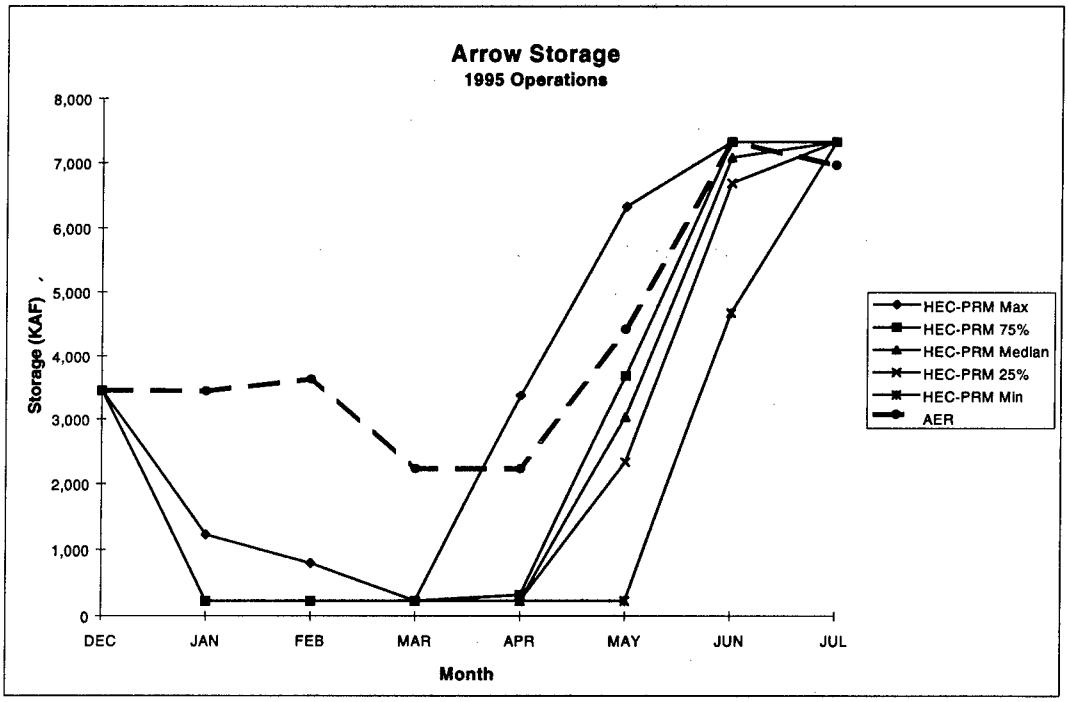


Figure 3.18 Comparison of Arrow Storage for HEC-PRM 1995 Jan-July Study and 1995 AER Operation

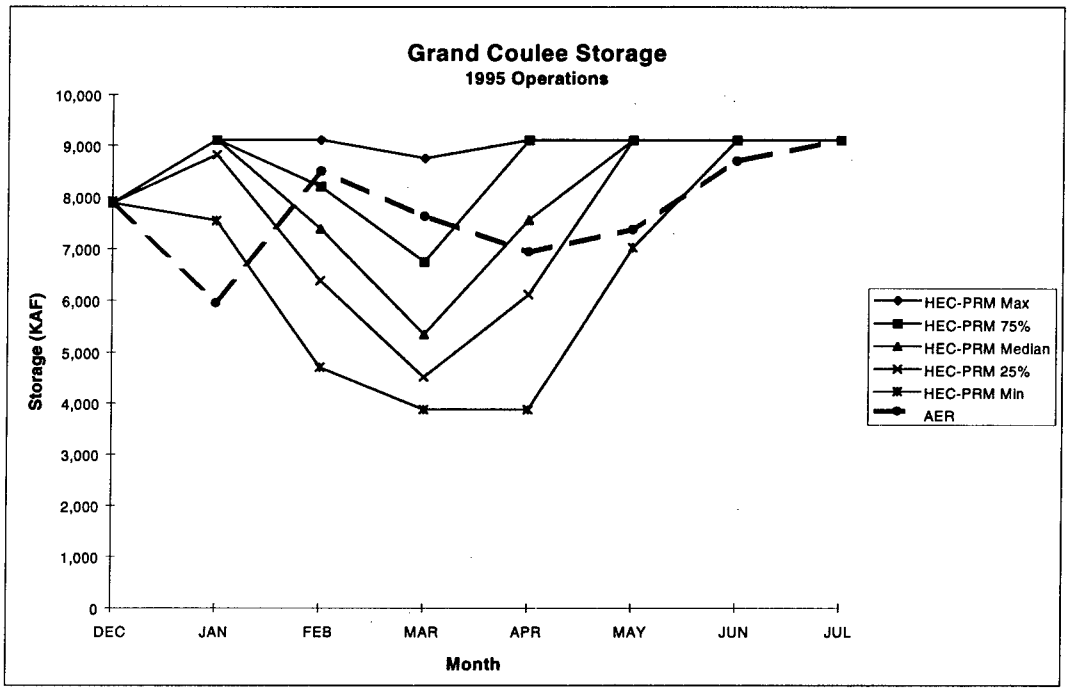


Figure 3.19 Comparison of Grand Coulee Storage for HEC-PRM 1995 Jan-July Study and 1995 AER Operation

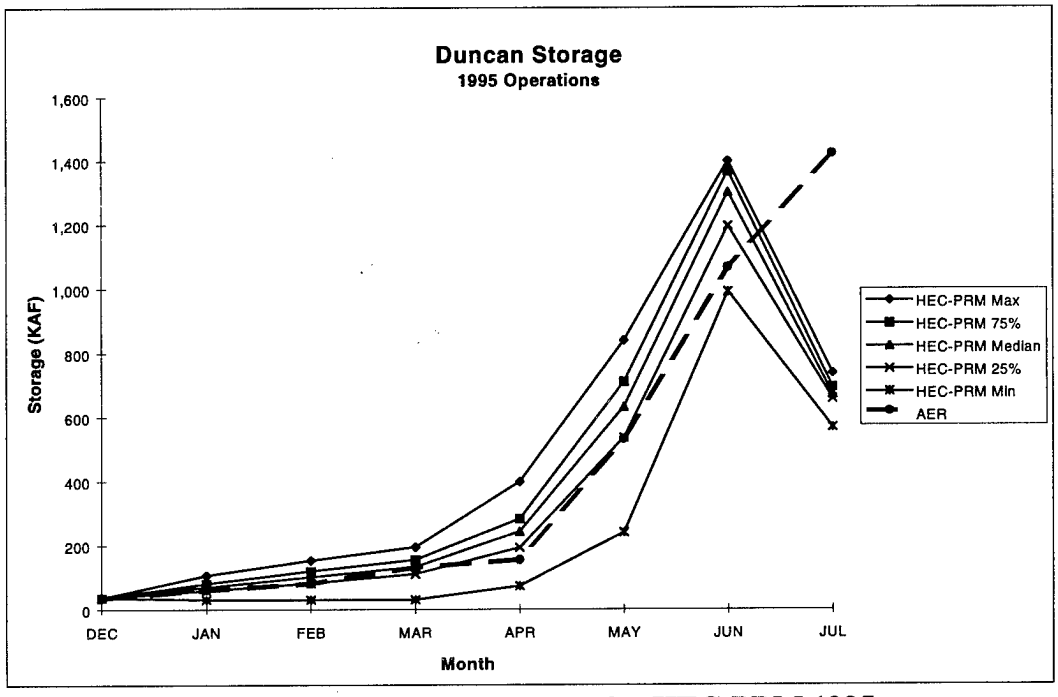


Figure 3.20 Comparison of Duncan Storage for HEC-PRM 1995 Jan-July Study and 1995 AER Operation

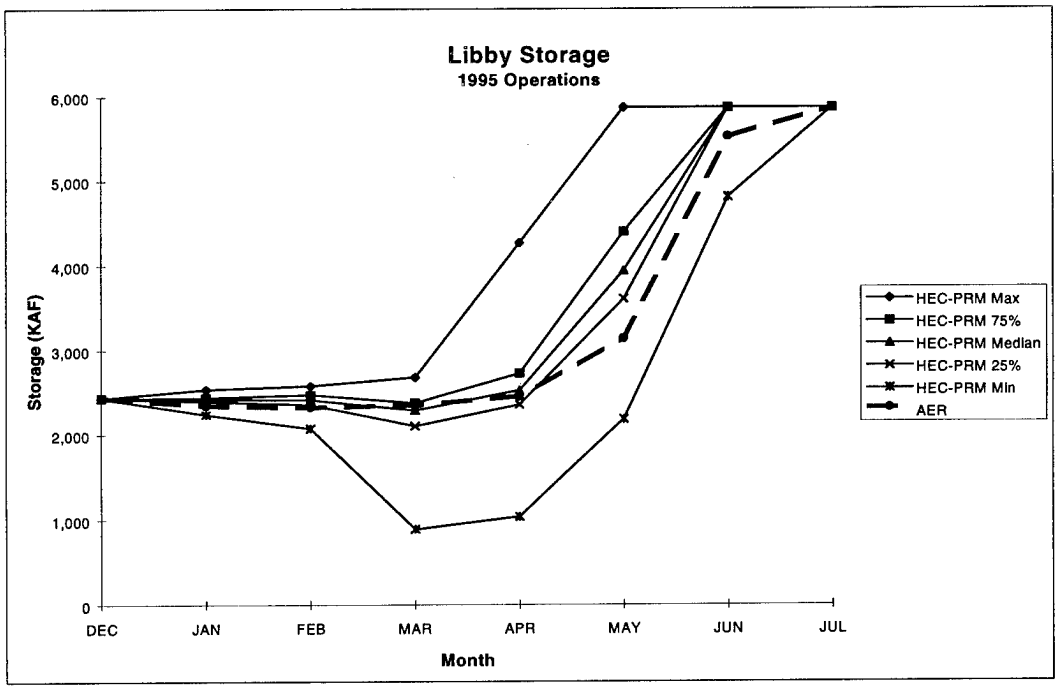


Figure 3.21 Comparison of Libby Storage for HEC-PRM 1995 Jan-July Study and 1995 AER Operation

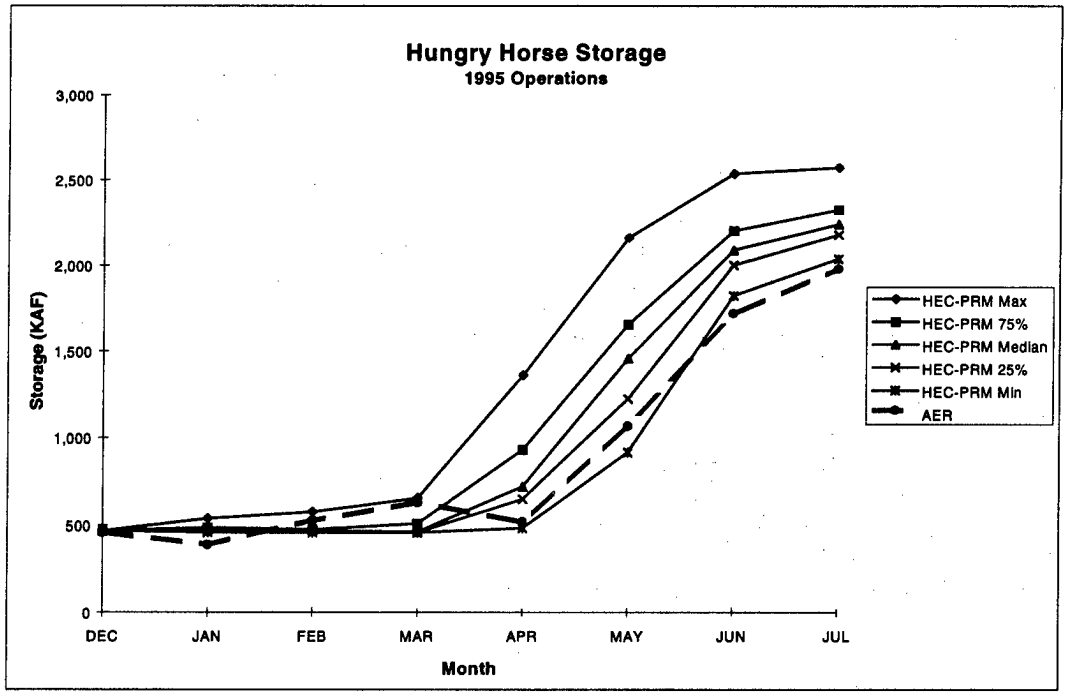


Figure 3.22 Comparison of Hungry Horse Storage for HEC-PRM 1995 Jan-July Study and 1995 AER Operation

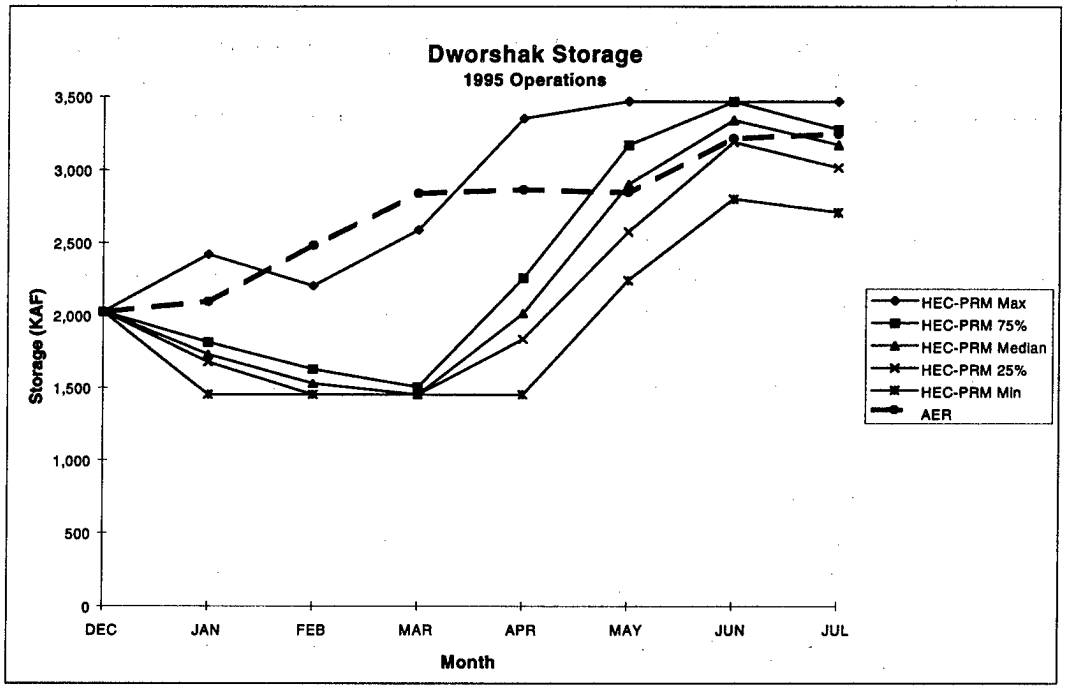


Figure 3.23 Comparison of Dworshak Storage for 1995 HEC-PRM Jan-July Study and 1995 AER Operation

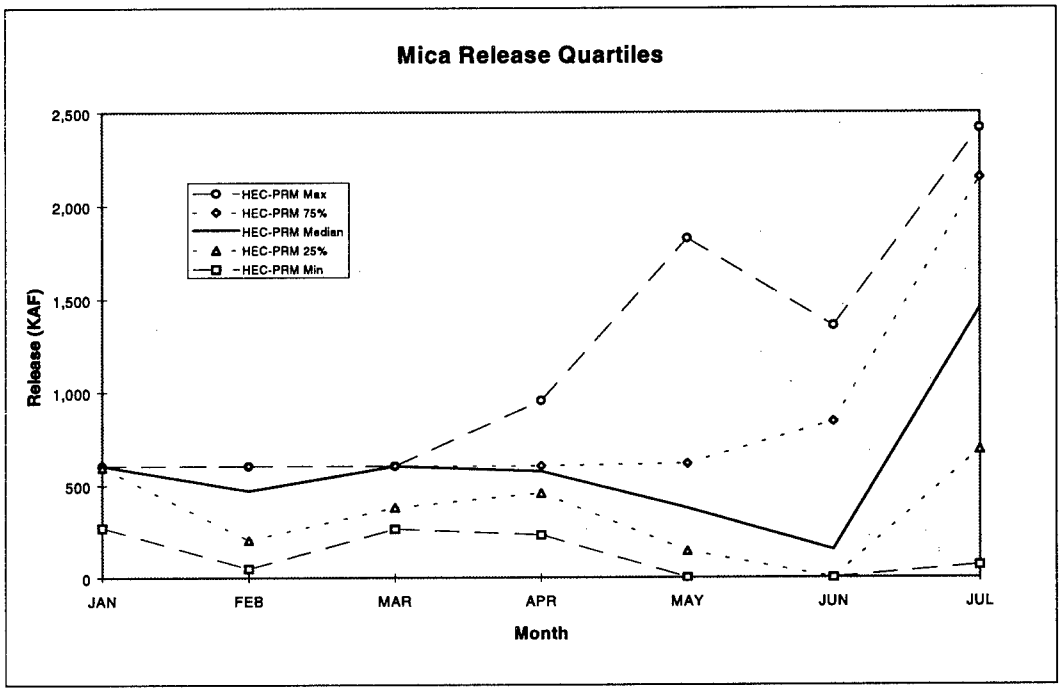


Figure 3.24 Mica Release Quartiles for HEC-PRM 1995 Jan-July Study

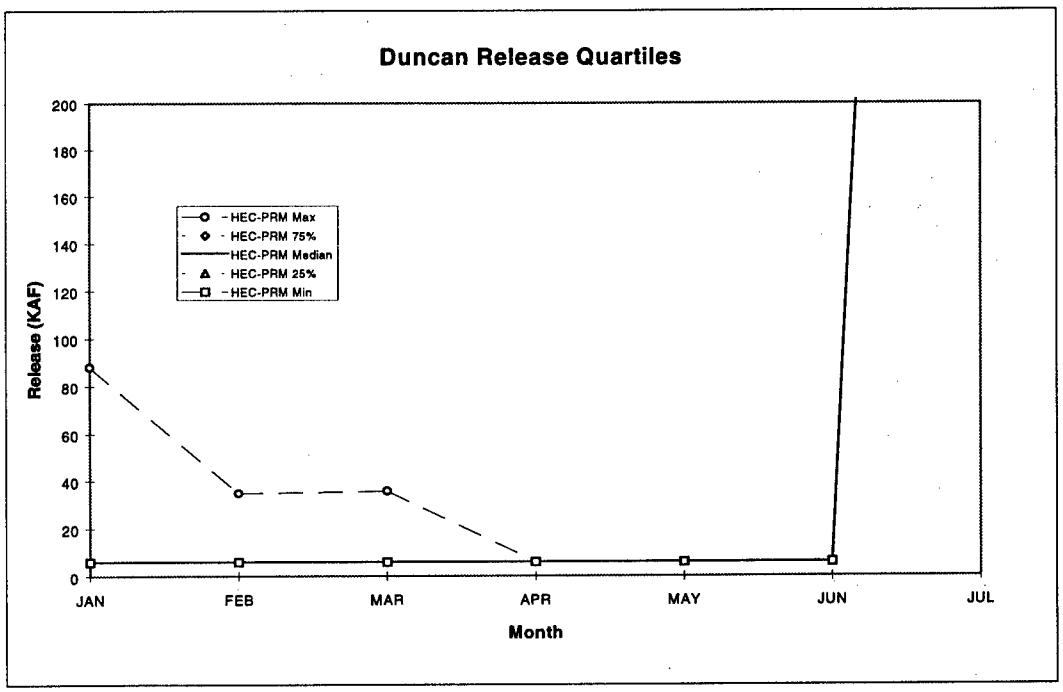


Figure 3.25 Duncan Release Quartiles for HEC-PRM 1995 Jan-July Study

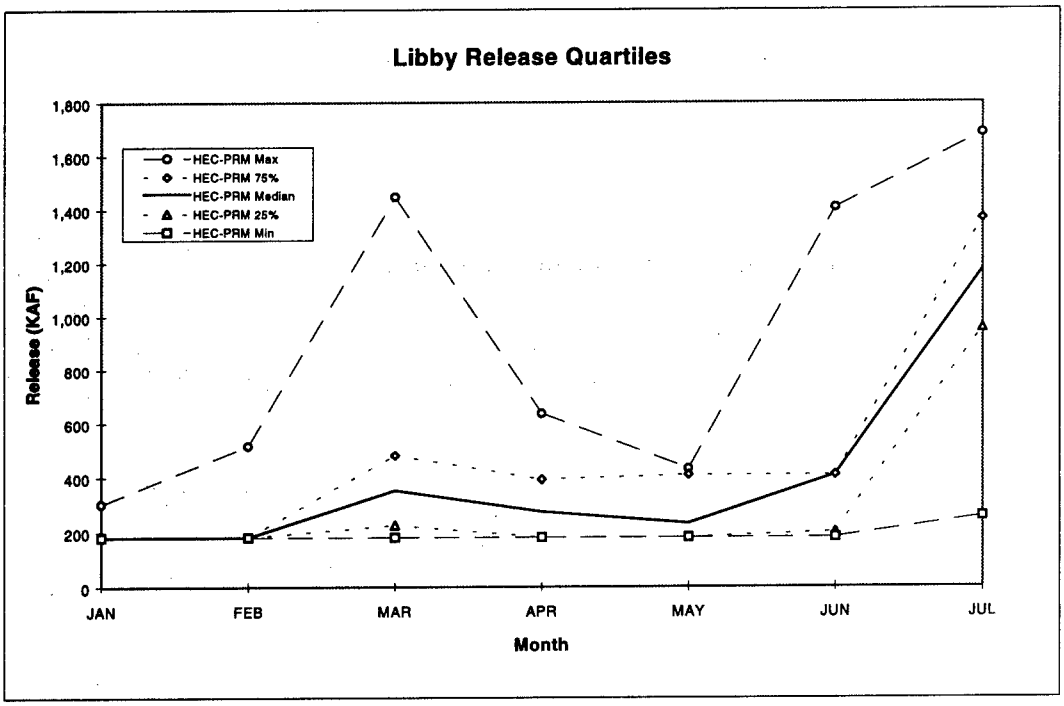


Figure 3.26 Libby Release Quartiles for HEC-PRM 1995 Jan-July Study

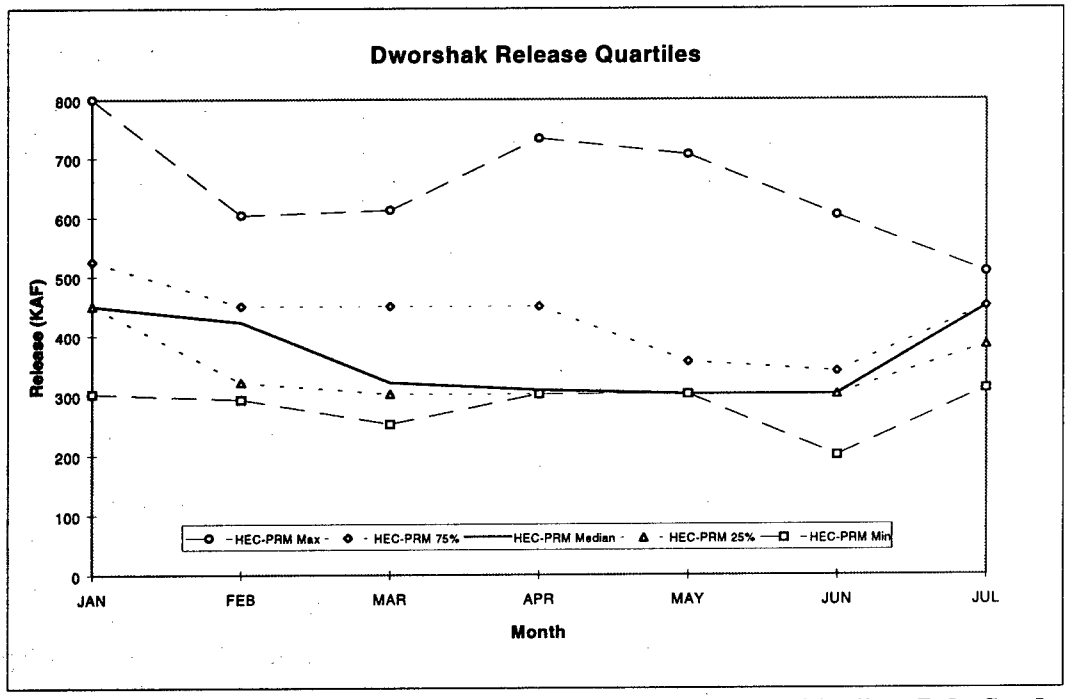


Figure 3.27 Dworshak Release Quartiles for HEC-PRM 1995 Jan-July Study

Chapter 4

1995 April - July Seasonal Update Study

The intent of the 1995 April - July seasonal update study is to use the updated inflow forecasts and initial storages for April 1st and update HEC-PRM April - July operation. This seasonal update approach is modeled after actual reservoir operation procedures; forecast updates throughout the January - July period are used to make mid-season changes to reservoir operations.

There are two sections in this chapter. Section 1 presents the HEC-PRM results and advice for the 1995 April - July seasonal update study. Section 2 compares the April - July period operation for the 1995 January - July study and the 1995 April - July seasonal update study.

4.1 The 1995 April - July Seasonal Update Study

The 1995 April - July study is an update study for the refill season of the 1995 January - July period of the Columbia River System. As an update to the 1995 January - July season study, the 1995 April - July study offers an example of how HEC-PRM might be applied several times during the year to complement traditional HYSSR simulation studies. This section discusses HEC-PRM's refill season operations for the 1995 April - July period. The probability of reservoir refill in July, the comparison of HEC-PRM results with the Actual Energy Regulation (AER) operation and the HEC-PRM refill advice are presented. To properly establish the conditions of the system in April, the initial storage values and forecasted inflows are provided.

4.1.1 Initial Storage and Forecasted Inflows

April Initial Storage Values

The initial storages for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs on April 1st are given in Table 4.1. The initial storage values are Actual Energy Regulation (AER) storage values. The U. S. Army Corps Engineers North Pacific Division (NPD) provided the AER values for the HEC-PRM study. AER storage values allow for non-firm energy production (USDOE, 1991).

Forecasted Inflows

Forty-eight years of annual inflow sequences, from 1929 to 1976, are used in the 1995 April - July season study. Some of inflows reflect April forecasts; other inflow sequences are the historic inflows. Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak inflows in the April - July 1995 study are all forecasted inflows.

Table 4.1 April 1, 1995 Initial Storages (AER Values)

Reservoir	April 1 Initial Storage (KAF)
Mica	11950
Arrow	2226
Grand Coulee	7627
Duncan	131
Libby	2351
Hungry Horse	627
Dworshak	2839

4.1.2 Probability of Refill in 1995

A main operational objective of the refill period is meeting the July storage target. Basically, storage reservoirs should be full in July. The probability of refilling Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs in July 1995 is an important indicator of HEC-PRM's utility for seasonal operational advice. As a result, HEC-PRM's refill operations are most valuable when the reservoir storage targets are reached in July.

Mica, Grand Coulee and Libby reservoirs always reached their target storages in July 1995 (Figures 4.1, 4.3 and 4.5). Figure 4.8 shows the probability of refill for Arrow, Duncan, Hungry Horse and Dworshak reservoirs. The target storages for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs are the median HYSSR storage values generated in a previous HYSSR simulation study (USACE, 1995). Table 4.2 presents the target storage values and the percent of the years that the target storage is reached for the seven reservoirs.

Mica and Libby probably always refill in July because their inflows are the first and third largest inflows in the system in July (Figure 4.9). The second largest inflows occur at Arrow reservoir. HEC-PRM likely uses Arrow water to reach Grand Coulee's target storage for all inflow sequences.

Arrow reservoir reaches its July target storage for fifteen of the forty-eight inflow sequences. For the remaining inflow years, Arrow typically draws down below the target (Figure 4.2). Arrow reservoir experiences this drawdown in July probably to supply Grand Coulee reservoir with water since Grand Coulee's inflows decrease significantly and pumping from the reservoir peaks in July (Figure 4.9). Arrow reservoir is an ideal source of water for Grand Coulee because Arrow is largely without penalty functions.

Duncan and Dworshak reservoirs draw down in July, likely to allow Hungry Horse and

Libby to fill (Figures 4.4 and 4.7). Hungry Horse is filling in July, but the reservoir remains ~1MAF less than the July target storage (Figure 4.6). An explanation is that Hungry Horse's initial storage on April 1st is remarkably low, and a steady release of 60KAF appears to inhibit refilling to its target.

Table 4.2 July 1995 Target Storage Analysis for 1995 April - July Study

Reservoir	July 1995 Target Storage (KAF)	Percentage of Years Target Storage Met (%)	July 1995 Median HEC-PRM Storage (KAF)	July 1995 AER Storage (KAF)
Mica	19045	100	19045	18088
Arrow	7327	31	6930	6965
Grand Coulee	9107	100	9107 (Max)	9107
Duncan	1399	0	540	1423
Libby	5869	100	5869 (Max)	5869
Hungry Horse	3072	0	1960	1977
Dworshak	3468	0	2430	3246

4.1.3 HEC-PRM System Operations for April - July 1995

The refill season extends from April to July. During this refill period, the Columbia River System experiences peak inflows. As Figure 4.10 shows, the seven reservoir system typically refills from April to July.

HEC-PRM allocates enough water to three of seven reservoirs for reliable July refill for all inflow sequences. Without sufficient water to operate all seven reservoirs always at their July target storage, Mica, Grand Coulee and Libby reservoirs were chosen by HEC-PRM. HEC-PRM included Grand Coulee reservoir because the hydropower generation from Grand Coulee is most successful with the highest head. The inflows for Mica, Arrow and Libby reservoirs are also the three largest inflows for the system in July (Figure 4.9). HEC-PRM likely uses Arrow's July inflows to allow Grand Coulee to meet its July refill target.

Insight into HEC-PRM's refill operation is provided by the storage allocation plots (Figures 4.11 - 4.14). The storage allocation graphs allow one to discover the order in which HEC-PRM refills the system of reservoirs. The individual reservoir storages are graphed against the total system storage values. Therefore, as the storage in the system increases, the refill activity in each individual reservoir can be observed.

Studying Figure 4.11, follow the refill pattern from the lowest total system storage value on the left to the highest value on the right. Grand Coulee reservoir is the first reservoir to refill significantly. Libby, Hungry Horse and Dworshak reservoirs refill gradually until Grand Coulee reservoir reaches its maximum allowable storage of 9107KAF. Subsequently, Libby reservoir dramatically refills until the July target storage is reached. When Libby reached its target, Dworshak reservoirs draws down and Hungry Horse continues to refill. These findings are supported by the storage position analysis plots for Libby, Hungry Horse and Dworshak reservoirs (Figures 4.11 and 4.12).

The storage allocation of the entire seven reservoir system is shown in Figure 4.12. As described above, Grand Coulee refills first, and refills quickly. Arrow reservoir is the second reservoir to refill significantly. The remaining reservoirs are refilling gradually. As soon as Grand Coulee reservoir reaches its maximum allowable storage, 9107KAF, Arrow and Mica reservoir refill dramatically. As Mica and Libby reservoirs reach their maximum storage, Arrow, Duncan and Dworshak draw down. Grand Coulee reservoir maintains its storage and Hungry Horse continues to refill. Close-up views of HEC-PRM's operation of Arrow, Duncan and Libby reservoirs (Figure 4.13) and Mica, Arrow, Grand Coulee and Duncan reservoirs (Figure 4.14) are provided.

4.1.4 Comparison of HEC-PRM with AER Operation for April - June

This section discusses the comparison of the near-term HEC-PRM results for the 1995 April - July season study to the AER operation. The near-term period extends from April to June. The HEC-PRM results and the AER operation are compared on the basis of storage trends and storage magnitudes.

Near-Term Storage Trend Comparison

Table 4.3 lists the storage trends of HEC-PRM and AER operations for each reservoir in the 1995 variable drawdown period. The storage trends for HEC-PRM and AER operations matched for twelve of twenty-one possible instances. Though April to June is the peak inflow season and refill is expected, the agreement of the majority of the comparisons between the HEC-PRM and AER operations is encouraging. HEC-PRM provided realistic seasonal operation trends.

<u>April</u>

HEC-PRM draws down four of the seven reservoirs in April. The AER operations are variable: three reservoirs draw down, three refill, and one maintains its current storage level. The HEC-PRM and AER operations agree for two of the seven reservoirs. Duncan and Libby are refilled by both operations.

<u>May</u>

The dominant storage trend for both HEC-PRM and the AER operation is refill. The

Table 4.3 Near-Term Comparison of Storage Trends for HEC-PRM 1995 April - July Study and 1995 AER Operation

RESERVOIR	HEC-PRM	1995 AER
April		
Mica	Maintain 11950KAF	Drawdown
Arrow	Drawdown	Maintain 2226KAF
Grand Coulee	Refill	Drawdown
Duncan	Refill	Refill
Libby	Refill	Refill
Hungry Horse	Refill	Drawdown
Dworshak	Drawdown	Refill
May		
Mica	Refill	Refill
Arrow	Refill	Refill
Grand Coulee	Maintain 9107KAF (Max)	Refill
Duncan	Refill	Refill
Libby	Refill	Refill
Hungry Horse	Refill	Refill
Dworshak	Refill	Drawdown
June		
Mica	Refill	Refill
Arrow	Refill	Refill
Grand Coulee	Maintain 9107KAF (Max)	Refill
Duncan	Refill	Refill
Libby	Refill	Refill
Hungry Horse	Refill	Refill
Dworshak	Drawdown	Refill

HEC-PRM and AER operations matched for five of the seven reservoirs. Mica, Arrow, Duncan, Libby and Hungry Horse reservoirs are refilled by both HEC-PRM and AER operations in May.

June

HEC-PRM and AER operations mainly refill the reservoirs in June also. Five of the seven reservoirs have the same storage trend operation in HEC-PRM and AER operations. HEC-PRM and the AER operation both refill Mica, Arrow, Duncan, Libby and Hungry Horse.

Near-Term Storage Magnitude Comparison

HEC-PRM's value as a seasonal reservoir operation model largely depends on its ability to offer storage and release results that compare well to the AER operation on the basis of magnitude. In general, HEC-PRM results are useful because they are based on formal economic derivations. If the storage magnitudes between the HEC-PRM results and the AER operation are very different, simulation testing should be used to explore operations suggested by HEC-PRM.

The differences in storage magnitudes between HEC-PRM and the AER operation are measured in absolute terms, and relative to the reservoir's total storage. The HEC-PRM quartile curves are plotted with the AER operation (Figures 4.15 - 4.21). One way that the differences in magnitude are quantified is by measuring the difference between the AER operation and HEC-PRM's median storage value.

System-Wide

HEC-PRM typically stores more water in the system than the AER operation (Figure 4.10). The median HEC-PRM storage values for April, May and June are typically at least 2MAF greater than the AER storage. In July, the HEC-PRM and AER storage values are very close together.

HEC-PRM stores more water in Mica, Grand Coulee, Duncan, Libby and Hungry Horse reservoirs than the AER operation (Figures 4.15 and 4.17 - 4.20). The AER operation for Arrow reservoir matches closely to the median HEC-PRM storage curve (Figure 4.16). The AER operations for Dworshak reservoir fluctuate near the median HEC-PRM storage values (Figure 4.21).

Mica Reservoir

HEC-PRM typically stores more water in Mica than the AER operation throughout April, May and June (Figure 4.15). All of the HEC-PRM storage values are larger than the AER storage in April. The median HEC-PRM storage in April is ~400KAF greater than AER. Over seventy-five percent of the HEC-PRM storages in May and June exceed the AER operation and the measured differences in magnitude between the median HEC-PRM storage and the AER operation increases in May and June. The median HEC-PRM operation is ~800KAF larger than the AER operation in May, and ~1.6MAF greater in June.

The three storage magnitude differences between HEC-PRM median and AER are minimal, ~2% - 8% of Mica's total storage capacity. Despite these magnitude differences, the storage trajectories of HEC-PRM and the AER operation follow the same basic trend. HEC-PRM may be able to store more water in Mica than the AER operation because HEC-PRM always knows the size of future inflows and can store large amounts of water without the threat of flooding.

Arrow Reservoir

HEC-PRM stores more and less water in Arrow reservoir than the AER operation (Figure 4.16). The AER operation follows the median HEC-PRM curve. In April and May, the median HEC-PRM values are ~400KAF less than the AER operation, ~6% of Arrow's total storage capacity. In June, the median HEC-PRM storage and AER storage are equal. Throughout April, May and June, both operation trajectories show refill, as expected. HEC-PRM's variable operation of Arrow may be due to the minimal penalty functions for the reservoir. As a result, Arrow reservoir can be operate to meet system-wide operation objectives.

Grand Coulee Reservoir

In April, May and June, HEC-PRM always stores more water in Grand Coulee than the AER operation (Figure 4.17). The difference between the median HEC-PRM and AER operation in April is ~2.2MAF, 24% of Grand Coulee's total capacity. This magnitude difference decreases a little in May and a substantial amount in June, to ~1800KAF and ~400KAF, respectively. The difference lessens in June as the AER operation fills Grand Coulee to a higher storage level. HEC-PRM typically tries to maintain Grand Coulee reservoir at a high level, likely for hydropower objectives. The AER operation promotes keeping Grand Coulee high also, simply later in the refill season.

Duncan Reservoir

HEC-PRM typically stores more water in Duncan than the AER operation in April, May and June of the refill season (Figure 4.18). All of HEC-PRM's storage curves are greater than the AER operation in April, and the median HEC-PRM value is ~80KAF larger than AER. In May and June, over half of the HEC-PRM storage values are greater than the AER storage. The differences between the median HEC-PRM storages and AER are ~80KAF in May and ~160KAF in June.

These differences are fairly small relative to Duncan's total storage, ~6% - 12% of the capacity. In addition, both operations have similar trajectories in April, May and June, as Duncan is refilled. HEC-PRM probably stores more water in Duncan because HEC-PRM's knowledge of future inflows allows the model to store a large quantity of water without the problem of flooding.

Libby Reservoir

HEC-PRM typically keeps Libby reservoir higher than the AER operation in April, May

and June (Figure 4.19). Over 75% of the HEC-PRM storage values exceed the AER storage in April and May. The median HEC-PRM storage is ~170KAF greater than AER in April and ~750KAF larger in May. These magnitude differences are ~ 3% and 13% of Libby's total storage capacity. In June, over half of HEC-PRM storages are ~200KAF greater than the AER value, ~3% of Libby's total allowable storage.

The measured magnitude differences are fairly small and the basic trajectories for HEC-PRM and AER match each other. Two reasons are proposed to explain why HEC-PRM stores more water in Libby than AER operation. HEC-PRM's knowledge of future inflows permits storing greater amounts of water without concern for flooding. In addition, the lack of extensive HEC-PRM fish flow penalty functions allows HEC-PRM to store water that should be designated for fish.

Hungry Horse Reservoir

HEC-PRM stores more water in Hungry Horse in April, May and June than the AER operation (Figure 4.20). All of HEC-PRM's storages in April are greater than the AER storage. The median HEC-PRM storage is ~250KAF larger than AER, ~8% of Hungry Horse's total storage capacity. In May and June, over 75% of HEC-PRM's storages are larger than AER values. Specifically, the median HEC-PRM storage is ~300KAF greater than AER in May, and ~170KAF more in June. These differences range from 6% to 10% of Hungry Horse's total storage capacity, a fairly small amount.

The refill trajectories for HEC-PRM and AER in April, May and June are the same for Hungry Horse. Possibly, HEC-PRM stores more water than the AER operation because HEC-PRM has knowledge of future inflows and can avoid operations that will result in flooding. In addition, HEC-PRM does not make releases for fish requirements throughout the seven reservoir system.

Dworshak Reservoir

In April and May, HEC-PRM stores more, and less, water in Dworshak than AER (Figure 4.21). The median HEC-PRM curve and the AER operation curve match in April and May. In June, over 75% of HEC-PRM storage values are less than AER. The differences in magnitude between the median HEC-PRM and AER operations are ~100KAF in April, ~80KAF in May and ~400KAF in June. These differences are between 2% and 12% of Dworshak's total storage capacity.

The storage trajectories of HEC-PRM and AER differ for Dworshak. Noticeably, HEC-PRM's drawdown in May conflicts with AER's refill operation. HEC-PRM must drawdown Dworshak in the refill season to promote overall system-wide benefits. Dworshak releases likely are more useful downstream and possibly for Hungry Horse and Libby to be kept at high storage levels.

4.1.5 HEC-PRM Near-Term Advice for 1995 April - July Study

HEC-PRM advice for the 1995 April - July season study is given for the near-term months of April, May and June 1995. HEC-PRM's near-term advice includes system-wide advice, and advice specific to each individual reservoir. In addition, the advice discusses general trends and quantitative advice. Though advice is given only for the first three months of study, the entire refill period needs to be included in the HEC-PRM run to ensure that the July refill target storages influence the operations.

Near-Term HEC-PRM System-Wide Operation Advice

HEC-PRM advises refilling the system during the months of April - June 1995 (Figure 4.10). System refill is supported by the AER system operation (Figure 4.10). HEC-PRM advises that Mica, Grand Coulee and Libby reservoirs always reach their target storages in July (Figures 4.1, 4.3 and 4.5). Arrow, Duncan and Dworshak reservoirs should draw down to supply water downstream. The purpose is probably to maintain Grand Coulee reservoir's storage at 9107KAF, and to allow Libby and Hungry Horse to fill. Hungry Horse will not reach its target storage. HEC-PRM appears to value keeping Grand Coulee high over reaching more reservoirs' target storages. This is probably due to the value of the additional head in Grand Coulee when the reservoir is full and making hydropower releases.

The storage allocation advice for the refill season begins with refilling Grand Coulee first (Figure 4.12). Grand Coulee should be refilled to 9107KAF before any of the other reservoirs significantly increase their storage. Mica and Arrow reservoirs should refill next. Duncan, Libby, Hungry Horse and Dworshak reservoirs should gradually fill. Grand Coulee maintains 9107KAF throughout the remainder of the refill period. Mica, Arrow and Libby should reach their target storages, but only Mica and Libby storages should maintain this level. In fact, Arrow, Duncan and Dworshak reservoirs should draw down when the total system storage nears its maximum. Hungry Horse should simply continue its gradual refill until the end.

HEC-PRM advises that only Mica, Grand Coulee and Libby reservoirs should reach their target storages. There appears to be inadequate water in the system to meet all reservoir targets storage. It may be that Arrow, Duncan and Dworshak reservoir are used to supply water for downstream uses, e.g. the storage maintenance of Grand Coulee reservoir and the refill of Libby and Hungry Horse reservoirs. Water is probably needed in Grand Coulee because Grand Coulee's inflows significantly decreased at the same time that the reservoir's pumping peaked during the month.

Throughout April, May and June, HEC-PRM and the AER operation have similar storage trajectories for the operation of Mica, Arrow, Duncan, Libby and Hungry Horse. In addition, HEC-PRM advises storing more water in Mica, Grand Coulee, Duncan, Libby and Hungry Horse reservoirs than the AER operation. HEC-PRM can store a great amount of water and still prevent flooding because the model knows the future inflows.

Near-Term HEC-PRM Individual Reservoir Storage Trend and Magnitude Advice

Mica Reservoir

Throughout April, May and June, HEC-PRM advises storing more water than the AER operation, while maintaining the same basic refill trajectory (Figure 4.15). HEC-PRM's operation with additional water should be explored with simulation testing.

The greater amount of water stored in Mica reservoir by HEC-PRM than AER is likely because HEC-PRM can store a large amount of water without flooding since the model always knows what inflows will arrive in the future. In addition, HEC-PRM may store considerable water because April inflow forecasts are higher than the updated forecasts used to develop the AER storages. The lack of consideration for the fish requirements in the majority of HEC-PRM's penalty functions could be another reason that HEC-PRM stores more than the AER operation. HEC-PRM probably stores the water that would have been allocated for fish flows.

Arrow Reservoir

HEC-PRM advises the same refill trend as the AER operation (Figure 4.16). HEC-PRM typically does not meet the July target storage; the AER operation fails to meet the target also. During drier inflow sequences, HEC-PRM suggests that Arrow water should be discharged to the system rather than fill Arrow to its target storage. This is evident because Arrow reservoir does not meet its target storage for 33 of the 48 inflow sequences.

Grand Coulee Reservoir

Grand Coulee reservoir should maintain 9107KAF, its maximum allowable storage, in April, May and June 1995 (Figure 4.3). This HEC-PRM advice for Grand Coulee is supported in past HEC-PRM studies. HEC-PRM typically keeps Grand Coulee reservoir filled high for hydropower and other operational objectives, except when episodic flood control or drought conditions occur (USACE, 1995). HEC-PRM's operation allows Grand Coulee to reach the target storage in July.

Duncan Reservoir

HEC-PRM fails to meet the Duncan July target storage by a considerable amount (Figure 4.4). The AER operation of Duncan is more favorable than the HEC-PRM operation because the AER operation near HEC-PRM's target storage (Figure 4.18). HEC-PRM draws down Duncan reservoir in July probably to supply Grand Coulee reservoir with water, and to allow Libby and Hungry Horse reservoirs to fill. Grand Coulee may require water because inflows significantly decrease in July, and pumping is at its maximum.

Libby Reservoir

HEC-PRM advises a steady refill of Libby reservoir that results in the desired target storage in July (Figure 4.5). The AER storage trajectory is similar to HEC-PRM, but HEC-PRM

stores a larger amount of water (Figure 4.19). Simulation testing should be used to explore the potential advantage of storing a greater amount of water in Libby reservoir than given in the AER operation.

Hungry Horse Reservoir

HEC-PRM advises keeping Hungry Horse at low storage levels, though the July target storage is not met (Figure 4.6). The AER operation does not approach the July target storage either. In fact, the AER operation never exceeds the HEC-PRM storage values throughout the refill season. The refill trajectories of HEC-PRM and AER are very similar (Figure 4.20).

Dworshak Reservoir

HEC-PRM's advice for Dworshak operation is to draw down the reservoir gradually (Figure 4.21). As a result, Dworshak does not reach the target storage for July based on HEC-PRM operation. HEC-PRM must allocate Dworshak's releases elsewhere in the system to allow Libby and Hungry Horse to fill.

Near-Term HEC-PRM Individual Reservoir Specific Storage and Release Advice

HEC-PRM provides specific quantitative storage and release advice for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs. Specific advice is defined as HEC-PRM results that are suggested for 25% or more of the inflow sequences. Table 4.4 lists the specific advice.

Mica Reservoir

Mica reservoir should store 11950KAF in April (Figure 4.1). Over 50% of the storage results in April equal 11950KAF. For May and June, HEC-PRM suggests that Mica reservoir not release any water (Figure 4.22). Fifty percent of the May releases are zero flow and at least 75% of the HEC-PRM releases in June are zero flow.

Arrow Reservoir

In April, Arrow reservoir should release between 302KAF (minimum allowable release) and 770KAF, as suggested for over 25% of the results (Figure 4.24). Over 75% of the May releases are 302KAF. Similarly, releases exceed 302KAF in June.

Grand Coulee Reservoir

HEC-PRM advises storing the maximum, 9107KAF, in Grand Coulee reservoir throughout April, May and June (Figure 4.3). At least 50% of the storage values equal 9107KAF in April and a minimum of 75% in May. All of the storage results equal 9107KAF in June.

Table 4.4 HEC-PRM Specific Quantitative Advice for 1995 April - June Period of 1995 April - July Study

Reservoir	Month	Operation	HEC-PRM Advice (KAF)	Percentage of Results (%)
Mica	April	Storage	11950	50
	May	Release	0	50
	June	Release	0	75
Arrow	April	Release	302 (Min)-771	25
	May	Release	302	75
	June	Release	302	25
Grand Coulee	April	Storage	9107 (Max)	50
	May	Storage	9107	75
	June	Storage	9107	100
Duncan	April	Release	6 (Min)	100
	May	Release	6	100
	June	Release	6	100
Libby	April	Release	181 (Min)	100
	May	Release	181	100
	June	Release	181	75
Hungry Horse	April	Release	60	75
	May	Release	60	100
	June	Release	60	75
Dworshak	April	Release	300-450	50
	May	Release	300-450	75
	June	Release	300-450	75

Duncan Reservoir

Duncan reservoir should release 6KAF (minimum release) in April, May and June (Figure 4.25). All release results for these months are 6KAF.

Libby Reservoir

HEC-PRM advises a release of 181KAF, the minimum allowable release, from Libby reservoir throughout April, May and June (Figure 4.26). All the releases for April and May are 181KAF. At least 75% of the results in June are 181KAF.

Hungry Horse Reservoir

Hungry Horse reservoir should release 60KAF all three months (Figure 4.27). At least 75% of the release results for April and June equal 60KAF. All 100% of the results equal 60KAF in May.

Dworshak Reservoir

Dworshak reservoir should release between 300KAF and 450KAF in April; at least 50% of the release results fall within this range (Figure 4.28). The advice improves in May and June, release between 300KAF and 450KAF, as indicated by 75% of the results.

4.1.6 Conclusions for 1995 April - July Study

1. Overall, HEC-PRM offered strong specific release advice for all seven reservoirs. HEC-PRM typically stores more water in the reservoirs than the AER operation. Storage allocation shows that a priority of HEC-PRM is to keep Grand Coulee's storage level high. HEC-PRM operations have a moderate probability to satisfy July refill. Simulation testing should be used to explore HEC-PRM's advice.

2. The HEC-PRM operational advice indicated that Mica, Grand Coulee and Libby reservoirs should always reach their target storages in the 1995 refill season study. It is likely that Arrow, Duncan and Dworshak did not reach their target storages because HEC-PRM drew these reservoirs down to maintain Grand Coulee's 9107KAF level, and fill Libby and Hungry Horse. Hungry Horse never comes close to its target storage in July, probably because its initial storage is remarkably lower than the target storage.

3. HEC-PRM and the AER operation both refill the system in the 1995 refill season, as expected. The total system storage plot shows that HEC-PRM typically stores more water in the system than AER. Three reasons for HEC-PRM's tendency to store more water are proposed. HEC-PRM may be able to store the largest amount of water possible in a given month because the model knows the future inflows and can operate the reservoirs high while preventing flooding. In addition, April forecasted inflows may be larger than the actual inflows used to determine AER storage levels in the refill season. Lastly, HEC-PRM does not include fish requirements in system reservoirs' penalty functions. Therefore, water that would be for the fish releases is stored in the system instead.

4. The storage allocation plots show that HEC-PRM advises refilling Grand Coulee first, Arrow and Mica next, followed by Duncan, Libby, Hungry Horse and Dworshak reservoirs. Grand Coulee should immediately refill to 9107KAF and maintain this level throughout the refill season. Mica and Libby eventually reach their target storages for all inflow sequences. When Mica, Grand Coulee and Libby are at their target storages, Arrow, Duncan and Dworshak draw down to provide Grand Coulee reservoir with enough water to stay at 9107KAF.

5. HEC-PRM's storage trend advice matched the AER storage trends for 12 of 21

comparisons. Typically both operations encouraged refill. The HEC-PRM and AER operation trends for Duncan and Libby reservoirs are always the same in April, May and June; the trend is refill.

6. HEC-PRM typically operated Mica, Grand Coulee, Duncan, Libby and Hungry Horse reservoirs with more water than the AER operation. The viability of storing this additional water should be tested with simulation. Three explanations for HEC-PRM's tendency to store more water than the AER operation are presented above in Conclusion 3.

7. HEC-PRM provides strong specific quantitative advice for the 1995 refill season. For example, a release of 6KAF (minimum allowable release) is always suggested for Duncan reservoir for April, May and June 1995. Grand Coulee reservoir should be kept at 9107KAF (maximum allowable storage) throughout the refill season. Overall, specific quantitative advice is available for each reservoir. Arrow should release 302KAF, the minimum allowable release, each month.

Libby releases should equal the minimum, 181KAF, each month, and Hungry Horse should release 60KAF in April, May and June. Dworshak reservoir should release between 300KAF and 450KAF in April, May and June. Mica should store 11950KAF in April. In May and June, Mica should maintain its storage by releasing no flow at all. It is encouraging to discover HEC-PRM produced definite storage or release advice. This advice should be tested with simulation to determine if any reliable operations can be derived from the HEC-PRM operation advice.

4.2 Comparison of Refill Season Operations for 1995 January - July Study and 1995 April - July Study

This section explores the feasibility of HEC-PRM seasonal update runs by comparing the seasonal update run (1995 April - July season study) to the original run (1995 January - July season study). The comparisons include forecasted inflows, July 1995 refill probability, system-wide operations, storage allocation, storage trends and magnitude differences and HEC-PRM advice.

Feasibility of HEC-PRM Seasonal Update Runs

HEC-PRM seasonal update runs would be performed to gain additional HEC-PRM reservoir operation advice throughout an operating season. For instance, the two HEC-PRM runs conducted for the 1995 January - July period are an example. The first run, the 1995 January - July season study, includes both the variable drawdown season and the refill season. The second run, the 1995 April - July season study, concentrated on the 1995 refill season only.

A seasonal update run uses the most recent inflow forecasts and initial storage values. The April 1 forecasted inflows were used for the inflow sequences of the 1995 April - July seasonal update study, and updated initial storages were available to describe the April storage conditions more accurately. The new HEC-PRM advice will reflect the most recent conditions.

HEC-PRM seasonal update runs are useful, as evident from comparisons of the 1995 January - July season study and the 1995 April - July season study. Figure 4.40 shows that the seasonal update run, the 1995 April - July season study, offers different system operation advice than the 1995 January - July season study. In fact, the 1995 April - July study compares better to the AER operation than the 1995 January - July run. Since the update run operates the system closer to the AER operation than the original 1995 January - July run, the seasonal update appears to be worthwhile. Clearly, update studies have the potential to offer new, valuable operation advice. If the seasonal update run differs significantly from the AER operation and the original HEC-PRM advice, it still may be useful. Simulation modeling would be used to check the value of new seasonal reservoir operation advice.

Comparison of Forecasted Inflows

Forty-eight years of inflows, from 1929 to 1976, are used for the both 1995 seasonal studies. The April 1 forecasted inflows for the 1995 April - July season are different than the January 1st forecasted inflows April - July period in the 1995 January - July season study. Typically, the January 1st forecasted inflows are larger than the April 1 forecasted inflows for the April - July period (Figure 4.29 - 4.35). Only Mica reservoir's April 1 forecasted inflows are greater in magnitude than the January 1st forecasts (Figure 4.29). The greatest magnitude differences between the forecasted inflows from January 1st and April 1st typically occurs in June and July, when the peak inflows reach the system. Forecasting the peak runoff volume must be subject to error, which would account for the June and July inflow differences.

Comparison of July Refill Probability

Four reservoirs, Mica, Arrow, Grand Coulee and Libby, always reach their July target storage in the 1995 January - July season study (Figures 3.1, 3.2, 3.3 and 3.5). Only three reservoirs, Mica, Grand Coulee and Libby, always meet the target in the 1995 April - July season study (Figures 4.1, 4.3 and 4.5). Mica, Grand Coulee and Libby reservoirs are the only reservoirs that reach their July target storage for both studies. Figures 4.36 - 4.39 show the percentage of target storage reached for the other reservoirs for both 1995 studies. Arrow reservoir always reaches its target storage in the 1995 January - July study, but it meets the target for only 15 of the 48 years in the drier 1995 April - July study (Figure 4.36).

The difference in HEC-PRM refill results arise from the size of forecasted inflows. As mentioned in the previous section, the inflows in the 1995 January - July study are significantly greater than the April 1 forecasts (Figures 4.29 - 4.35). Therefore, it is reasonable that more reservoirs always reached their target storage in the 1995 January - July study. This reinforces the use of re-running HEC-PRM for seasonal updates to discover these differences and explore possible operation advice.

Comparison of System-Wide Operations

The same total system storage trajectory is evident for both the 1995 January - July study and the 1995 April - July study, but the storage magnitudes of the two studies differ (Figure 4.40). The 1995 January - July study stores less water than the 1995 April - July study in April and more water in June and July. The median total system storage values are approximately the same in May.

The 1995 April - July median total system storages are closer to the AER storages throughout the refill season than the 1995 January - July storages are to the AER operation (Figure 4.40). The use of seasonal update runs for improving seasonal reservoir operation appears worthwhile.

Comparison of Storage Allocation Plots

The storage allocation plots show that the order of refill differs between the two studies (Figure 3.13 and 4.12). Grand Coulee is among the first to refill in the April - July run, and second in the January - July run. Libby is the first reservoir to refill in the 1995 April - July run. In both studies, Mica and Arrow reservoirs significantly refill when Grand Coulee reservoir reaches and maintains its target storage of 9107KAF. In both studies, Hungry Horse is refilled gradually. Duncan and Dworshak also refill consistently in both studies, but ultimately both reservoirs draw down.

Comparison of Storage Magnitudes

HEC-PRM stores more water in Mica, Grand Coulee, Duncan, Libby and Hungry Horse reservoirs in April, May and June, than the AER operation for both the 1995 January - July study (Figures 3.17 and 3.19 - 3.22) and the 1995 April - July study (Figures 4.15 and 4.17 - 4.20).

HEC-PRM may store more water than AER because HEC-PRM knows all future inflows at any time during the optimization process. As a result, the model can determine the largest amount of water reservoirs can store without the threat of flooding. Lastly, HEC-PRM does not take into account all reservoir fish flow requirements in the penalty functions. Therefore, some water that HEC-PRM is storing should be released for fish flow purposes.

Both HEC-PRM studies encourage operating Grand Coulee at 9107KAF throughout the refill season (Figures 3.19 and 4.17). For the month of April, for the 1995 January - July study, there is a struggle to maintain Grand Coulee at 9107KAF, while, for the 1995 April - July study, this operation is achieved. The 1995 April - July study results for Grand Coulee in April are straightforward because the HEC-PRM update run incorporates the recent initial storages and forecasted inflows. Clearly, HEC-PRM update runs confirm the desirability of keeping Grand Coulee full.

HEC-PRM operates Arrow and Dworshak reservoirs in April, May and June at lower storage levels than the AER operation. HEC-PRM typically stores less water in Dworshak than the AER operation (Figures 3.23 and 4.21). For the 1995 January - July study, the AER operation stores more water in Arrow reservoir than HEC-PRM in April, May and June (Figure 3.18). The comparison for Arrow reservoir shows that the AER operation basically matches the median HEC-PRM results for the 1995 April - July study (Figure 4.16).

Comparison of Storage Trends

The HEC-PRM storage trends for both studies compared well to the AER operation. Table 4.5 shows the comparison of storage trends for the 1995 January - July study, the 1995 April - July study and the AER operation. The two HEC-PRM studies and the AER operation have the same storage trend of refill for twelve of the twenty-one comparisons. Specifically, Duncan and Libby reservoirs are refilled by the three operations all three months, April, May and June.

The storage trend advice for the 1995 January - July study and the 1995 April - July study matches in 16 of the 21 instances. The 1995 January - July study matches the AER operation more than the 1995 April - July study does. Fifteen of twenty-one instances compare successfully for the 1995 January - July study and AER, while the 1995 April - July study matches to the AER operation only 12 of the 21 times. In general, the high success rate for storage trend comparisons is reasonable in the refill season because both HEC-PRM and the AER operation aim to refill the system as peak inflows reach the reservoirs in May, June and July.

Comparison of HEC-PRM Specific Quantitative Advice

The specific quantitative HEC-PRM advice provided for the 1995 January - July study and the 1995 April - July study compare very well (Table 4.6). Both studies always advised releasing 6KAF, the minimum allowable release, from Duncan in April, May and June (Figures 3.25 and 4.25). At least 50% of the results in both studies suggest storing 9107KAF (maximum allowable storage) in Grand Coulee (Figures 3.19 and 4.17) and releasing 60KAF from Hungry

Horse (Figures 3.10 and 4.27). Arrow reservoir should release minimum allowable release of 302KAF in May and June, according to both 1995 seasonal studies (Figures 4.23 and 4.24). In the 1995 January - July study, HEC-PRM advised that 227KAF (minimum storage) be stored in Arrow reservoir in April (Figure 3.18). The 1995 April - July study recommends an April release of 302KAF, the minimum allowable release, as in May and June (Figure 4.24).

Both 1995 seasonal studies recommend that Libby reservoir release the minimum allowed, 181KAF, in April, May and June (Figure 3.26 and 4.26). The 1995 April - July study advice for the Libby release is stronger than the 1995 January - July study advice (Table 4.6). Both studies advise that Dworshak reservoir should release at least 300KAF in April, May and June (Figures 3.27 and 4.28). The two seasonal studies advise storage operations for Mica reservoir in April and releases in May and June (Table 4.6). The 1995 April - July study advises that Mica store 11950KAF in April and release no water in May and June (Figures 4.1 and 4.22). Mica should store 14075KAF in April and release between 0KAF - 145KAF in May and 0KAF - 150KAF in June in the 1995 January - July study (Figures 3.17 and 3.24).

Comparison Conclusions

1. Seasonal update runs, such as the 1995 April - July study, can provide useful advice for reservoir operation. With the use of recent forecasted inflows and initial reservoir storages, the seasonal update run provides updated HEC-PRM advice. This advice should be compared to the original seasonal run, i.e. the 1995 January - July study, and the AER operation to identify any possibly useful changes to the seasonal reservoir operation.

2. More reservoirs reach their July target storages in the 1995 January - July study operation than the generally drier 1995 April - July study. Four reservoirs, Mica, Arrow, Grand Coulee and Libby, always refill to their target level in July for the 1995 January - July study, while only three reservoirs, Mica, Grand Coulee and Libby, always reach their target storages in the 1995 April - July study.

3. The 1995 April - July study operates the system very closely to the AER operation in April. The 1995 January - July study stores considerably less water than the AER operation in April. In May, both studies operate the system approximately the same; HEC-PRM holds more water in the system than the AER operation. During the months of June and July, the seasonal update run (1995 April - July study) compares closer to the AER operation on a system-wide basis than the 1995 January - July study. Overall, HEC-PRM tends to store more water in the reservoirs than the AER operation in both studies. The 1995 April - July results provide clearer updated operating advice than the earlier 1995 January - July results and are closer to AER operations.

4. For both studies, HEC-PRM typically stores more water in Mica, Grand Coulee, Duncan, Libby and Hungry Horse than the AER operation throughout the April - June period. Typically, HEC-PRM keeps less water in Arrow and Dworshak reservoirs in April, May and June. Notably, Grand Coulee is kept as close to 9107KAF throughout the refill period as possible, in both HEC-PRM studies.

Table 4.5 Comparison of Storage Trends for April - June 1995 HEC-PRM 1995 January - July Study, HEC-PRM 1995 April - July Study and 1995 AER Operation

RESERVOIR	1995 Jan - July Study	1995 April - July Study	1995 AER
April			
Mica	Variable	Maintain 11950KAF	Drawdown
Arrow	Maintain 227KAF	Drawdown	Mtn2226KAF
Grand Coulee	Refill	Refill	Drawdown
Duncan	Refill	Refill	Refill
Libby	Refill	Refill	Refill
Hungry Horse	Refill	Refill	Drawdown
Dworshak	Refill	Drawdown	Refill
May			
Mica	Refill	Refill	Refill
Arrow	Refill	Refill	Refill
Grand Coulee	Refill	Maintain 9107KAF	Refill
Duncan	Refill	Refill	Refill
Libby	Refill	Refill	Refill
Hungry Horse	Refill	Refill	Refill
Dworshak	Refill	Refill	Drawdown
June			
Mica	Refill	Refill	Refill
Arrow	Refill	Refill	Refill
Grand Coulee	Maintain 9107KAF	Maintain 9107KAF	Refill
Duncan	Refill	Refill	Refill
Libby	Refill	Refill	Refill
Hungry Horse	Refill	Refill	Refill
Dworshak	Refill	Drawdown	Refill

Table 4.6 Comparison of HEC-PRM Specific Advice (KAF) for Both 1995 Studies

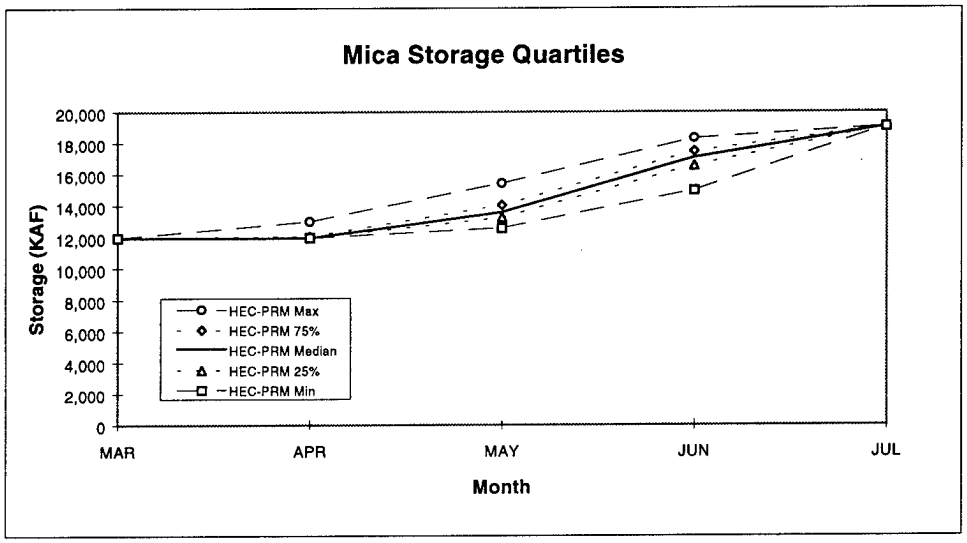
Mica	1995 Apr-July	%	1995 Jan-July	%
April	Store 11950	50	Store 14075	50
May	Release 0	50	Release 0 - 145	25
June	Release 0	75	Release 0 - 150	50
Arrow				
April	Release 302(Min)-771	25	Store 227	50
May	Release 302	75	SAME	50
June	Release 302	25	SAME	50
Grand Coulee				
April	Store 9107(Max)	50	SAME	75
May	Store 9107	75	SAME	100
June	Store 9107	100	SAME	100
Duncan				
April	Release 6(Min)	100	SAME	100
May	Release 6	100	SAME	100
June	Release 6	100	SAME	100
Libby				
April	Release 181(Min)	100	SAME	25
May	Release 181	100	SAME	25
June	Release 181	75	SAME	25
Hungry Horse				
April	Release 60	75	SAME	75
May	Release 60	100	SAME	75
June	Release 60	75	SAME	75
Dworshak				
April	Release 300-450	50	SAME	75
May	Release 300-450	75	SAME	75
June	Release 300-450	75	SAME	50

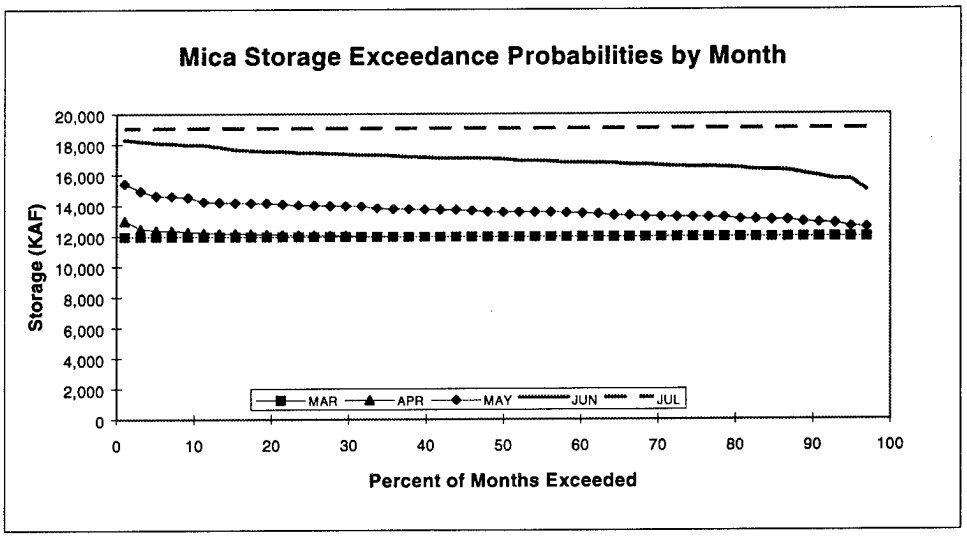
A comparison of the median total system storages for the 1995 January - July study and the 1995 April - July study shows that, in April, the 1995 January - July study stores less than the 1995 April - July study. In May, the median system storage is approximately the same between the two seasonal studies. In June and July, the 1995 January - July study stores more water than the 1995 April - July study. The 1995 January - July study stores less water in the system than the 1995 April - July study at the end of the variable drawdown season (April) because HEC-PRM knows that the 1995 January - July study's forecasted inflows are larger than the 1995 April forecasted inflows in May and June and will refill the system sufficiently.

5. The storage trend results for both studies compare well to the AER trends. The HEC-PRM storage trend results for both the 1995 January - July study and the 1995 April - July study match the AER trends for twelve of the twenty-one comparisons. Sixteen of the twenty-one comparisons match between the two HEC-PRM studies. The 1995 January - July study trends agree with the AER trends 15 of 21 instances. The 1995 April - July study trends match the AER operation trends for 12 of 21 comparisons. The large number of matching comparisons is reasonable for the refill season because it is expected that HEC-PRM and the AER operation refill the reservoirs when peak inflows arrive in May, June and July.

6. HEC-PRM provides strong specific, quantitative advice in both studies. In fact, for Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs, the same specific advice is given in each study. Grand Coulee should store 9107KAF, the maximum allowable storage, in April, May and June. Duncan should release 6KAF (minimum release) each month and Libby releases should equal the minimum allowed, 181KAF per month. Hungry Horse releases should be 60KAF per month. Dworshak releases should range between 300KAF and 450KAF in April, May and June.

The advice for Libby reservoir is stronger in the 1995 April - July study. The specific HEC-PRM advice for Grand Coulee is stronger in the 1995 January - July study. The strength of the HEC-PRM advice for Duncan, Hungry Horse and Dworshak are basically the same for both studies. The advice for Mica and Arrow reservoirs is variable between the studies.





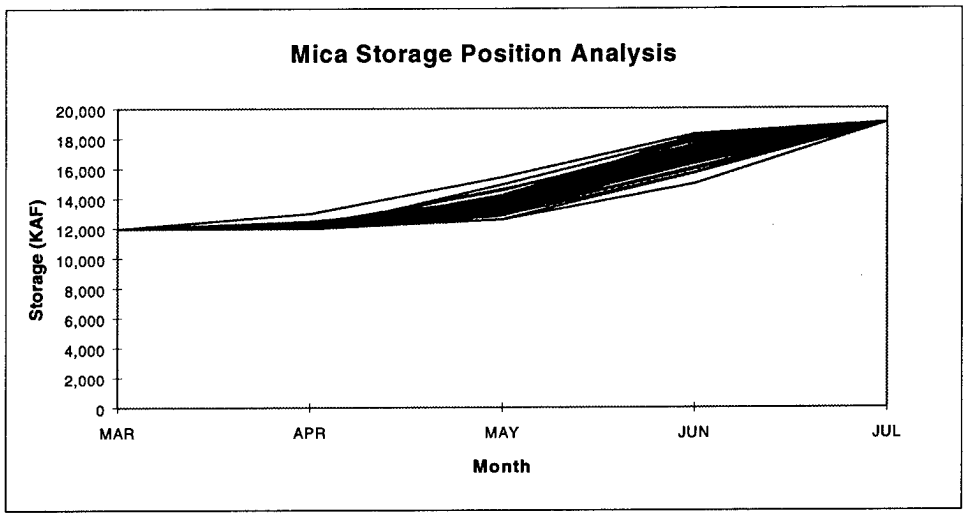
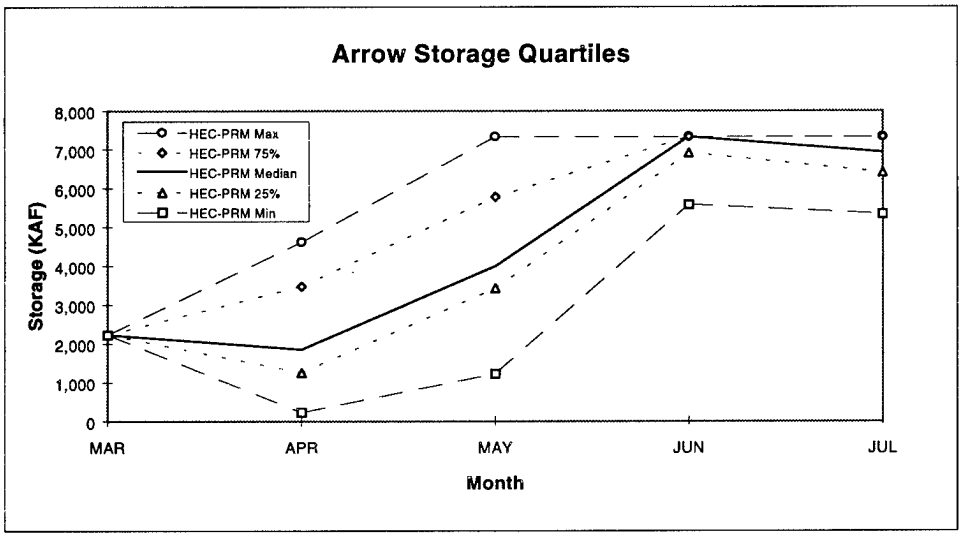
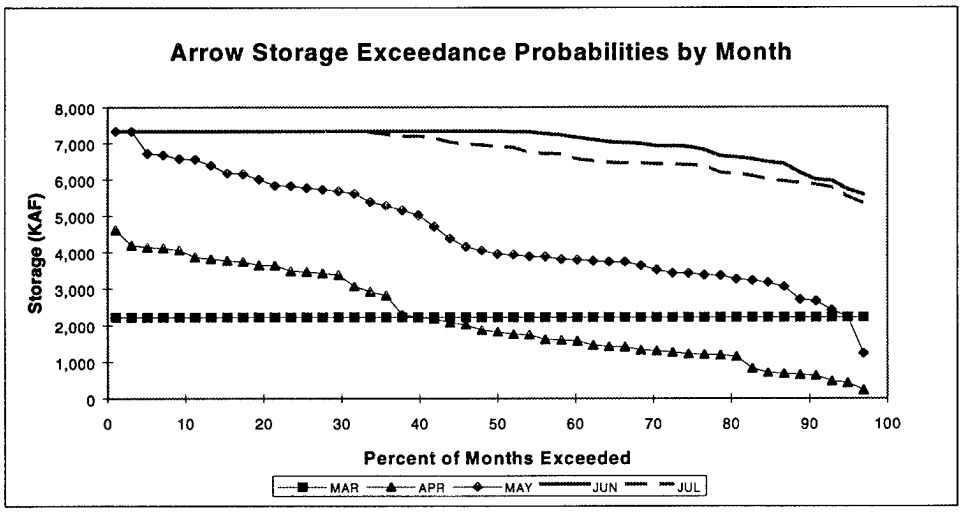


Figure 4.1 Mica Storage Results for HEC-PRM 1995 Apr-July Study





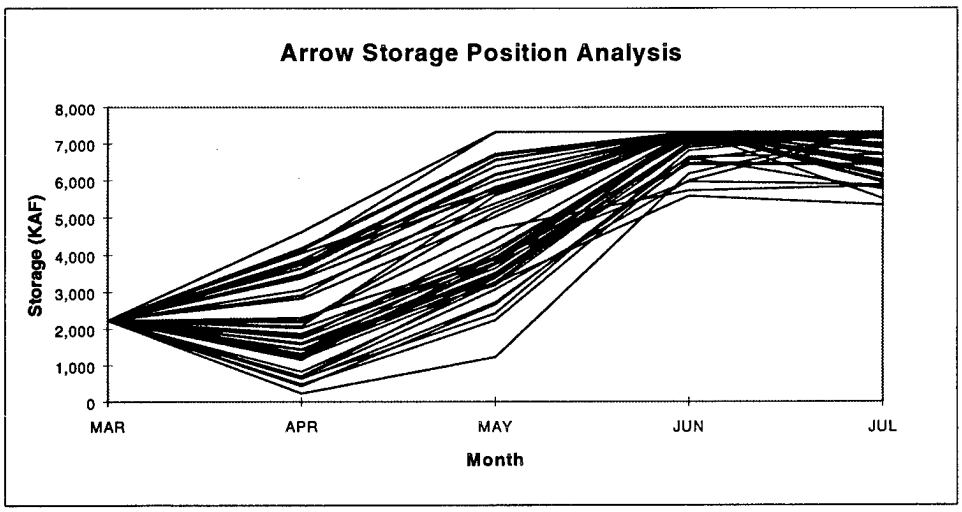
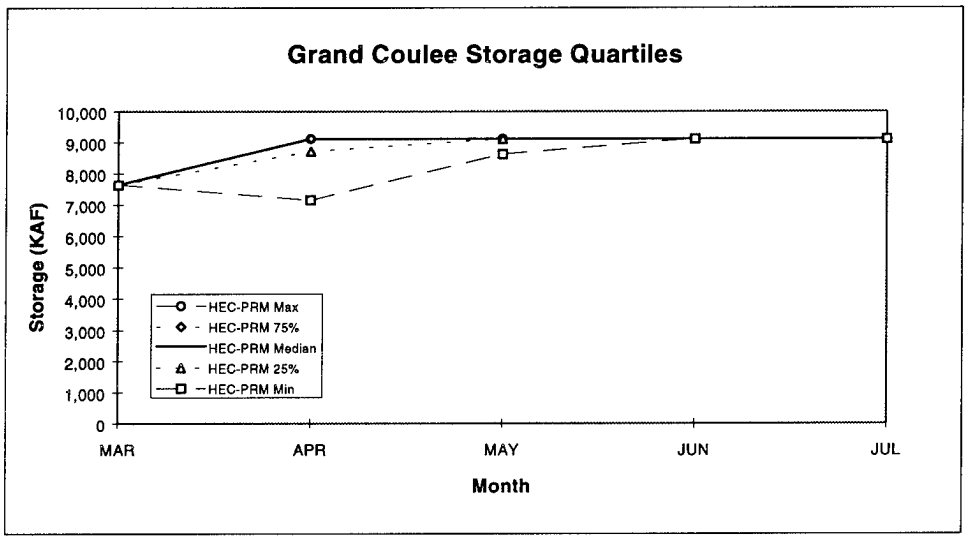
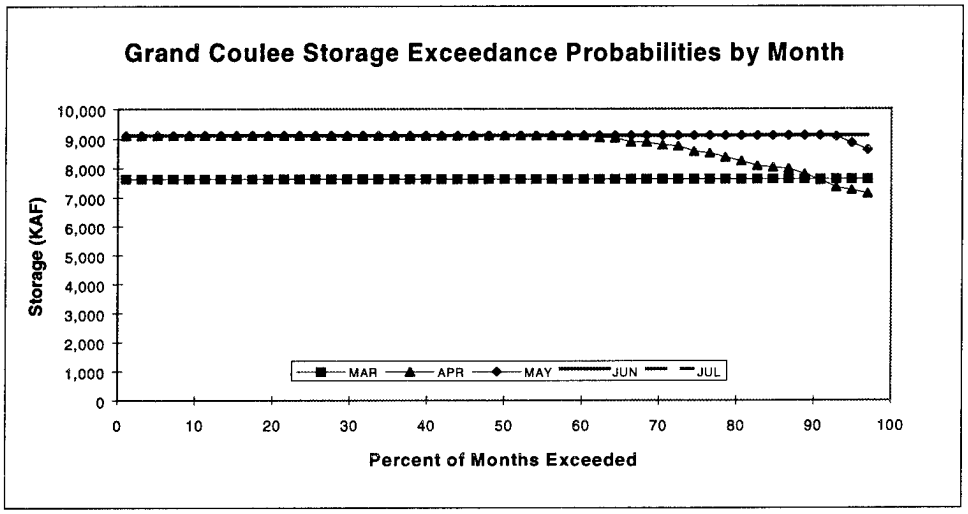


Figure 4.2 Arrow Storage Results for HEC-PRM 1995 Apr-July Study





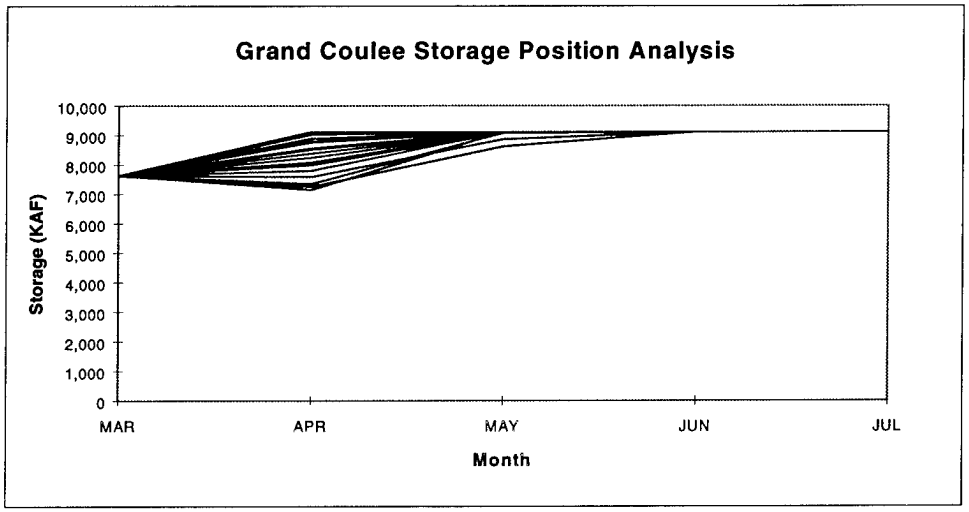
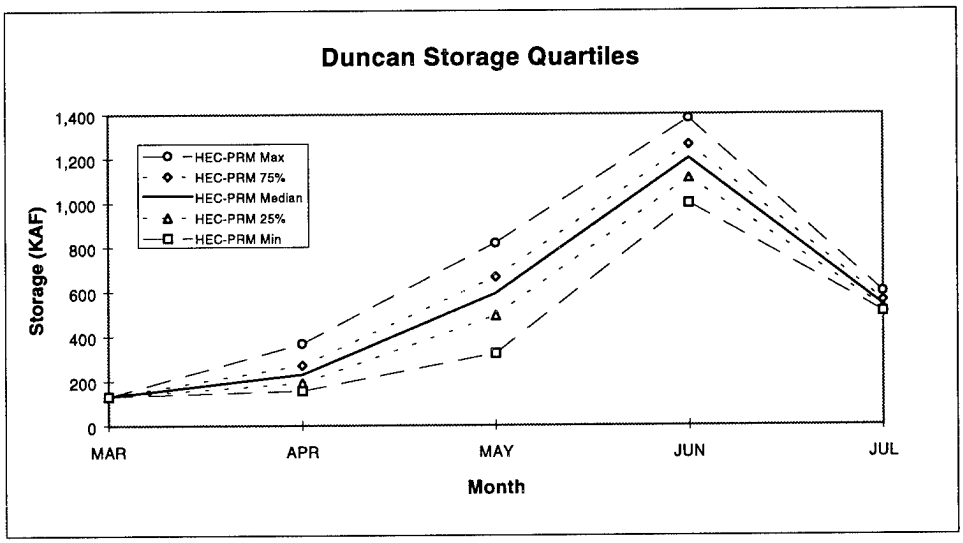
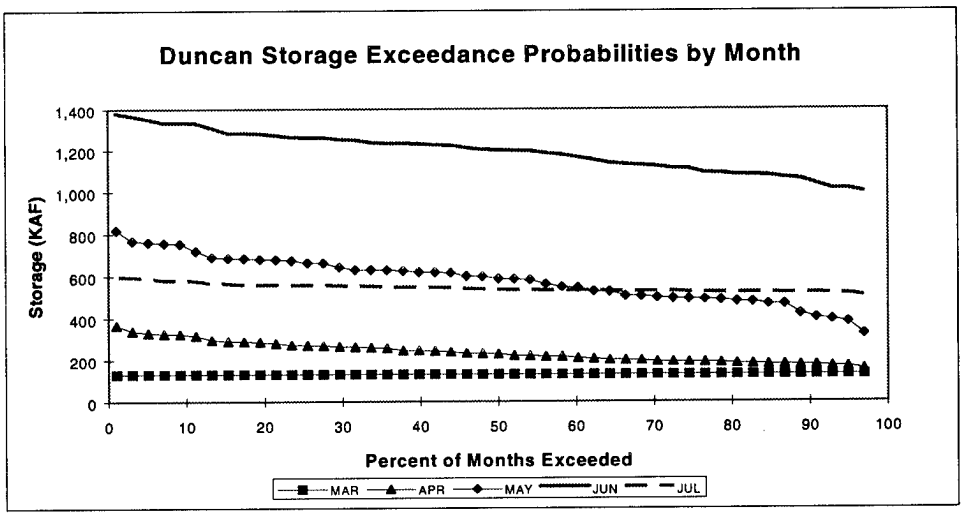


Figure 4.3 Grand Coulee Storage Results for HEC-PRM 1995 Apr-July Study





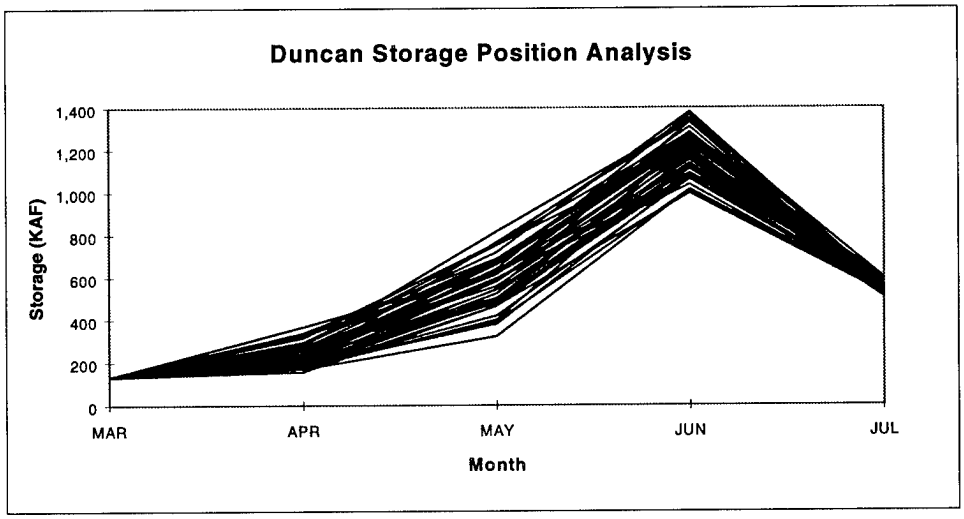
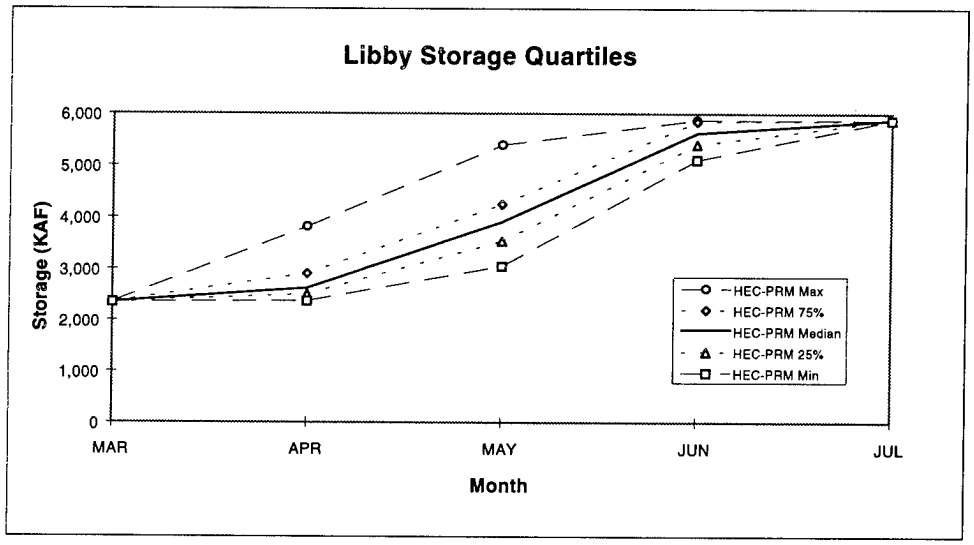
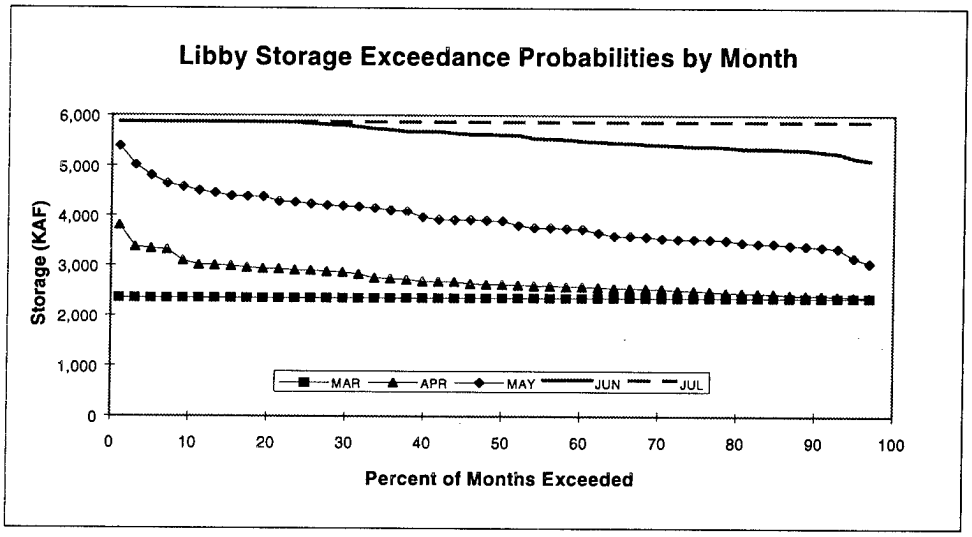


Figure 4.4 Duncan Storage Results for HEC-PRM 1995 Apr-July Study





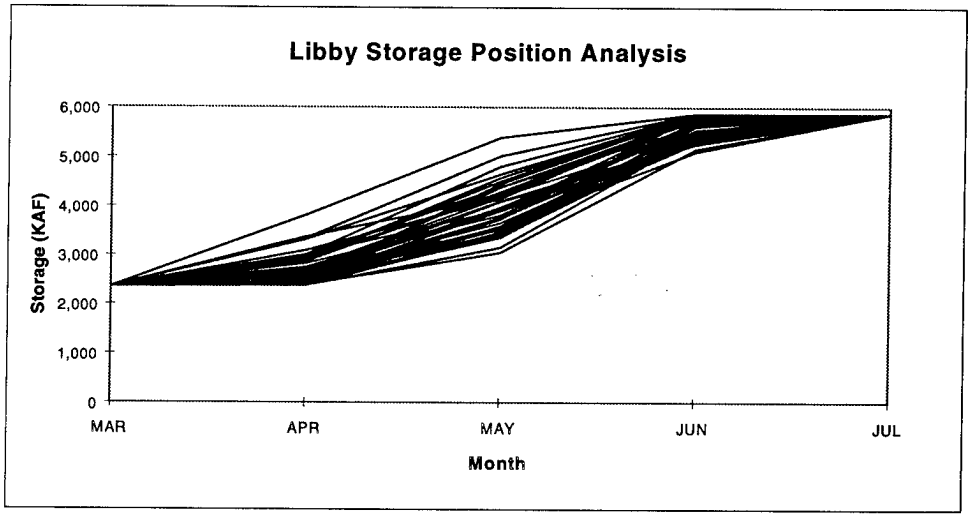
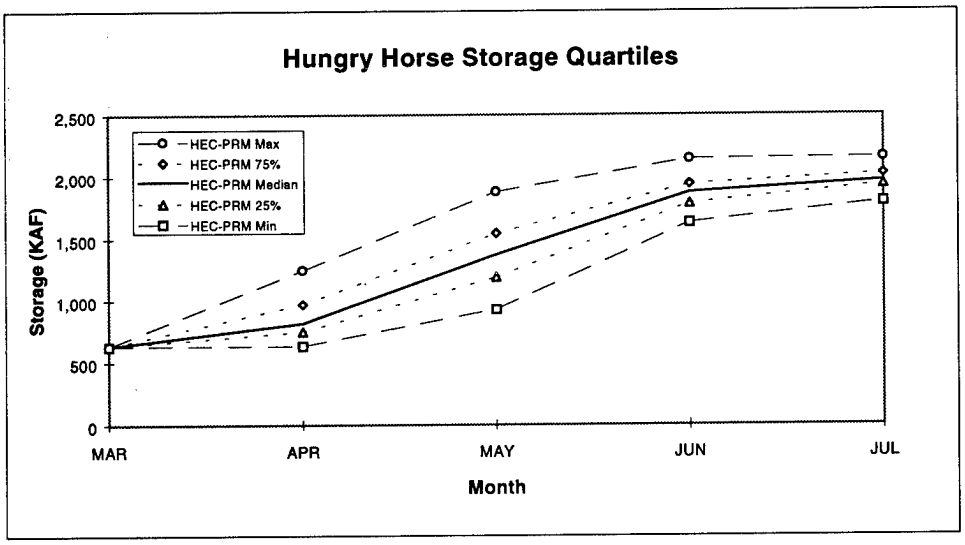
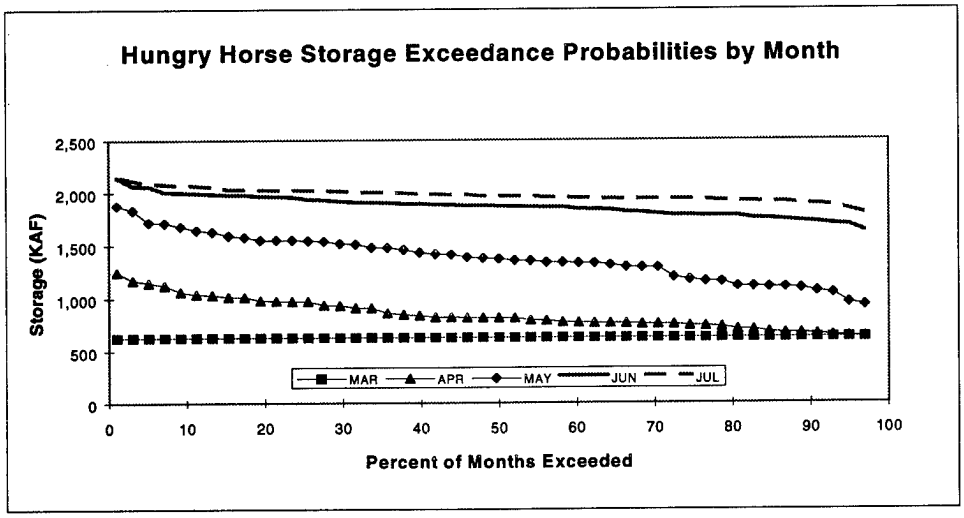


Figure 4.5 Libby Storage Results for HEC-PRM 1995 Apr-July Study





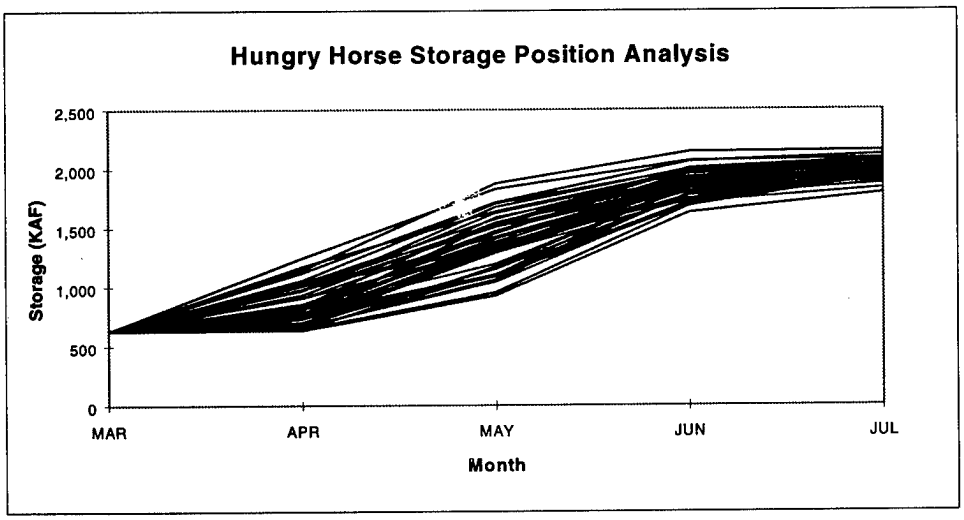
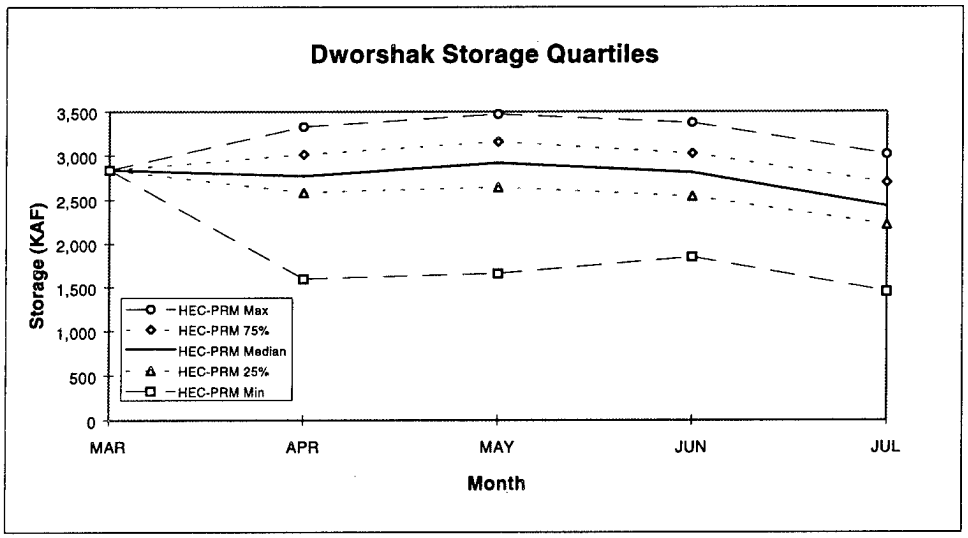
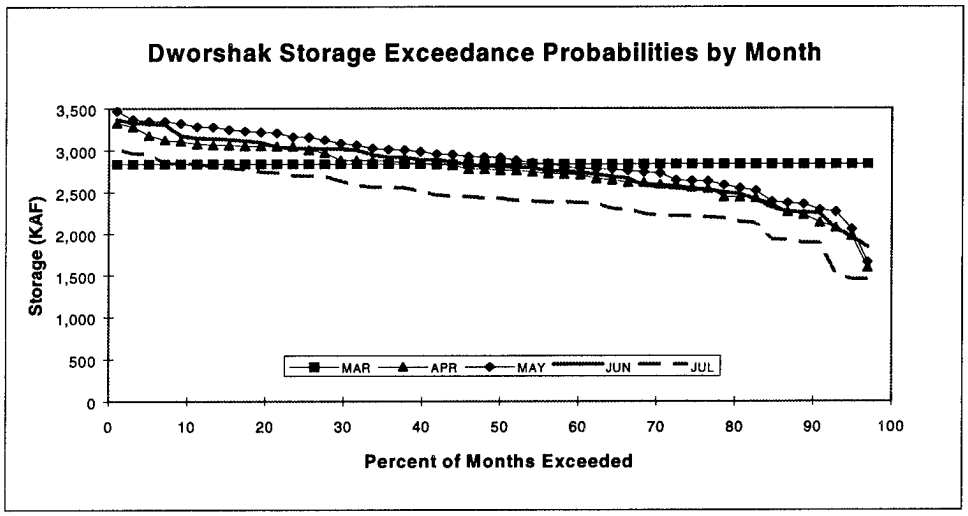


Figure 4.6 Hungry Horse Storage Results for HEC-PRM 1995 Apr-July Study





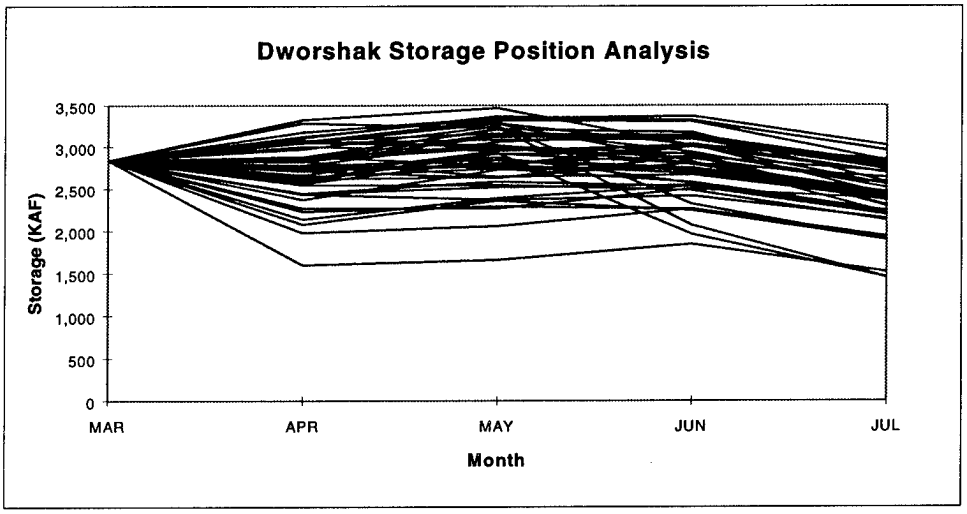


Figure 4.7 Dworshak Storage Results for HEC-PRM 1995 Apr-July Study

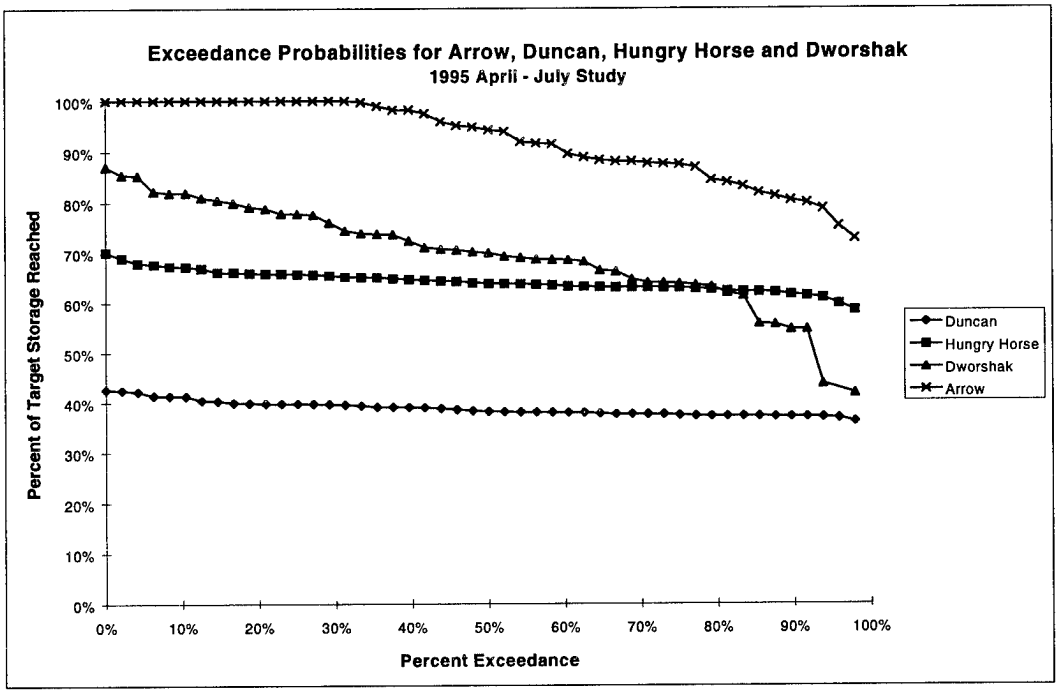


Figure 4.8 Exceedance Probabilities of Percent of Target Storage Reached for Arrow, Duncan, Hungry Horse and Dworshak for 1995 Apr-July Study

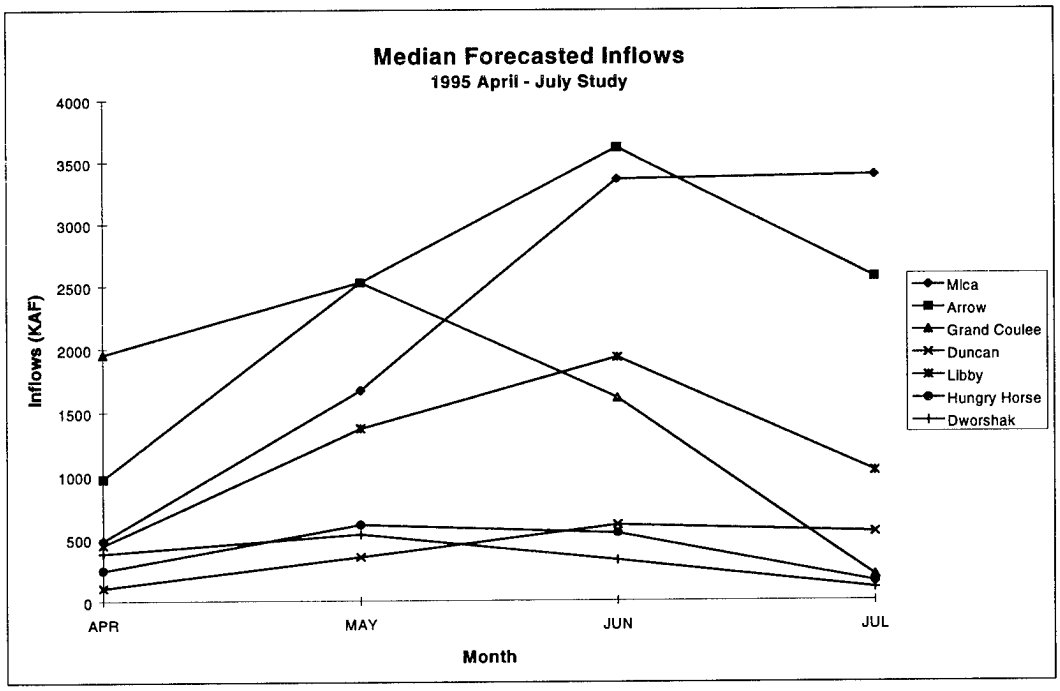


Figure 4.9 Median 1995 Forecasted Inflows for System Reservoirs for HEC-PRM 1995 Apr-July Study

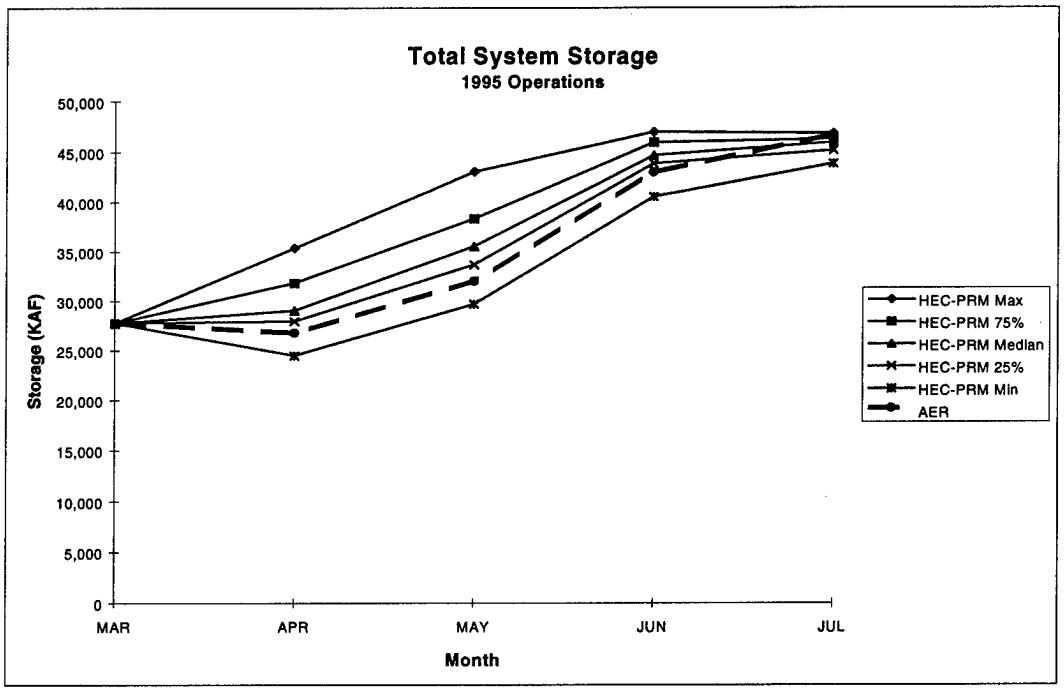


Figure 4.10 Comparison of Total System Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operations

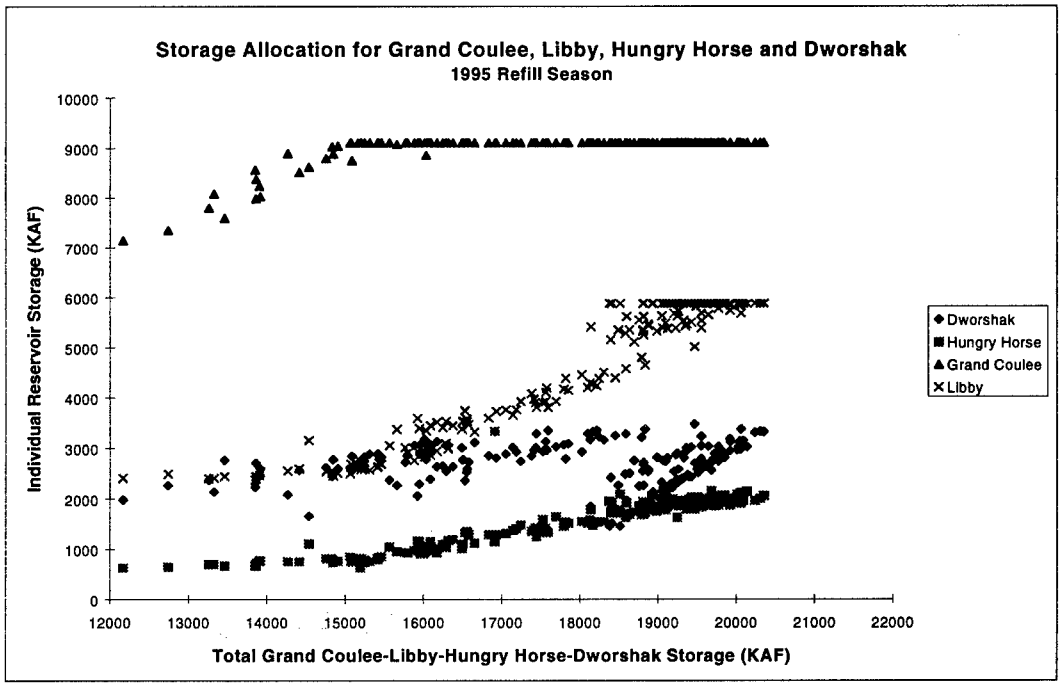


Figure 4.11 Storage Allocation for Grand Coulee, Libby, Hungry Horse and Dworshak for Refill for 1995 Apr-July Study

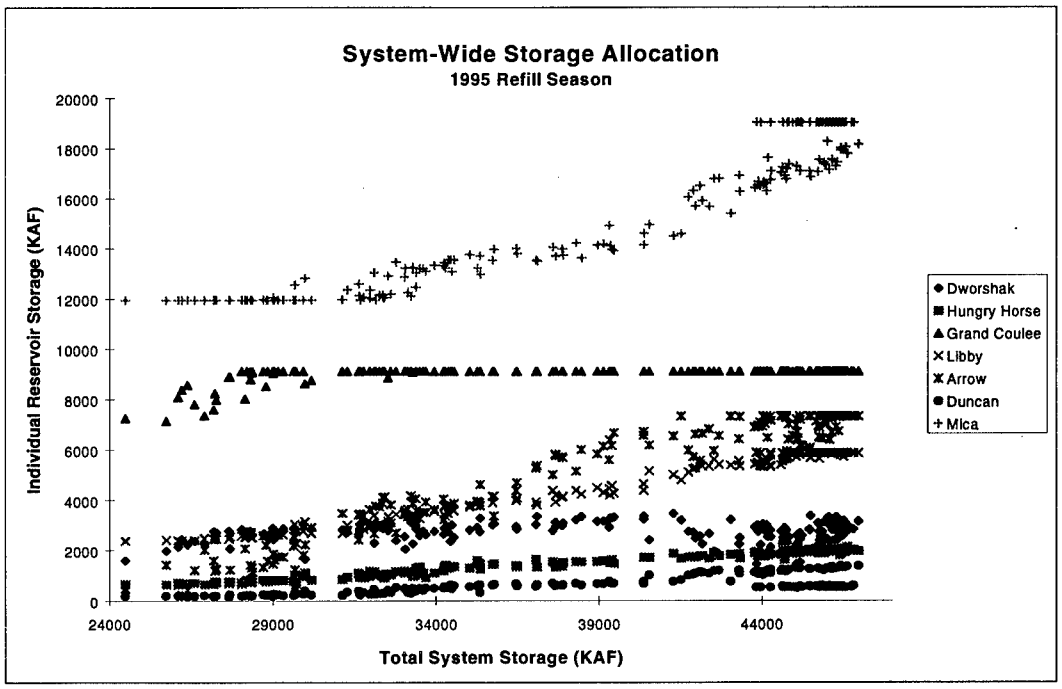


Figure 4.12 System-Wide Storage Allocation for Refill for HEC-PRM 1995 Apr-July Study

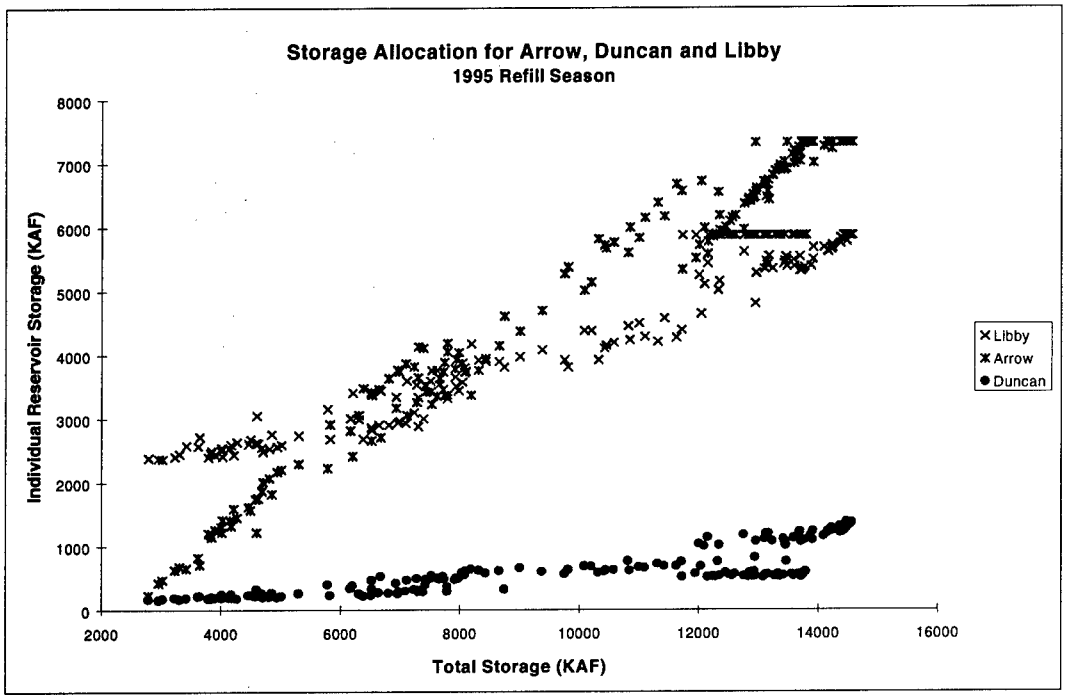


Figure 4.13 Storage Allocation for Arrow, Duncan and Libby for Refill for HEC-PRM 1995 Apr-July Study

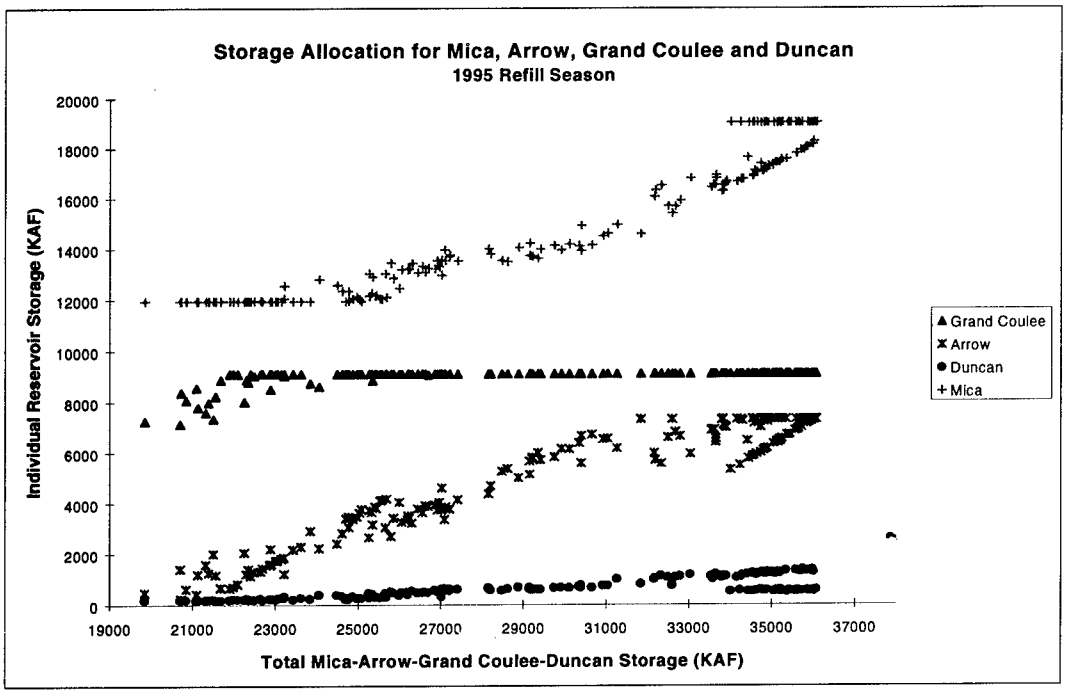


Figure 4.14 Storage Allocation for Mica, Arrow, Grand Coulee and Duncan for Refill for HEC-PRM 1995 Apr-July Study

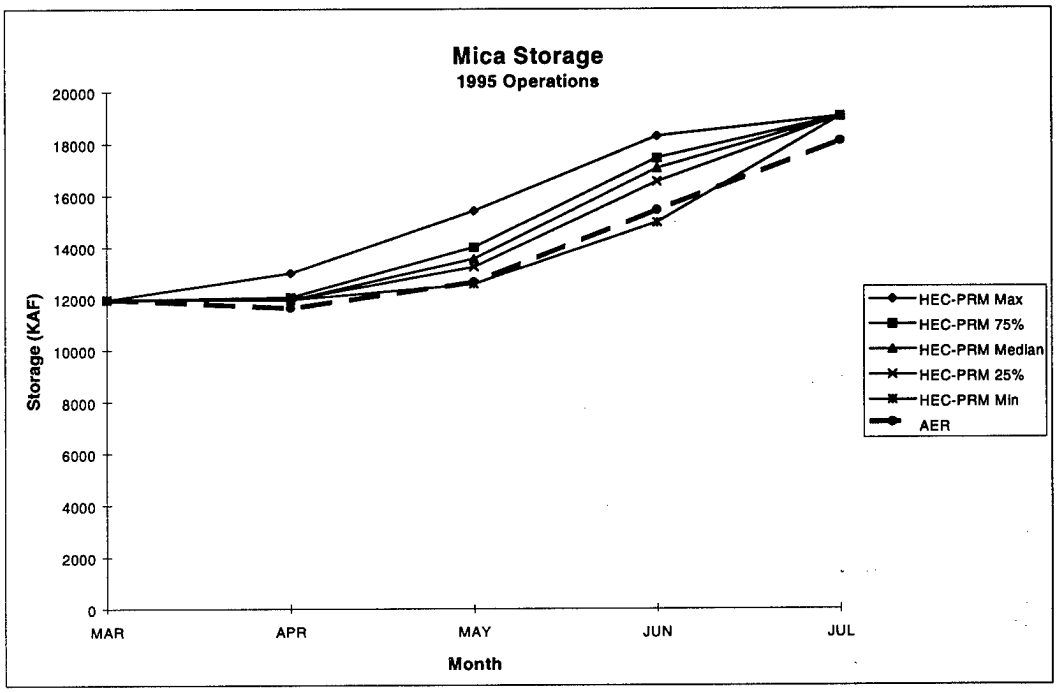


Figure 4.15 Comparison of Mica Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operation

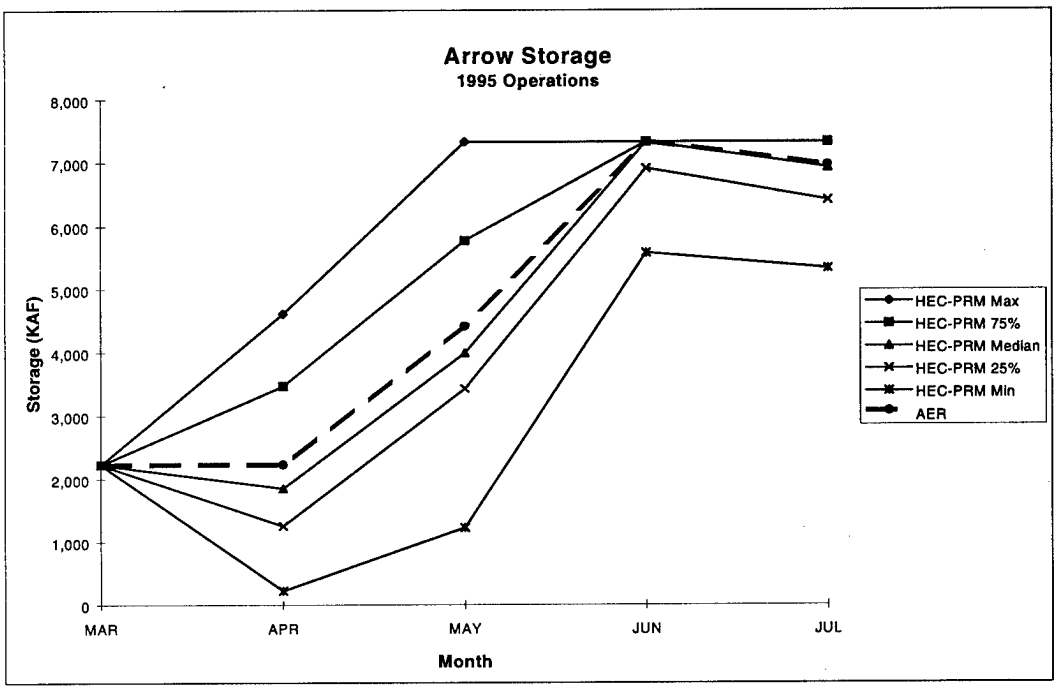


Figure 4.16 Comparison of Arrow Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operation

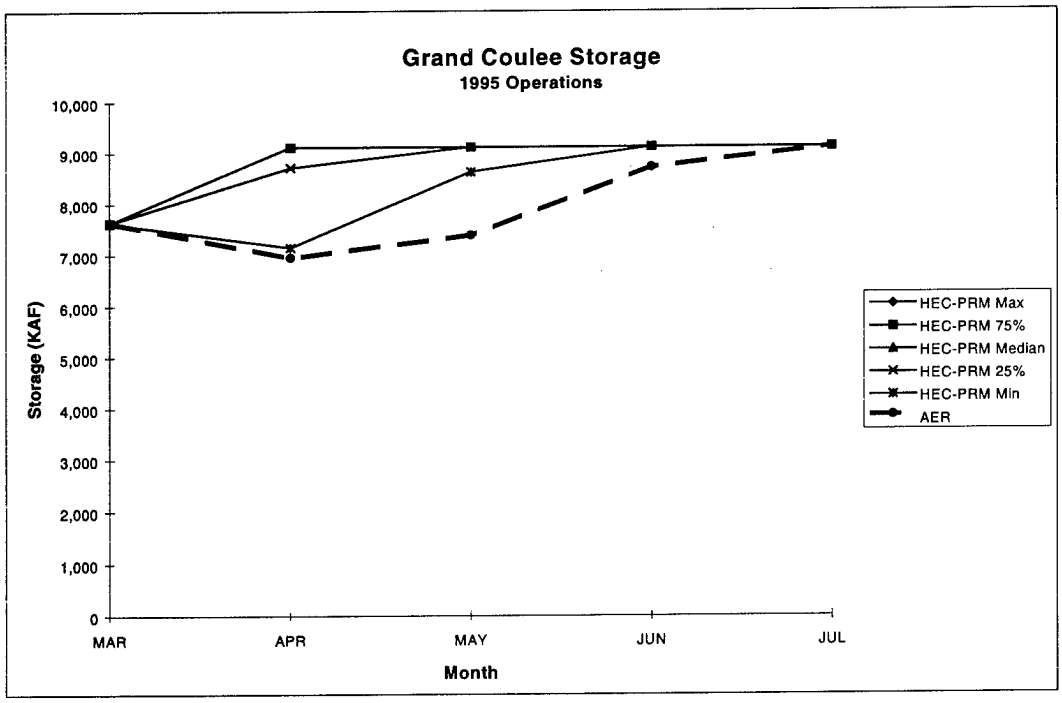


Figure 4.17 Comparison of Grand Coulee Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operation

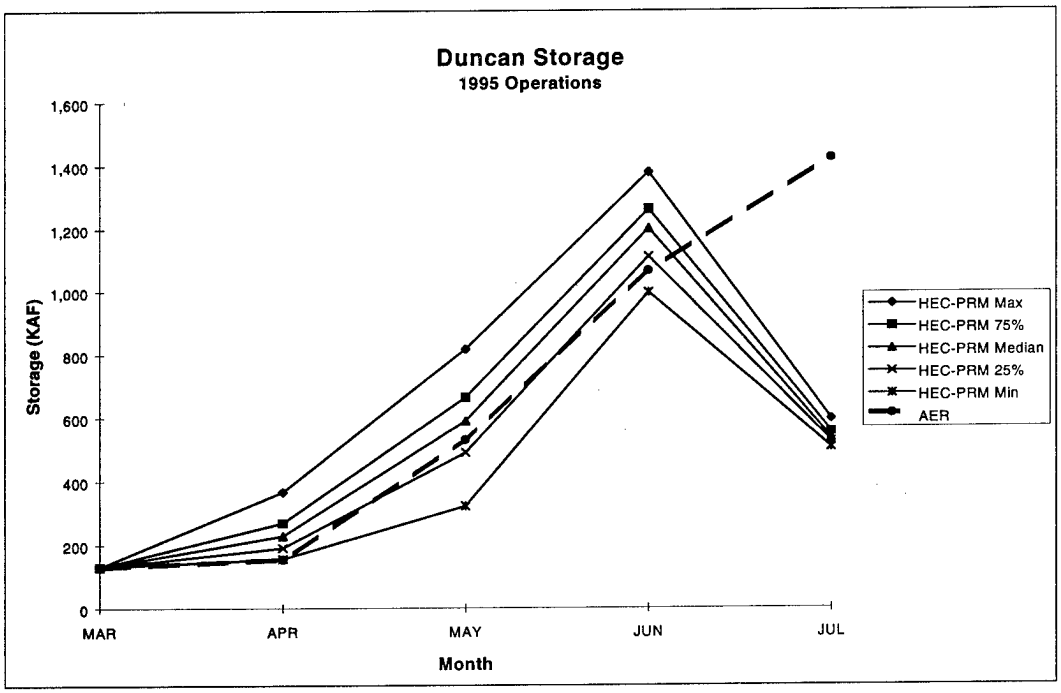


Figure 4.18 Comparison of Duncan Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operation

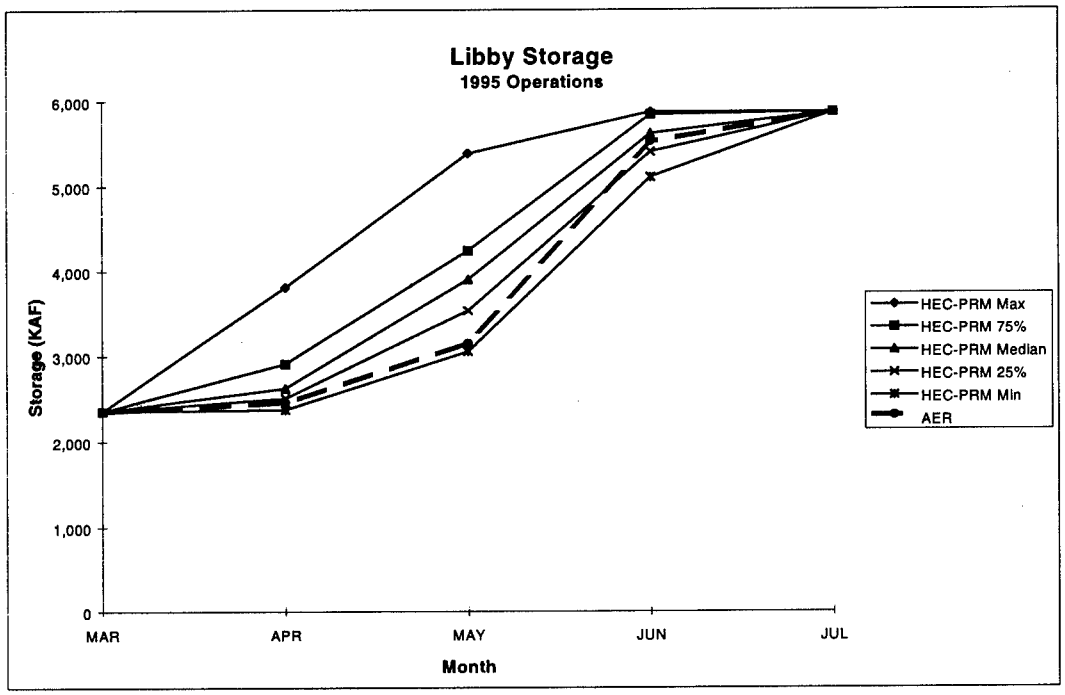


Figure 4.19 Comparison of Libby Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operation

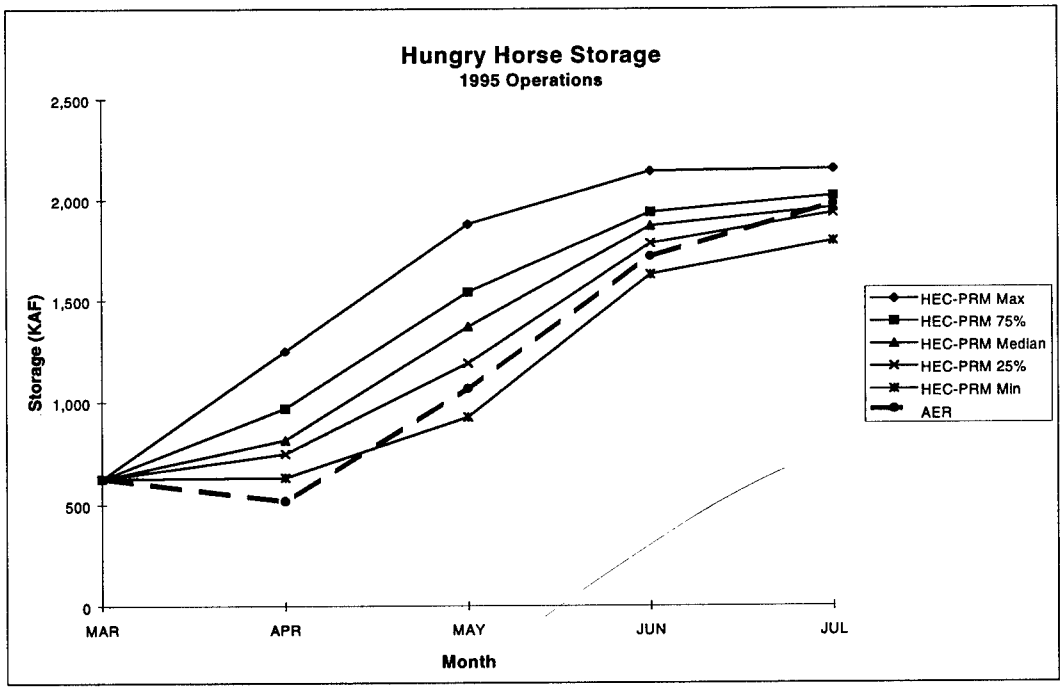


Figure 4.20 Comparison of Hungry Horse Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operation

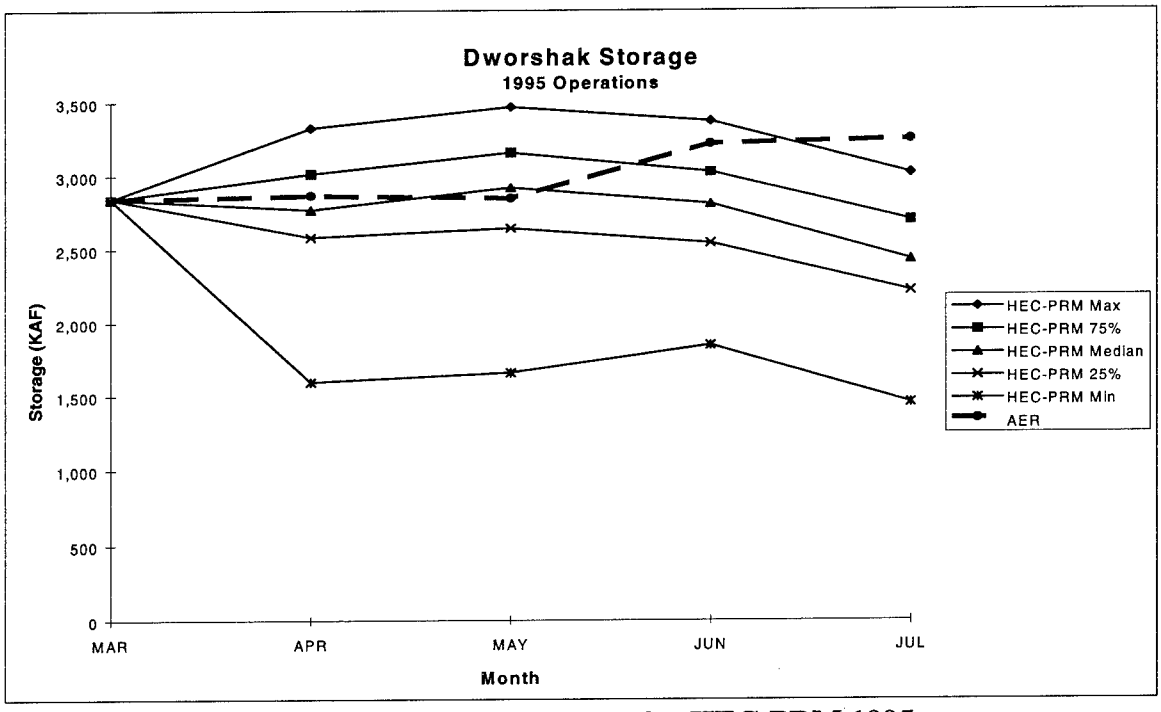


Figure 4.21 Comparison of Dworshak Storage for HEC-PRM 1995 Apr-July Study and 1995 AER Operation

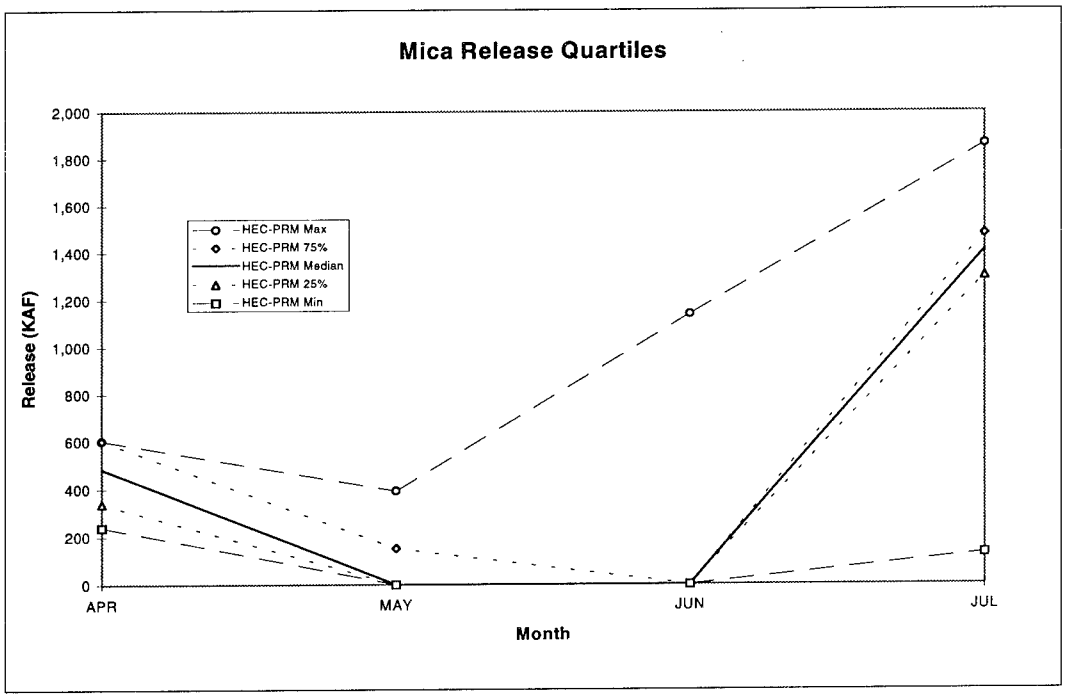


Figure 4.22 Mica Release Quartiles for HEC-PRM 1995 Apr-July Study

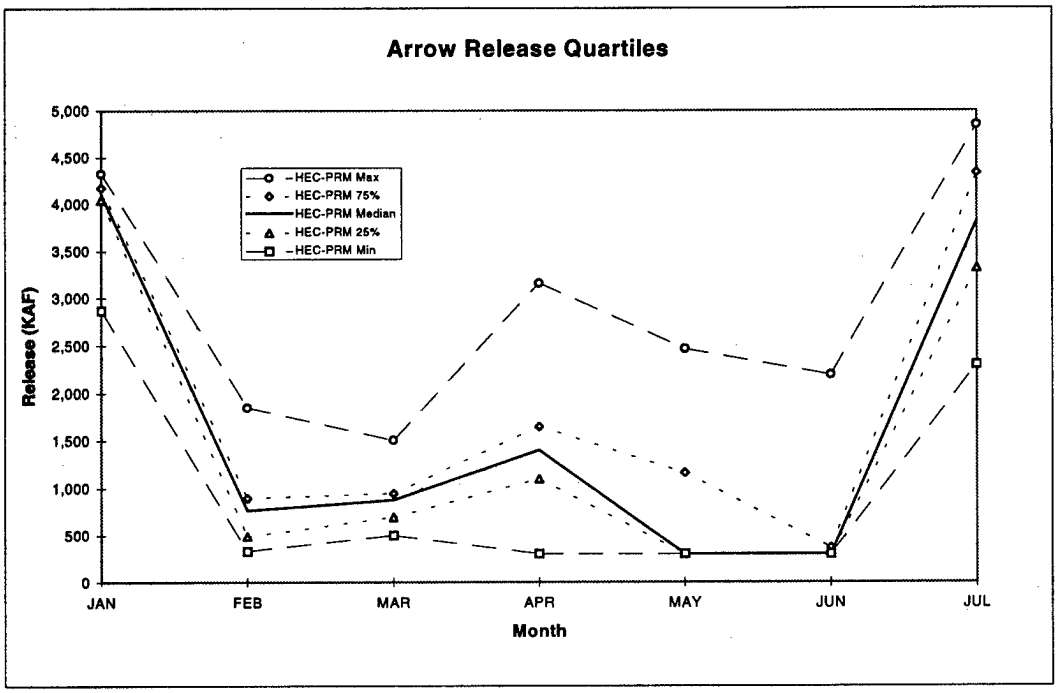


Figure 4.23 Arrow Release Quartiles for HEC-PRM 1995 Jan-July Study

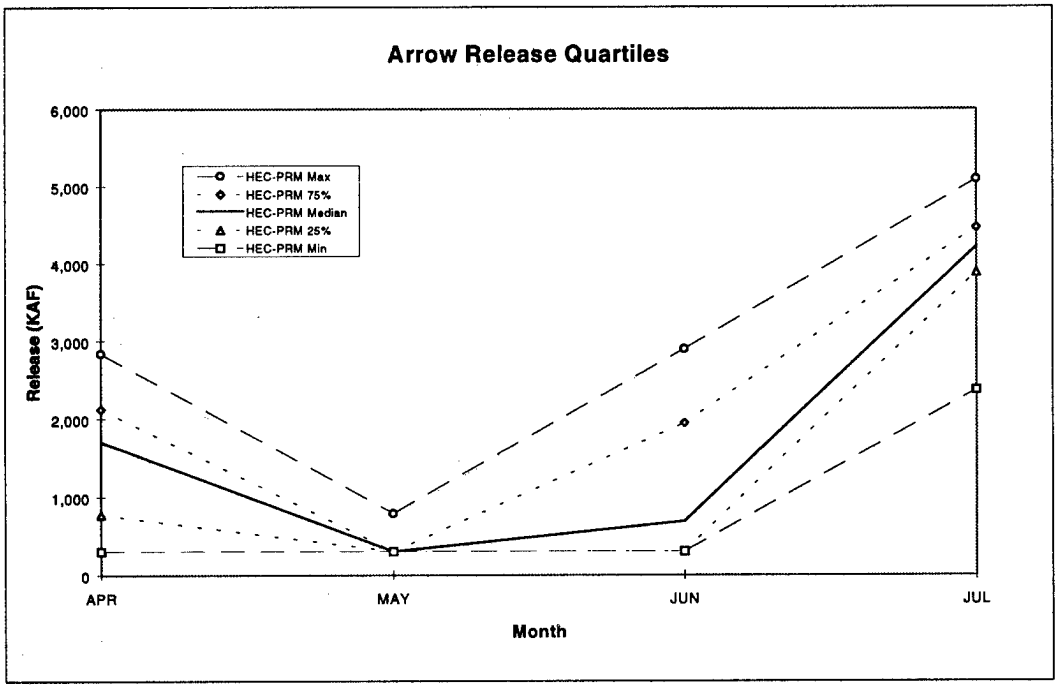


Figure 4.24 Arrow Release Quartiles for HEC-PRM 1995 Apr-July Study

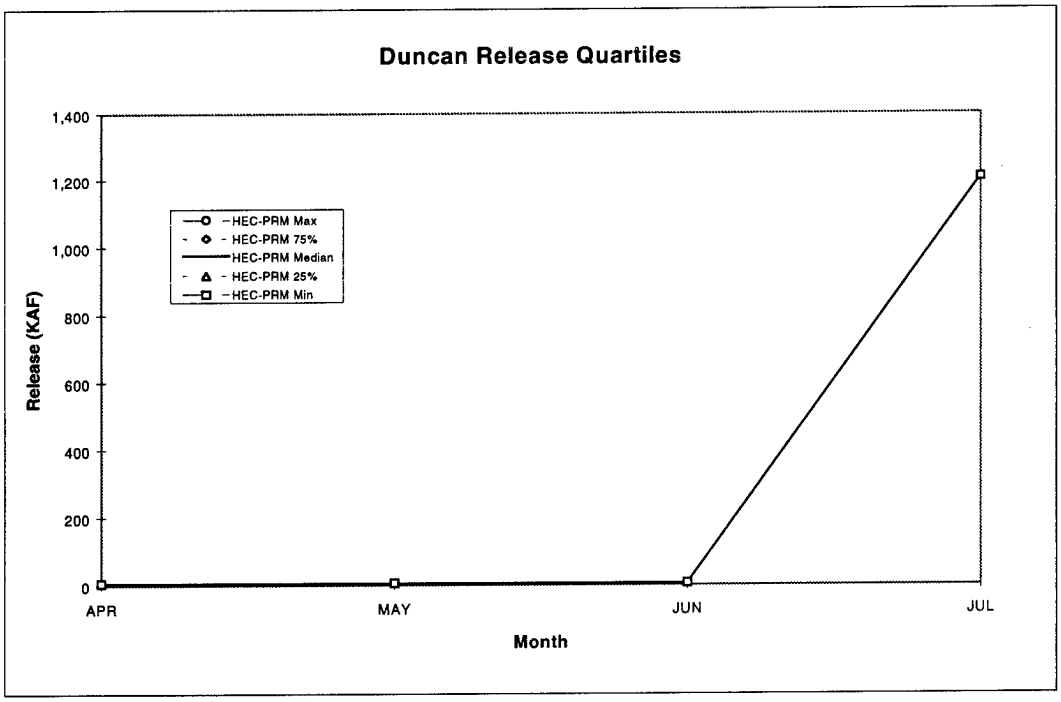


Figure 4.25 Duncan Release Quartiles for HEC-PRM 1995 Apr-July Study

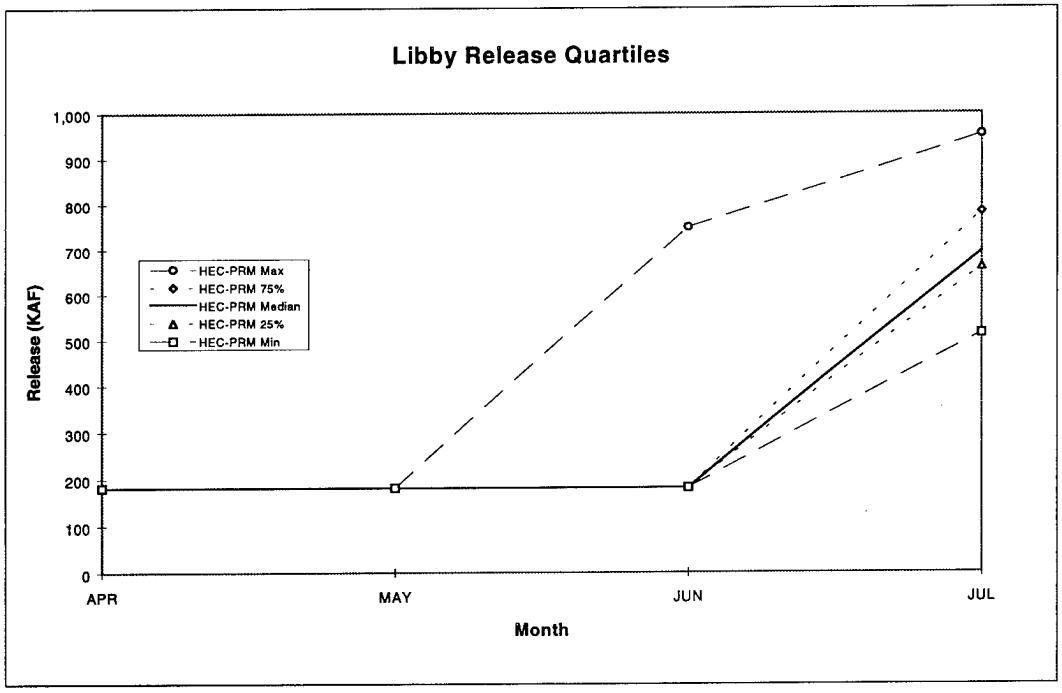


Figure 4.26 Libby Release Quartiles for HEC-PRM 1995 Apr-July Study

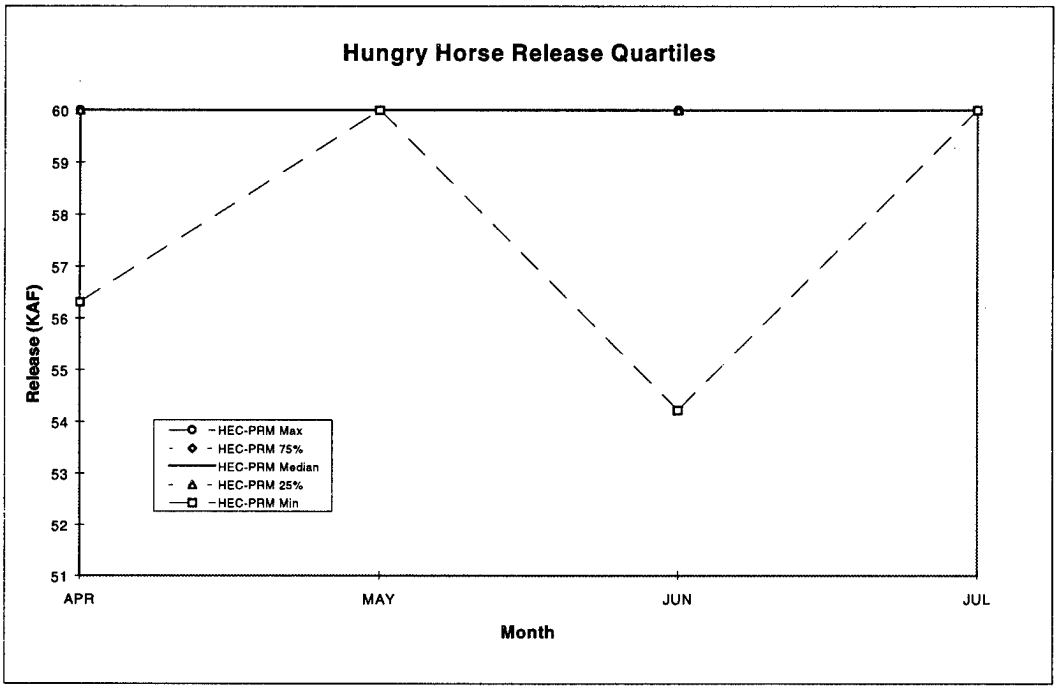


Figure 4.27 Hungry Horse Release Quartiles for HEC-PRM 1995 Apr-July Study

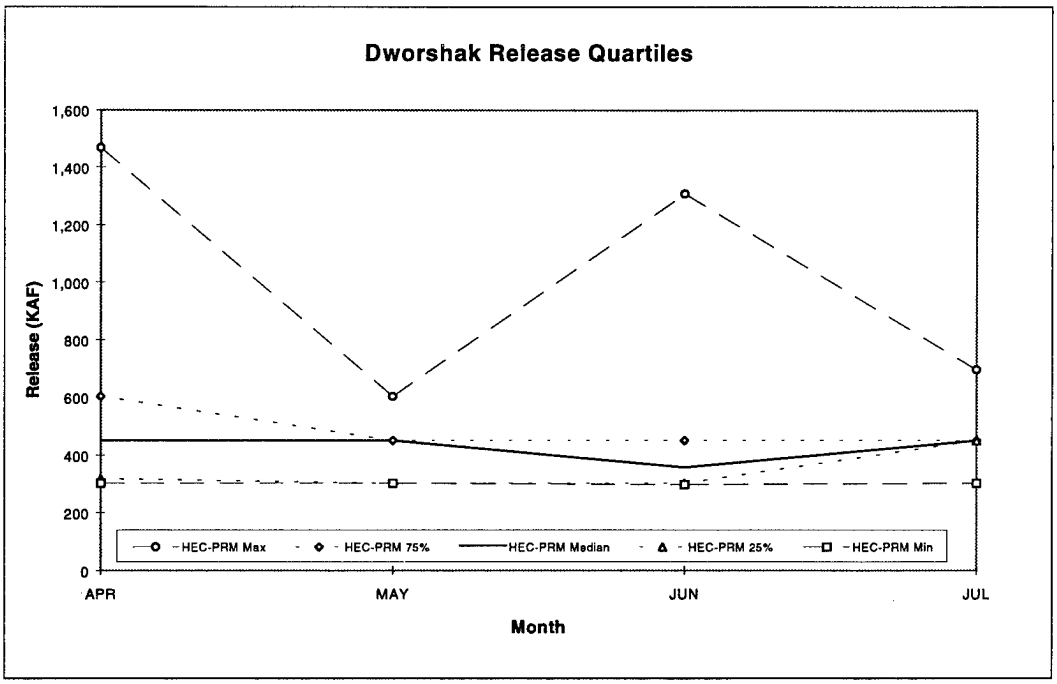


Figure 4.28 Dworshak Release Quartiles for HEC-PRM 1995 Apr-July Study

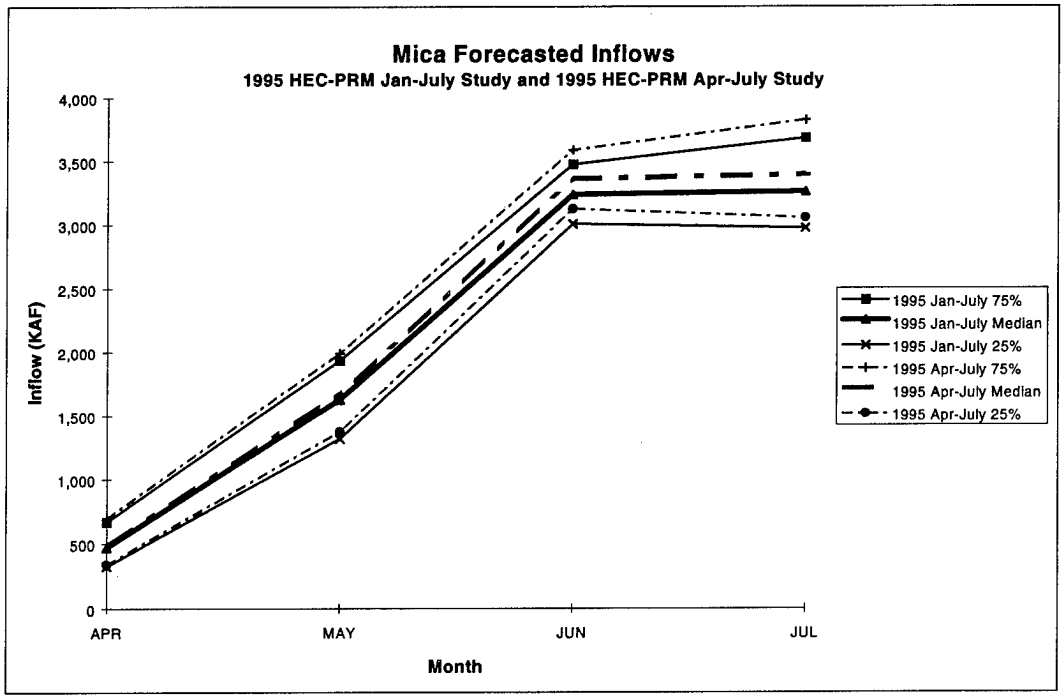


Figure 4.29 Comparison of Mica Forecasted Inflows for 1995 Jan-July Study and 1995 Apr-July Study

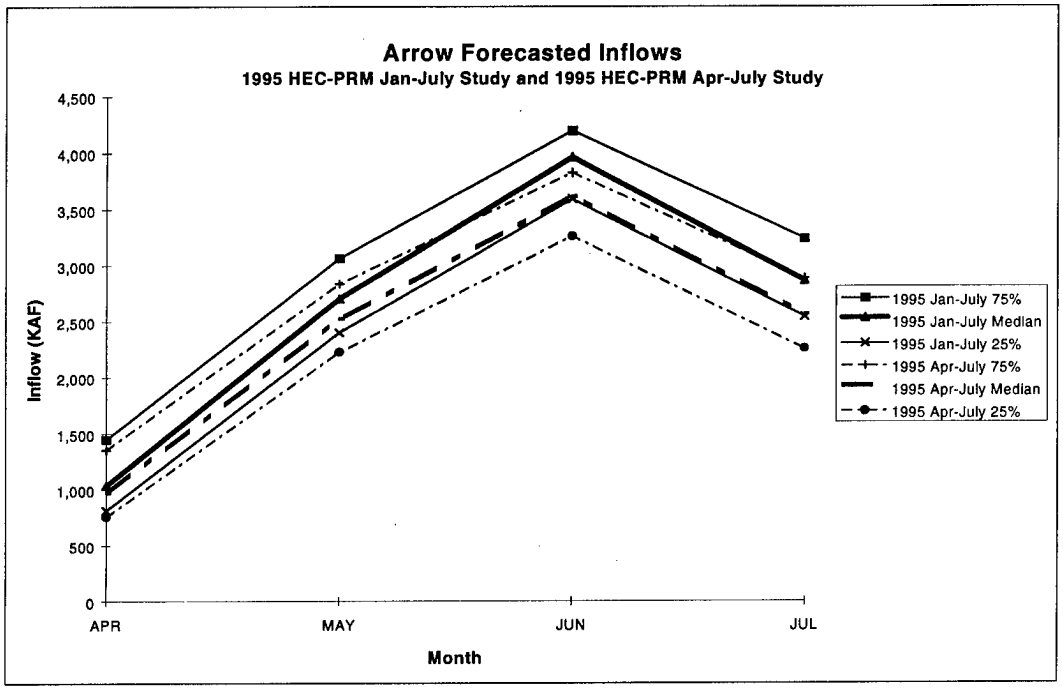


Figure 4.30 Comparison of Arrow Forecasted Inflows for 1995 Jan-July Study and 1995 Apr-July Study

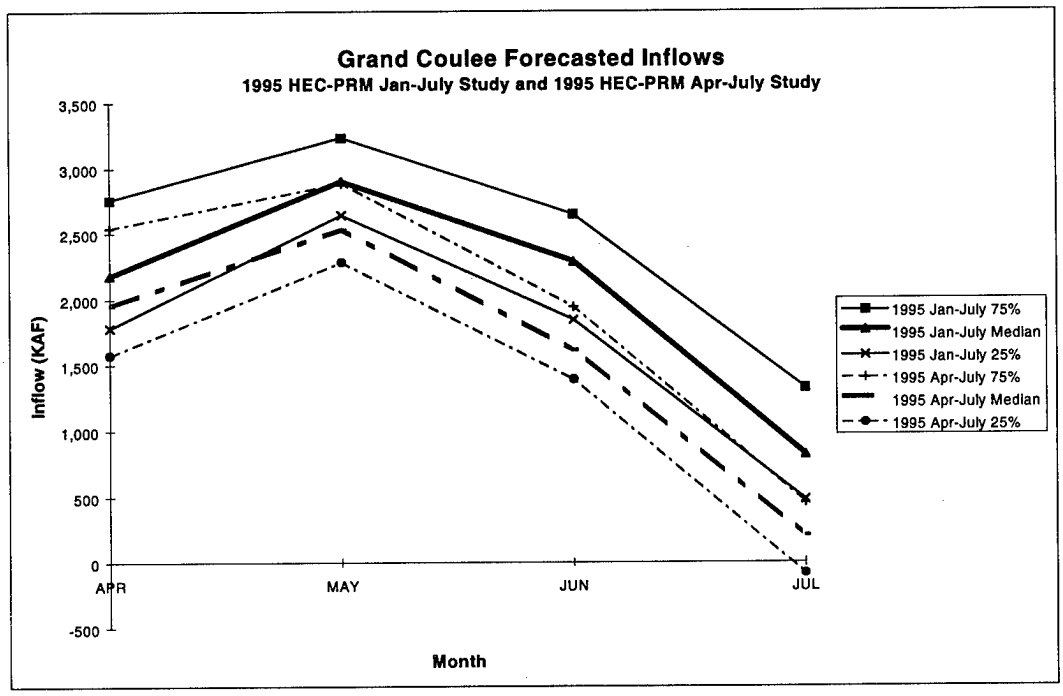


Figure 4.31 Comparison of Grand Coulee Forecasted Inflows for 1995 Jan-July Study and 1995 Apr-July Study

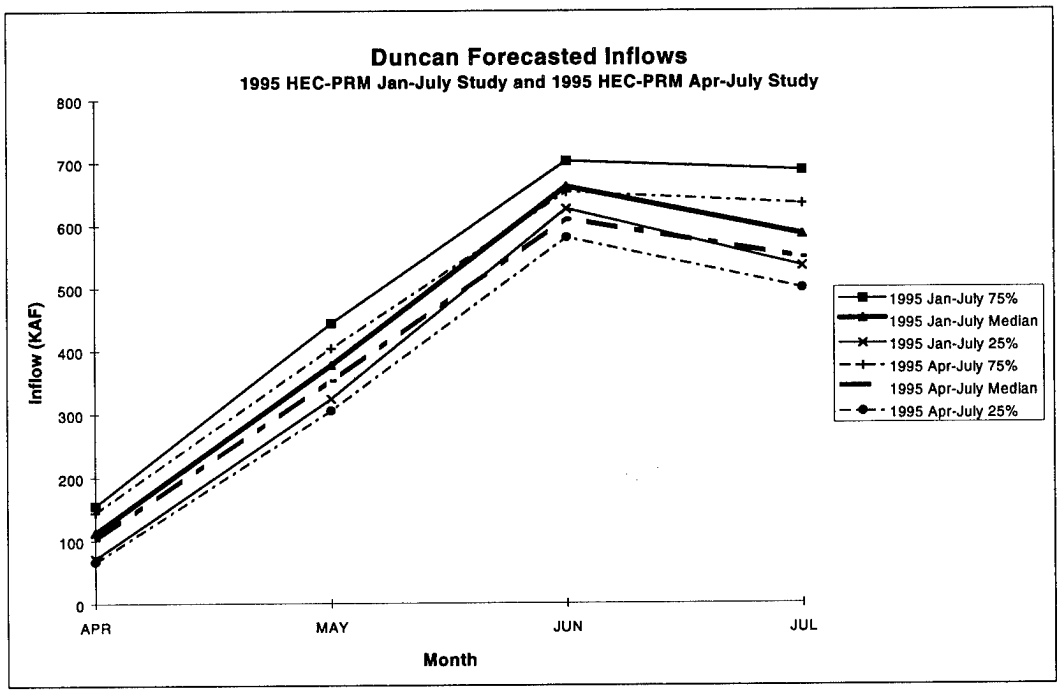


Figure 4.32 Comparison of Duncan Forecasted Inflows for 1995 Jan-July Study and 1995 Apr-July Study

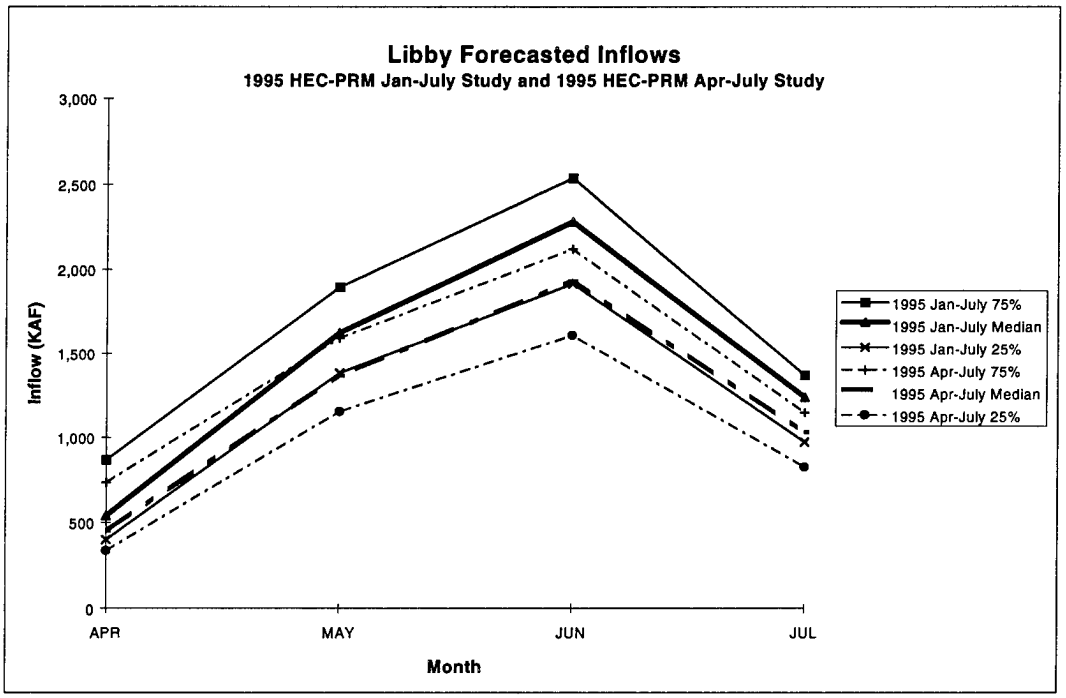


Figure 4.33 Comparison of Libby Forecasted Inflows for 1995 Jan-July Study and 1995 Apr-July Study

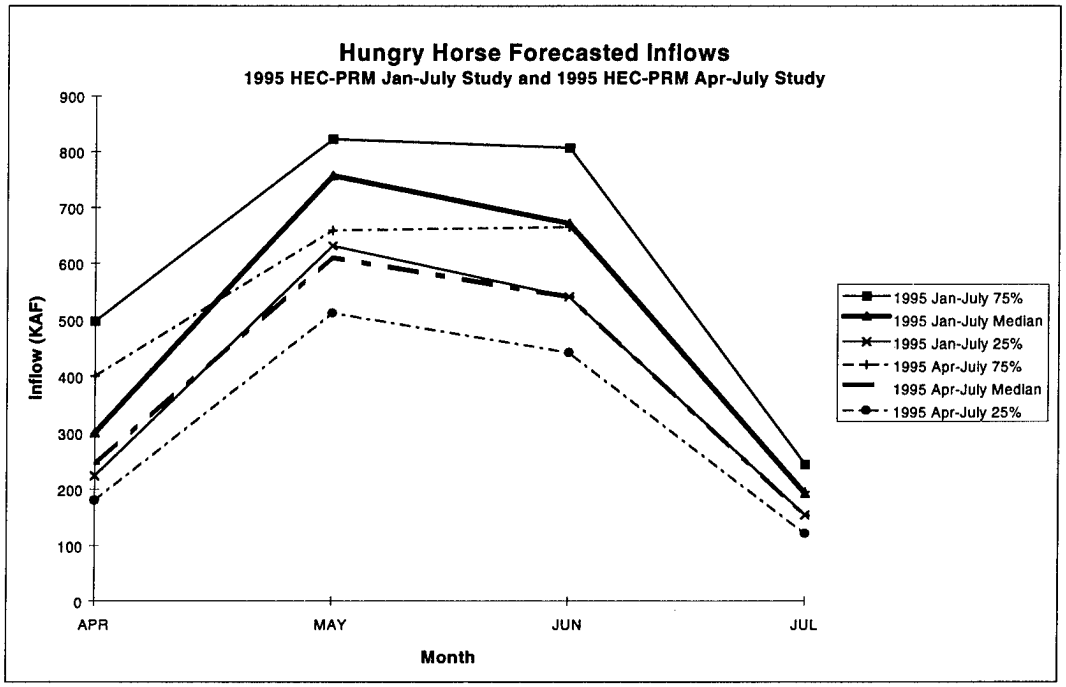


Figure 4.34 Comparison of Hungry Horse Forecasted Inflows for 1995 Jan-July Study and 1995 Apr-July Study

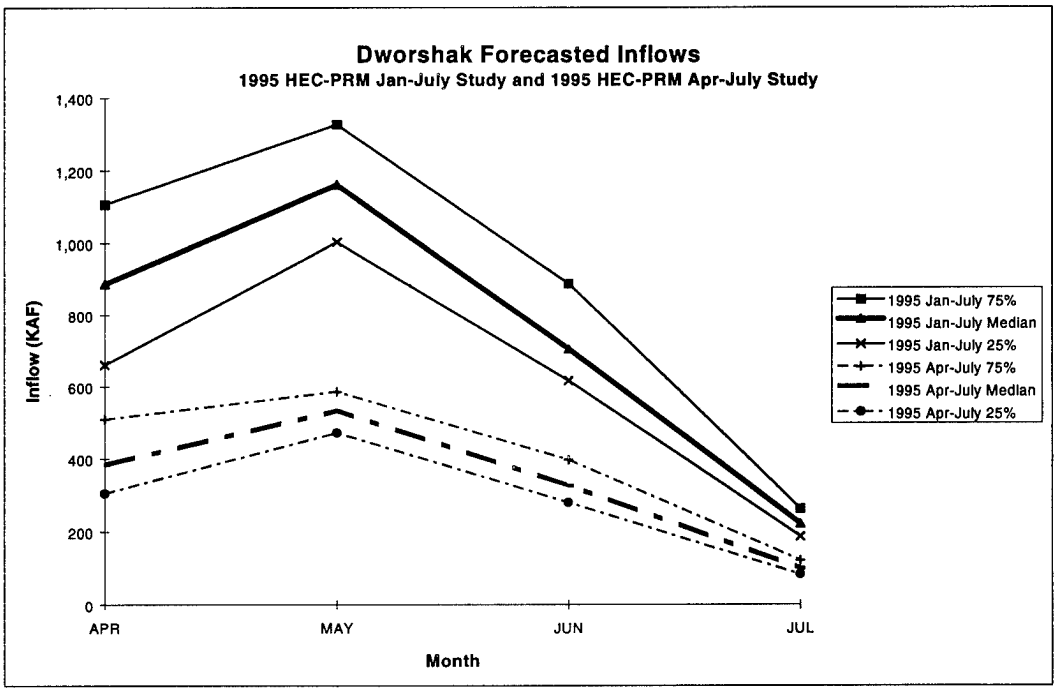


Figure 4.35 Comparison of Dworshak Forecasted Inflows for 1995 Jan-July Study and 1995 Apr-July Study

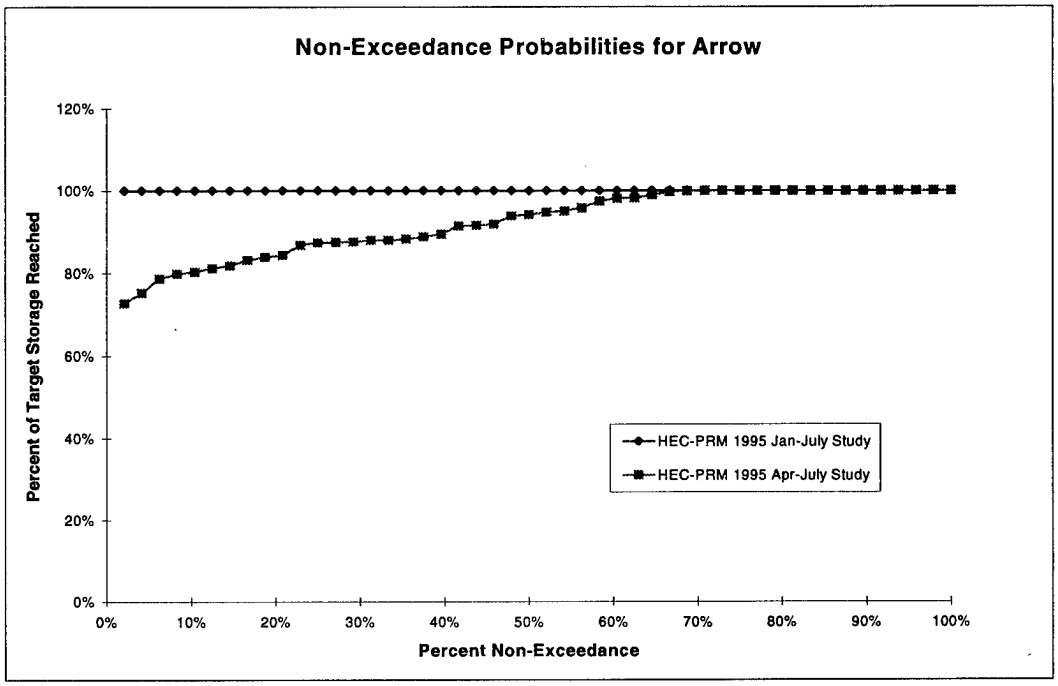


Figure 4.36 Comparison of Non-Exceedance Probabilities of Percent of Target Storage Reached for Arrow

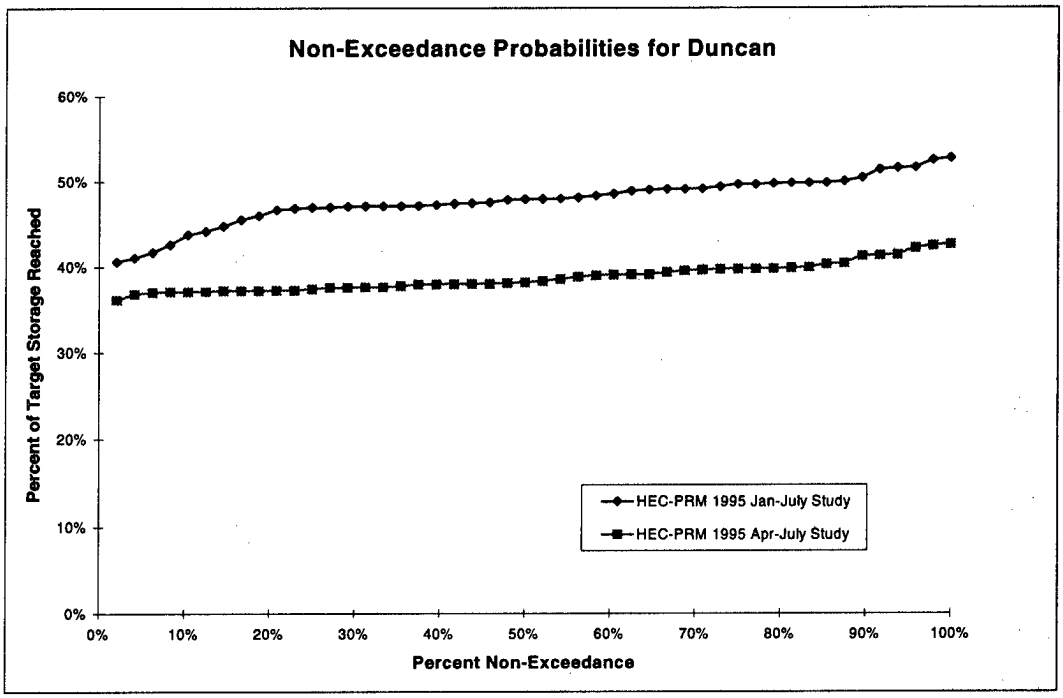


Figure 4.37 Comparison of Non-Exceedance Probabilities of Percent of Target Storage Reached for Duncan

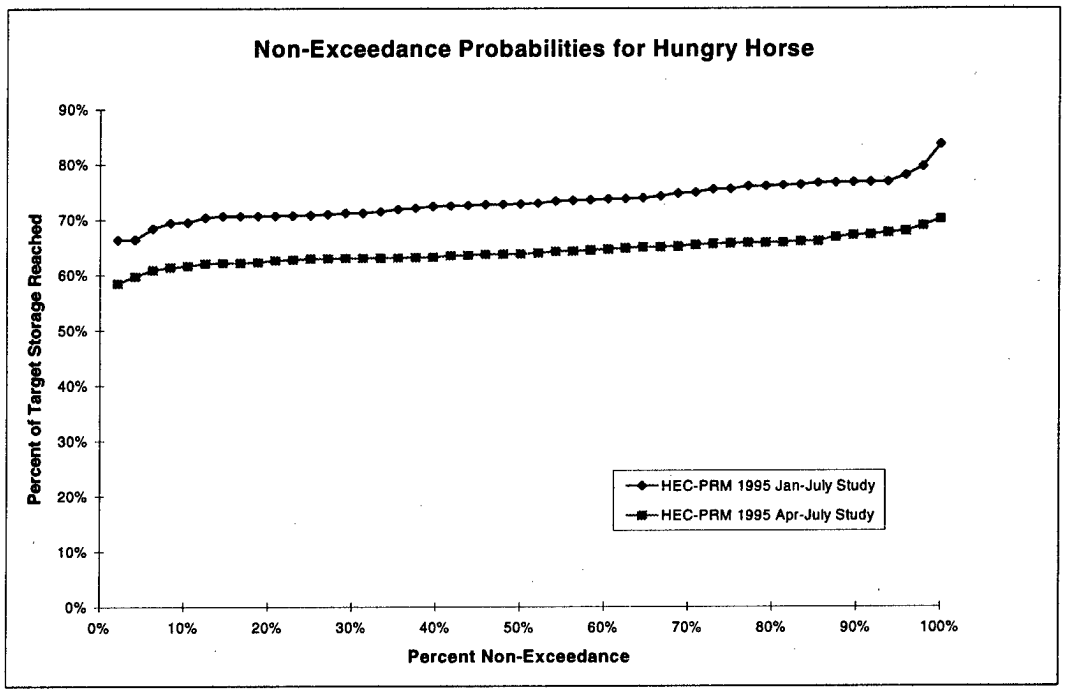


Figure 4.38 Comparison of Non-Exceedance Probabilities of Percent of Target Storage Reached for Hungry Horse

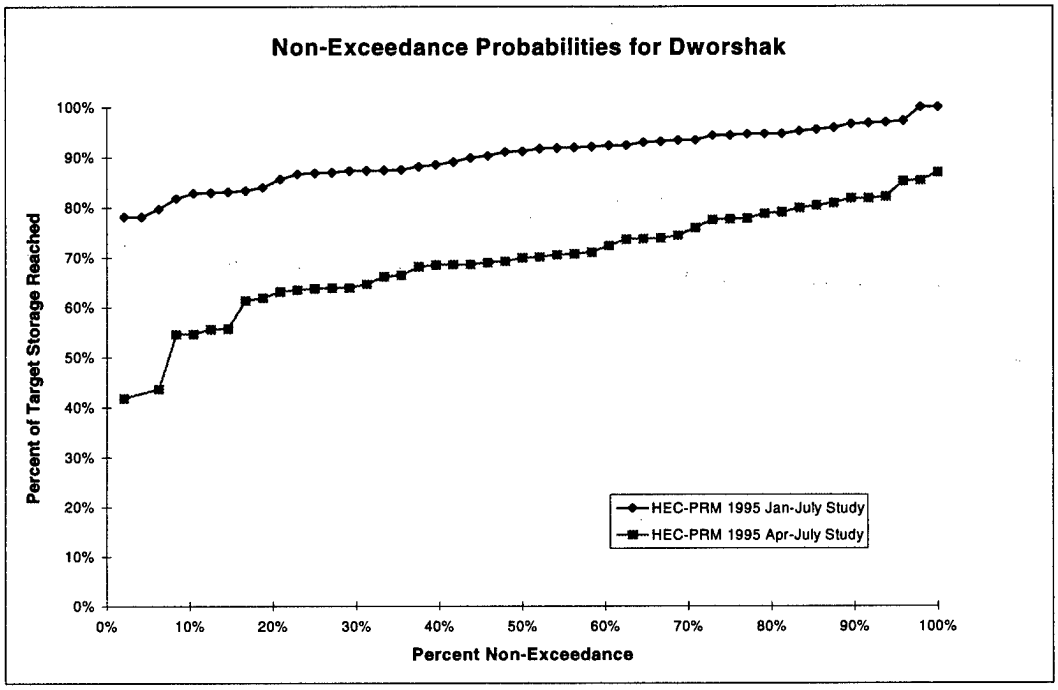


Figure 4.39 Comparison of Non-Exceedance Probabilities of Percent of Target Storage Reached for Dworshak

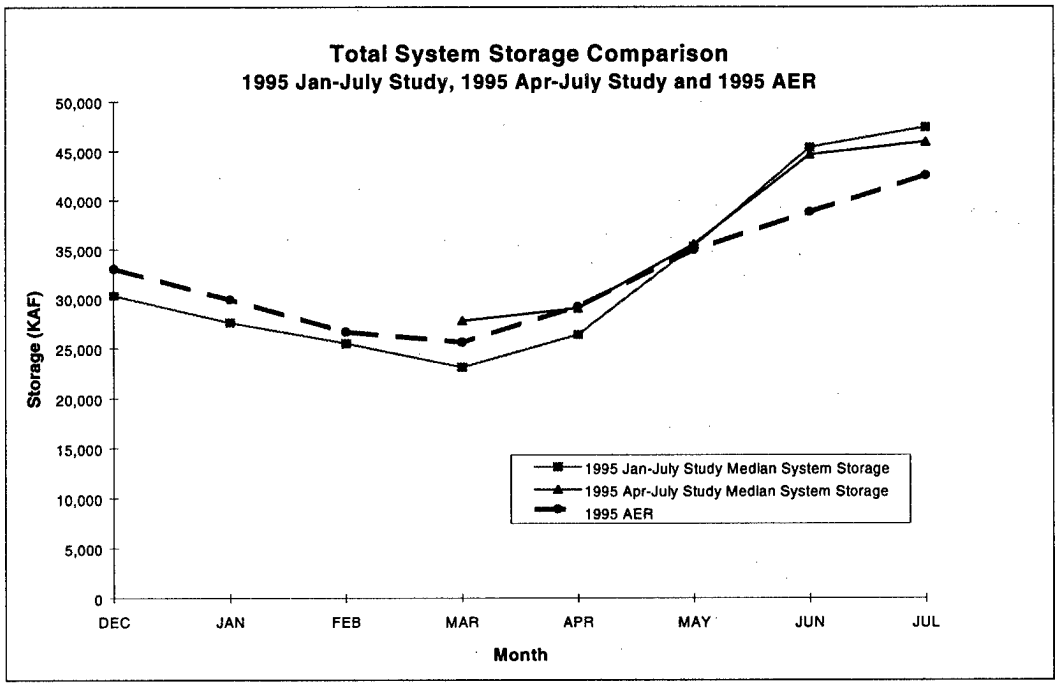


Figure 4.40 Comparison of Total System Storage for 1995 Jan-July Study, 1995 Apr-July Study and 1995 AER Operation

Chapter 5

1994 January - July Season Study

Chapter 5 discusses the 1994 January - July study and compares the results to the 1995 January - July study. There are two main sections to this chapter. Section 1 discusses the probability of reservoir refill in July 1994, HEC-PRM system-wide operations, and HEC-PRM's comparison to the AER operation. In addition, HEC-PRM near-term advice is presented for the system as a whole and for each reservoir individually. Section 2 describes the comparison of the drier 1994 January - July study with the 1995 January - July study.

5.1 The 1994 January - July Season Study

The 1994 January - July study focuses on two of the three operation seasons of the Columbia River System, the variable drawdown season (January-March) and the refill season (April-July). The initial storage conditions and the inflow sequences used for this study are described. The probability of refilling the seven storage reservoirs, Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak, in July is discussed. HEC-PRM's system-wide operations are given and the near-term HEC-PRM results are compared with the AER operation. The near-term HEC-PRM advice is presented also.

5.1.1 Initial Storage and Forecasted Inflows

January Initial Storage Values

The initial storage values given for January 1, 1994 are Actual Energy Regulation (AER) values. These AER storage values define the legal drafting limit, or the proportional drafting limit, for the reservoirs. AER operations permit non-firm energy production in a wet year, or satisfy firm energy production in dry years. The initial storage for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs for the 1994 January - July study are given in Table 5.1.

Forecasted and Historical Inflows

Forty-nine years of inflow sequences, from 1929 to 1977, are used for the 1994 January - July study. Forecasted inflows are available for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs. January inflow forecasts are used to modify the

Table 5.1 January 1, 1994 Initial Storages (AER Values)

Reservoir	January 1 Initial Storage (KAF)
Mica	14304
Arrow	5065
Grand Coulee	8532
Duncan	24
Libby	2427
Hungry Horse	871
Dworshak	1805

historical inflows whenever available. For the inflow points where forecasts are not available, the historical inflows are used.

The 1994 water year was a dry year. The forecasted inflows are smaller in 1994 than 1995 (Figures 5.1 - 5.7). The observed inflows were less in 1994 than the 1995 inflows, evident by the smaller observed system refill in 1994 than 1995 system storage (Figure 5.8). The precipitation amounts decreased in 1994 as a result of El Nino conditions in the Pacific Northwest (Columbia River Water Management Group (CRWMG), 1994). The precipitation in January, March and July 1994 was below normal. April, May and June 1994 precipitation was normal, but the dry season was already established and temperatures were high enough during this period to prevent the development of large amounts of snowpack.

5.1.2 Probability of Refill in 1994

HEC-PRM's probability of refill is important because the Columbia River System operation is driven to meet refill targets in July. HEC-PRM advice is valuable when HEC-PRM operates the reservoirs to reach their refill target levels. The probability of refill is discussed for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs.

The July targets for the reservoirs are the same target storages used in the 1995 January - July and the 1995 April - July studies. These target levels are the median storage results from a past HYSSR study (USACE, 1995). These refill targets are listed with the HEC-PRM probability of refill, median HEC-PRM July storage and AER July storage in Table 5.2. Mica and Grand Coulee reservoirs are the only reservoirs which always reached their target storage (Figures 5.9 - 5.15).

Arrow, Libby and Dworshak are all within 80% of their target storage (Figure 5.16). Libby reservoir reaches the target storage for 96% of the years. Arrow meets the target storage

for 55% of the inflow sequences. Dworshak reservoir only reaches its target once, but ~6% of the HEC-PRM results are within 5% of the target storage and the remainder do not fall below 80% of the target storage.

Hungry Horse typically stores about 60% of its target storage in July . Duncan's July storage is the farthest away from its goal. Except for one year where Duncan reaches its July target, Duncan stores approximately 33% of its storage goal.

Duncan reservoir typically draws down in July rather than meet its target (Figure 5.12). As a result, Duncan supplies water downstream for system-wide benefit and allows other reservoirs with higher energy content to store water. Hungry Horse reservoir's failure to meet its target storage could be caused by its low initial storage (Figure 5.14).

Table 5.2 July 1994 Target Storage Analysis for 1994 January - July Study

Reservoir	July 1994 Target Storage (KAF)	Percentage of Years Target Storage Met (%)	July 1995 Median HEC-PRM Storage (KAF)	July 1995 AER Storage (KAF)
Mica	19045	100	19045	18028
Arrow	7327	55	7327 (Max)	6219
Grand Coulee	9107	100	9107 (Max)	8855
Duncan	1399	2	460	513
Libby	5869	96	5869 (Max)	5202
Hungry Horse	3072	0	2200	1524
Dworshak	3468	2	2130	2204

Though Arrow and Libby do not reach their target storage for all 49 years, their results are encouraging. Libby reservoir is very close to refilling for all the inflow years; only twice did Libby reservoir not reach the target (Figure 5.16). Arrow reservoir reached its target of 7327KAF for 27 of the 49 inflow sequences (Figure 5.16). With less water available in the system, HEC-PRM is unable to operate many of the reservoirs at their targets in July and must choose the reservoirs in the system which should refill. HEC-PRM suggests that Mica and Grand Coulee reservoirs always refill in July.

5.1.3 HEC-PRM System Operations for 1994 January - July Study

1994 Variable Drawdown Period

Both HEC-PRM and AER operations draw down the system in the 1994 variable drawdown season (Figure 5.17). Typically, the lowest system storage levels for both the HEC-PRM results and AER operation are in March. The AER storage closely match the median HEC-PRM storage curve throughout the 1994 variable drawdown period.

Given the basic knowledge that HEC-PRM draws down the system in January, February and March, the storage allocation plots are useful to suggest the order of individual reservoir drawdown. The storage allocation plots graphically display the individual reservoir storage results versus the total reservoir system storage. Storage allocation plots should be read from one side of the graph to the other. For example, for the 1994 variable drawdown storage allocation plots, analyze the order of drawdown from the greatest total system storage on the right straight through to the smallest system storage on the left. As the total system storage decreases, one can discover the HEC-PRM drawdown order and magnitude of each individual reservoir.

For demonstration purposes, study the HEC-PRM storage allocation for Arrow, Duncan and Libby reservoirs in the 1994 variable drawdown season (Figure 5.18). Starting the analysis from the largest total system storage value on the right, Arrow draws down first among the three reservoirs. As Arrow reservoir dramatically draws down, Duncan and Libby reservoir remain relatively level. When Arrow reservoir draws down to its minimum allowable storage of 227KAF, the total system storage for the three reservoirs is ~2800KAF. At this point, Libby significantly draws down until the minimum total system storage is reached. Duncan only draws down a small amount.

Using the method of analysis described above, the following storage allocation operation has been determined for the 1994 variable drawdown period. All seven reservoirs are plotted together to provide HEC-PRM's storage allocation operation for the entire system under study (Figure 5.19). Arrow reservoir draws down first. As Arrow draws down to its minimum allowable storage, 227KAF, Duncan, Libby and Hungry Horse are relatively level. Mica and Dworshak reservoirs drawdown a moderate amount while Arrow is draining (Figures 5.19 and 5.20). Once Arrow reservoir levels at 227KAF, Grand Coulee reservoir draws down drastically to its minimum allowable storage of 3879KAF (Figure 5.21). Libby and Hungry Horse reservoirs are the last to drawdown; these two reservoirs discharge water downstream when Mica, Arrow, Grand Coulee, Duncan and Dworshak are at or near their minimum allowable storage levels (Figure 5.19).

1994 Refill Period

The 1994 refill season, which spans from April to July, is when peak inflows are expected in the Columbia River System. As a result, the reservoirs refill to store the inflows and capture possible floods. Figure 5.17 shows that HEC-PRM and AER operations refill the system throughout the refill season as expected. HEC-PRM stores considerably more water in the system in June and July than the AER operation. The January forecasted inflows generally were

greater than the observed inflows during the refill season.

The storage allocation plots developed for the 1994 refill season are given in Figures 5.22 - 5.25. Storage allocation graphs for the 1994 refill season are studied from left to right to capture the refill process. Libby and Hungry Horse reservoirs refill first, but only small amounts (Figure 5.22). Grand Coulee reservoir then dramatically refills to its target of 9107KAF and maintains this level. Simultaneously, Arrow, Duncan, Libby, Hungry Horse and Dworshak reservoirs gradually refill while Mica remains constant at 13075KAF, its minimum allowable storage. When Grand Coulee levels at 9107KAF, Mica and Arrow are the next two reservoirs to significantly refill (Figure 5.23). Duncan and Libby refill a considerable amount as well (Figure 5.24). Figure 5.25 shows how Hungry Horse and Dworshak refill a large amount once Grand Coulee reached its target storage. When the system stores more than 44000KAF, HEC-PRM draws down Duncan and Dworshak, while maintaining or refilling the other five reservoirs.

5.1.4 Comparison of HEC-PRM with AER Operation for January - March

The HEC-PRM storage trends and magnitudes for the near-term period of the 1994 January - July study are compared to the AER operation. When both the HEC-PRM storage trends and magnitudes are similar to the AER operation, it indicates that HEC-PRM can offer reasonable operations.

Near-Term Storage Trend Comparison

The near-term storage trends for HEC-PRM and AER operations are given in Table 5.3. Thirteen of the HEC-PRM storage trend operations matched the AER storage trends. Given that HEC-PRM runs its optimization based on AER storage for initial storage values, it is encouraging that most of the comparisons between HEC-PRM and AER operations agreed.

<u>January</u>

HEC-PRM and AER trends agree for 5 of 7 reservoirs in January. Both HEC-PRM and AER operations draw down Mica, Arrow, Libby, Hungry Horse and Dworshak reservoirs in January.

<u>February</u>

As in January, HEC-PRM storage trends match the AER operation for 5 of 7 reservoirs. Again, Mica, Arrow, Libby, Hungry Horse and Dworshak reservoirs are drawn down in February.

<u>March</u>

The HEC-PRM and AER trend operations compare well for only three reservoirs, Mica, Grand Coulee and Hungry Horse. Both operations draw down these reservoirs.

Table 5.3 Near-Term Comparison of Storage Trends for HEC-PRM 1994 January - July Study and 1994 AER Operation

RESERVOIR	HEC-PRM	1994 AER
January		
Mica	Drawdown	Drawdown
Arrow	Drawdown	Drawdown
Grand Coulee	Refill	Drawdown
Duncan	Refill	Maintain 24KAF
Libby	Drawdown	Drawdown
Hungry Horse	Drawdown	Drawdown
Dworshak	Drawdown	Drawdown
February		
Mica	Drawdown	Drawdown
Arrow	Drawdown	Drawdown
Grand Coulee	Variable	Drawdown
Duncan	Refill	Maintain 24KAF
Libby	Drawdown	Drawdown
Hungry Horse	Drawdown	Drawdown
Dworshak	Drawdown	Drawdown
March		
Mica	Drawdown	Drawdown
Arrow	Maintain 227KAF	Refill
Grand Coulee	Drawdown	Drawdown
Duncan	Refill	Maintain 24KAF
Libby	Drawdown	Maintain 2313KAF
Hungry Horse	Drawdown	Drawdown
Dworshak	Drawdown	Refill

Near-Term Storage Magnitude Comparison

HEC-PRM results are reasonable if HEC-PRM storage magnitudes compare well to the AER operation. Figures 5.26 - 5.32 show the HEC-PRM results for the 1994 January - July study plotted with the AER storage. The HEC-PRM results are graphed in quartile format; within each curve lies 25% of the storage values.

The magnitude comparisons are determined by measuring the difference between the median HEC-PRM storage and the AER storage. This difference is compared to the total storage capacity of the given reservoir to discover the relative size of the magnitude difference.

System-Wide

The median HEC-PRM storages in the variable drawdown season follow the AER operation closely (Figure 5.17). On the individual reservoir scale, HEC-PRM stores more water in Mica, Duncan, Libby and Hungry Horse in January, February and March than the AER operation (Figures 5.26, 5.29 - 5.31). HEC-PRM typically stores less water in Arrow and Dworshak reservoirs than the AER storage in the variable drawdown season (Figures 5.27 and 5.32).

Mica Reservoir

HEC-PRM stores more water in Mica reservoir than the AER operation throughout the variable drawdown season (Figure 5.26). The difference between the median HEC-PRM value and the AER operation increases from January to March. The magnitude difference between the median HEC-PRM storage and the AER storage in January is ~700KAF, only ~3% of Mica's total storage capacity. In February, the difference increased to ~1MAF, ~5% of the total storage capacity of Mica. Though the difference grows between the median HEC-PRM and the AER operation to ~1.4MAF in March, this amount is still fairly minimal at ~7% of Mica's total capacity.

HEC-PRM may store more water in Mica than the AER operation does because HEC-PRM is draining Arrow for downstream purposes. This operation of Arrow would make it possible for Mica to operate at a high level.

Arrow Reservoir

HEC-PRM stores considerably less water in Arrow in the variable drawdown season than the AER operation (Figure 5.27). In January, the median HEC-PRM is ~3.2MAF less than AER. This difference is approximately 44% of Arrow's total storage capacity. In February and March, 75% of the HEC-PRM values are Arrow's minimum allowable storage, and the median HEC-PRM is ~2.5MAF less than the AER storage.

Arrow is drawn down so dramatically by HEC-PRM because there are no significant penalty functions assigned to its operation. HEC-PRM can use Arrow water to improve operations in other parts of the system. For example, Mica can store more of its water if Arrow

drains.

Grand Coulee Reservoir

HEC-PRM encourages storing Grand Coulee's maximum allowable storage of 9107KAF as long into the variable drawdown season as possible. HEC-PRM typically stores more water in Grand Coulee reservoir in January and February than the AER operation (Figure 5.28). In March, the HEC-PRM storage curves are split around the AER operation. The magnitude difference between the median HEC-PRM storage and AER in January is ~1MAF, ~11% of Grand Coulee's total storage capacity. In February, the magnitude difference between the median HEC-PRM and the AER operation increased to ~1.5MAF, ~16% of the total storage capacity of Grand Coulee. Lastly, in March, HEC-PRM's median storage was essentially the same as the AER value.

Duncan Reservoir

HEC-PRM typically stores more water in Duncan throughout the variable drawdown season than the AER operation (Figure 5.29). The magnitude difference between the median HEC-PRM storage and the AER operation is small, though it increases from January to March. The median HEC-PRM storage is ~30KAF greater than AER in January, ~2% of Duncan's total storage capacity. In February, the magnitude difference doubled to ~60KAF, which is still only ~4% of the total capacity of Duncan. Lastly, in March, the difference between the median HEC-PRM storage and the AER operation is ~90KAF, ~6% of Duncan's capacity.

Duncan reservoir does not come close to meeting its July target storage of 1399KAF. In fact, Duncan stores only ~500KAF instead. Notably, this HEC-PRM July storage for Duncan is nearly the same as the AER July storage, 513KAF. HEC-PRM appears to discharge great quantities of water from Duncan in July for system benefit and, as a result, stores approximately the same amount of water in Duncan as the AER operation.

Libby Reservoir

The HEC-PRM storage for Libby reservoir is greater than the AER operation throughout the variable drawdown season (Figure 5.30). In January, February and March, the median HEC-PRM storage is consistently ~1MAF greater than the AER operation. This magnitude difference is ~17% of Libby's total storage capacity. HEC-PRM probably can keep Libby high because Dworshak is drawn down below the AER operation to meet downstream demands.

Hungry Horse Reservoir

HEC-PRM typically stores more water in Hungry Horse in January, February and March than the AER operation (Figure 5.31). The magnitude differences between the median HEC-PRM storage and AER operation is ~75KAF in January, which is ~2% of Hungry Horse's total storage capacity with 6% bank storage considered. The difference increases to ~120KAF in February and ~190KAF in March, between 4% and 6% of the total storage capacity of Hungry Horse. HEC-PRM probably can keep Hungry Horse high because Dworshak is drawn down

below the AER operation to supply water to the system instead.

Dworshak Reservoir

HEC-PRM stores less water in Dworshak reservoir than the AER operation throughout the variable drawdown season (Figure 5.32). The difference between HEC-PRM's median storage and the AER operation is ~150KAF in January and increases to ~300KAF by March. These magnitude differences are from ~4% to 9% of Dworshak's total storage capacity. HEC-PRM appears to draw Dworshak down below the AER operation possibly to permit Libby and Hungry Horse to store water instead.

5.1.5 HEC-PRM Near-Term Advice for 1994 January - July Study

HEC-PRM advice is discussed for the near-term period of the 1994 January - July season study. The near-term period, January to March, coincides with the traditional variable drawdown period of the Columbia River System. Though HEC-PRM's advice is determined only for the first three months of this seasonal study, the study was run from January to July to guarantee that HEC-PRM operates the reservoirs throughout the variable drawdown and refill seasons and tries to aim to meet the July refill targets. System-wide operation advice and individual reservoir advice is discussed. Both the general trend advice and specific quantitative advice is presented. HEC-PRM's storage advice should be tested with simulation to discover if the operations are reasonable.

Near-Term HEC-PRM System-Wide Operation Advice

HEC-PRM advises a continuous system drawdown throughout the 1994 variable drawdown season (Figure 5.17). The AER system operation draws down the seven reservoirs from January to March also (Figure 5.17). HEC-PRM's advice to draw down the system is expected, since customarily the variable drawdown season in the Columbia River System is designed to provide storage space for future peak inflows and flooding (USACE, 1993).

According to the storage allocation plots, HEC-PRM's advice for the order of drawdown should be as follows. Drawdown Arrow first, and drain the reservoir to its minimum allowable storage of 227KAF (Figure 5.19). As Arrow is drawing down, begin to drawdown Mica and Dworshak a small amount (Figure 5.19). When Arrow reaches its lowest storage level, Mica should drawdown significantly. Mica should level, and Grand Coulee should drain to 3879KAF, its lowest allowable storage (Figure 5.21). As Arrow and Grand Coulee each drain, Duncan, Libby and Hungry Horse should drawdown gradually, in small amounts relative to Arrow and Grand Coulee reservoirs' drawdown (Figure 5.19). With Mica, Arrow and Grand Coulee at their lowest allowable storage levels, Libby and Hungry Horse draw down to cover necessary discharges in the system (Figure 5.19).

Clearly, HEC-PRM uses Arrow and Grand Coulee to discharge the greatest amounts of water. Arrow reservoir is a good choice because it is not operated to meet any specific objectives. Grand Coulee's large drawdown is probably to meet hydropower demands and to

prepare for the prevention of flooding in late spring.

HEC-PRM advises always refilling Mica and Grand Coulee in July. HEC-PRM cannot refill all seven reservoirs because the 1994 water year is a dry year. Therefore, HEC-PRM prioritized the refill operations. The importance of refilling Grand Coulee is probably to keep the reservoir high for hydropower purposes.

Near-Term HEC-PRM Individual Reservoir Storage Trend and Magnitude Advice

Mica Reservoir

HEC-PRM results suggest that Mica reservoir should operate with more water during the variable drawdown season than in the 1994 AER operation (Figure 5.26). An average of 1MAF more water should be stored in Mica than available in the AER operation. An additional benefit to HEC-PRM's operation is that the July target storage is always met. The AER operation does not met the HEC-PRM July target.

Arrow Reservoir

HEC-PRM's advice for Arrow in the variable drawdown season is clear; draw down Arrow reservoir rapidly to its lowest allowable level of 227KAF (Figure 5.27). HEC-PRM takes advantage of the minimal constraints on Arrow reservoir's operation. The AER operation stored at least 2.5MAF more water in Arrow during the variable drawdown season. HEC-PRM discharges Arrow's water which appears to keep Mica at a high storage level and fill Grand Coulee. Simulation should be used to test HEC-PRM's advice to draw down Arrow reservoir to 227KAF.

Grand Coulee Reservoir

Grand Coulee reservoir should be kept full at 9107KAF in January and February, and then drawn down as necessary in March (Figure 5.28). The amount of drawdown in March is contingent on the quantity of inflows. Similar to the advice for Mica reservoir, HEC-PRM advises keeping more water in Grand Coulee than the AER operation. The water discharged from Arrow reservoir probably supplements the water needed for Grand Coulee to fill toward its target of 9107KAF. Simulation testing should be employed to determine the feasibility of maintaining Grand Coulee reservoir at a high level.

Duncan Reservoir

HEC-PRM advises gradual refill for Duncan reservoir throughout the variable drawdown season (Figure 5.29). Duncan refills rather than draws down during this period likely because the January 1 initial storage is very low, 24KAF. Since drawdown is expected in the variable drawdown season, test the refill advice with simulation. Though HEC-PRM's advice may offer useful operations for Duncan in the variable drawdown season, HEC-PRM's operation does not permit Duncan to reach its July refill target. Interestingly, HEC-PRM's July storage does compare well with AER July storage though it fails to reach the target.

Libby Reservoir

HEC-PRM's advice for Libby reservoir in the 1994 variable drawdown season is to store more water than the AER operation (Figure 5.30). On average, HEC-PRM suggests maintaining ~950KAF in Libby throughout January, February and March. This is the fourth time HEC-PRM suggests storing more water in the reservoir than the AER operation. Mica, Grand Coulee and Duncan reservoirs are the previous three cases. Simulation can explore this operation advice.

Hungry Horse Reservoir

HEC-PRM advises storing, on average, ~100KAF more water in Hungry Horse reservoir during the variable drawdown season than the AER operation (Figure 5.31).

Dworshak Reservoir

HEC-PRM's advice for Dworshak reservoir is to draw down the reservoir below the AER operation (Figure 5.32). An average difference of ~200KAF exists between the HEC-PRM and AER operations. HEC-PRM appears to draw down Dworshak to supply flows downstream and to allow Libby and Hungry Horse to store more water than the AER operation.

Near-Term Individual Reservoir Specific Storage and Release Advice

The HEC-PRM results offer strong specific storage and release advice (Table 5.4). An individual release or storage value, or a tight range of values, is defined as specific advice when it exists for at least 25% of the results. Simulation testing should be used to determine the worth of the following specific advice.

Mica Reservoir

HEC-PRM advises a release of 603KAF (minimum allowable release) to draw down Mica reservoir throughout the 1994 variable drawdown season (Figure 5.33). In January, over 25% of the release results equaled 603KAF. At least 50% of the release results in February and March indicate that 603KAF should be discharged from Mica reservoir.

Arrow Reservoir

Arrow reservoir should draw down and store 227KAF (minimum allowable storage) all three months of the variable drawdown season (Figure 5.27). At least seventy-five percent of the February and March results equal a storage of 227KAF. In January, the number of storage results equal to 227KAF is less; at least 25% of the results store between 227KAF and 590KAF.

Grand Coulee Reservoir

HEC-PRM's specific advice for Grand Coulee is clear. Refill and store 9107KAF, the maximum allowable storage, in Grand Coulee all three months (Figure 5.28). All of the storage results in January equal 9107KAF. At least 50% of the February results are 9107KAF. Twenty-

five percent of the storage results in March fall within the range of 8350KAF and 9107KAF.

Duncan Reservoir

Duncan should release 6KAF (minimum allowable release) in January, February and March to allow the reservoir to refill (Figure 5.34). A minimum of 75% of the release results each month equal 6KAF.

Table 5.4 HEC-PRM Specific Quantitative Advice for 1994 Variable Drawdown Season for 1994 January - July Study

Reservoir	Month	Operation	HEC-PRM Advice (KAF)	Percentage of Results (%)
Mica	January	Release	603 (Min)	25
	February	Release	603	50
	March	Release	603	50
Arrow	January	Storage	227 (Min) -590	25
	February	Storage	227	75
	March	Storage	227	75
Grand Coulee	January	Storage	9107 (Max)	100
	February	Storage	9107	50
	March	Storage	8350-9107	25
Duncan	January	Release	6 (Min)	75
	February	Release	6	75
	March	Release	6	75
Libby	January	Release	181 (Min)	100
	February	Release	181	75
	March	Release	181	25
Hungry Horse	January	Release	60	100
	February	Release	60	100
	March	Release	60	50
Dworshak	January	Release	300-350	50
	February	Release	230-300	50
	March	Storage	200-300	50

Libby Reservoir

HEC-PRM advises that Libby reservoir release 181KAF, the minimum allowable release, from January to March to draw down the reservoir (Figure 5.35). All of the January release results equal 181KAF. At least 75% of the results in February are 181KAF. The release of 181KAF occurred in at least 25% of the March release results.

Hungry Horse Reservoir

Release 60KAF and draw down Hungry Horse reservoir throughout the variable drawdown season (Figure 5.36). All of the release results in January and February equaled 60KAF. At least 50% of the release results in March are 60KAF.

Dworshak Reservoir

Dworshak reservoir should draw down by releasing between 300KAF and 350KAF in January, at least 50% of the results indicate a discharge within this range (Figure 5.37). In February, Dworshak releases to draw down the reservoir should be from 230KAF to 300KAF. Fifty percent of the February releases are in this range. Lastly, the March drawdown releases should be between 200KAF and 300KAF. Again 50% of the releases fall between these values.

5.1.6 Conclusions for 1994 January - July Season Study

1. Overall, HEC-PRM offers strong specific quantitative advice and reasonable trend advice in the 1994 variable drawdown season. The trend advice compares well with the AER operation on a system-wide basis and an individual reservoir basis. All HEC-PRM advice should be tested with simulation to discover if an improved approach to reservoir operation has been suggested by HEC-PRM.

2. Only Mica and Grand Coulee reservoirs always reached their target storage in July 1994. The 1994 water year is dry, therefore, HEC-PRM had to prioritize its refills and Mica and Grand Coulee reservoirs were chosen as the most important reservoirs to fill. Libby reservoir almost meets its target for every inflow sequence; Libby reaches its July target storage for 47 of 49 inflow years. The probability of refill for Arrow is considerably less, at 55%. Grand Coulee is valuable probably for hydropower purposes.

3. As expected for the variable drawdown season in the Columbia River System, the system-wide storage trend suggested by HEC-PRM in the 1994 January - July study is drawdown. The 1994 AER operation also draws down the system throughout the variable drawdown season.

4. HEC-PRM's storage allocation advice begins with Arrow drawdown. Arrow should be drawn down to its minimum allowable storage of 227KAF. Mica and Dworshak reservoirs draw down a moderate amount as Arrow drains. When Arrow reaches 227KAF, Grand Coulee draws down rapidly. Lastly, Libby and Hungry Horse draw down when Mica, Arrow and Grand Coulee

are at their minimum storage levels. HEC-PRM uses Arrow and Grand Coulee reservoirs to make the largest drawdown of the system. Arrow is a logical choice since there are no penalty functions placed on its operation.

5. Thirteen of the twenty-one storage trend comparisons between HEC-PRM and AER operations match. HEC-PRM's storage trends for Mica and Hungry Horse reservoir always agreed with the AER operation. Mica and Hungry Horse always should be drawn down throughout the variable drawdown season.

6. HEC-PRM advises that Mica, Grand Coulee, Duncan, Libby and Hungry Horse store more water than the AER operation. Conversely, Arrow and Dworshak reservoirs should be drawn down below the AER levels, likely to accommodate the higher storage levels of Mica, Grand Coulee, Duncan, Libby and Hungry Horse. Since Arrow drains to its lowest allowable storage, clearly HEC-PRM uses Arrow water for system-wide benefit. Arrow is ideal for drastic draw down because there are no significant penalty functions placed on its operation.

HEC-PRM stores more water than the AER operation for five of the seven reservoirs. HEC-PRM knows future inflows when operation decisions are made, therefore, the model can store large amounts of water without the threat of flooding. In addition, HEC-PRM does not consider fish requirements in its operation, and, as a result, HEC-PRM could be storing a significant amount of water that should be allotted to fish releases.

7. HEC-PRM's specific quantitative advice for the 1994 variable drawdown season is strong. There is HEC-PRM release or storage advice for all seven reservoirs. A release of 603KAF (minimum allowable release) should be made from Mica reservoir to draw it down all three months. Arrow reservoir should be drawn down to the minimum storage, 227KAF, in January and maintain in February and March. Grand Coulee reservoir should be filled to 9107KAF (maximum allowable storage) in the variable drawdown season. Duncan reservoir should release 6KAF and allow the reservoir to refill in January, February and March.

Libby reservoir should release 181KAF (minimum allowable release) throughout the 1994 variable drawdown season. For Hungry Horse, HEC-PRM advises a release of 60KAF in January, February and March. Dworshak reservoir should be drawn down with a release of 300KAF. This operational information should be tested further with simulation to explore its usefulness.

5.2 Comparison of Variable Drawdown Season Operations for the 1994 and 1995 January - July Studies

This section discusses the comparison of the 1994 and 1995 January - July season studies. The comparisons consider the near-term (January - July) results and advice. The topics compared include inflows, refill probability, storage allocation, storage trends and magnitudes, and HEC-PRM advice.

Comparison of Forecasted Inflows

The forecasted inflows for January to July for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs are greater in 1995 than in 1994 (Figures 5.1-5.7). In actuality, the 1994 water year was relatively dry; a majority of the monthly precipitation levels were below normal in 1994 (CRWMG, 1994).

The 1994 January - July study is run with 49 years of inflows (1929-1977). The 1995 January - July study uses 48 years of inflow (1929-1976). A one year difference should not disturb the comparison analysis or the conclusions of the 1994 and 1995 studies. Not all inflows are forecasted inflows. When forecasts are unavailable at inflow nodes, historical inflows are used. Forecasted inflows were available for Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs in both studies.

Comparison of July Refill Probability

More reservoirs always reach their July target storage in the 1995 January - July season study. The four reservoirs, Mica, Arrow, Grand Coulee and Libby, always meet their July targets in the 1995 study (Figures 3.1 - 3.3 and 3.5), while only two reservoirs, Mica and Grand Coulee, always reach the desired storage in the 1994 study (Figures 5.9 and 5.11). A notable mention is that Libby reservoir almost always meets its target in the 1994 study, 47 of 49 years (Figure 5.16). The probability of refill in the 1994 study is less than for the 1995 study because the 1994 is a drier water year. Typically, less inflow was forecasted for 1994 than 1995 (Figures 5.1 - 5.7).

Comparison of System-Wide Operations

On a system-wide basis, HEC-PRM tends to store less water in the variable drawdown season of 1995 than 1994 (Figures 3.11 and 5.17). A comparison of median HEC-PRM storage values shows the 1995 operation consistently storing less than the 1994 operation during the refill period. Since HEC-PRM knows that larger inflows are forecasted to arrive in refill 1995 than refill 1994, HEC-PRM can draw down the system more in the 1995 variable drawdown season.

In January, the 1995 AER operation stores less than the 1994 AER storage, similar to the HEC-PRM operations. However, in February and March, the 1995 AER operation stores more water in the 1995 variable drawdown season than the 1994 AER operation. The reason is a result of a giant increase in Grand Coulee's AER storage in February 1995 that causes dramatic refill

during the variable drawdown season (Figure 3.19).

The system-wide AER operation for 1994 stores about the same amount of water as the median system-wide HEC-PRM storage in the variable drawdown season (Figure 5.38). Due to the drastic refill in the AER operation of Grand Coulee in February 1995, the system-wide AER operation for 1995 is typically greater than the HEC-PRM system operation.

Comparison of Storage Allocation

HEC-PRM draws down the system in a very similar order in both the 1994 and 1995 studies (Figures 3.13 and 5.19). Arrow reservoir is the first reservoir to be drawn down. Mica and Dworshak reservoirs begin to draw down as Arrow drains to its minimum allowable storage of 227KAF. During this time, Grand Coulee, Duncan, Libby and Hungry remain fairly level relative to the drawdown of Arrow.

When Arrow drains to 227KAF, Grand Coulee reservoir starts to draw down dramatically and rapidly. Mica and Dworshak continue to draw down. Grand Coulee reaches its minimum allowable storage of 3879KAF. Mica and Dworshak are drained to minimum levels by this point.

In the 1995 study, Libby reservoir is the final reservoir to draw down. Both Libby and Hungry Horse draw down last in the 1994 study. Arrow is the sensible choice to be drawn down first since there are no costly penalties for draining the reservoir. Grand Coulee appears to be drawn down because it is capable of large discharges to meet downstream demands once Arrow is drained. While HEC-PRM's storage allocation advice varies with hydrologic conditions, HEC-PRM's general drawdown strategy is similar between years.

Comparison of Storage Trends

Table 5.5 lists the HEC-PRM storage trends for the variable drawdown season from the 1994 and 1995 January - July studies. Sixteen of twenty-one comparisons between the 1994 and 1995 trends agreed. HEC-PRM storage trends are fairly consistent between the two years.

<u>January</u>

Six of the seven reservoirs have the same storage trend operations between the 1994 and 1995 HEC-PRM January - July studies in January. Mica, Arrow, Libby and Dworshak are drawn down in January, while Grand Coulee and Duncan are refilled.

<u>February</u>

The 1994 and 1995 HEC-PRM January - July studies had the same storage trends for four of the seven reservoirs in February. Mica, Hungry Horse and Dworshak are drawn down, and Duncan is refilled.

Table 5.5 Comparison of Storage Trends for 1994 and 1995 Variable Drawdown Seasons

RESERVOIR	1995 Jan - July Study	1994 Jan - July Study
January		
Mica	Drawdown	Drawdown
Arrow	Drawdown	Drawdown
Grand Coulee	Refill	Refill
Duncan	Refill	Refill
Libby	Drawdown	Drawdown
Hungry Horse	Refill	Drawdown
Dworshak	Drawdown	Drawdown
February		
Mica	Drawdown	Drawdown
Arrow	Maintain 227KAF	Drawdown
Grand Coulee	Drawdown	Variable
Duncan	Refill	Refill
Libby	Variable	Drawdown
Hungry Horse	Drawdown	Drawdown
Dworshak	Drawdown	Drawdown
March		
Mica	Drawdown	Drawdown
Arrow	Maintain 227KAF	Maintain 227KAF
Grand Coulee	Drawdown	Drawdown
Duncan	Refill	Refill
Libby	Drawdown	Drawdown
Hungry Horse	Variable	Drawdown
Dworshak	Drawdown	Drawdown

March

In March, the storage trends for the two studies compare for six of the seven reservoirs. Mica, Grand Coulee, Libby and Dworshak reservoirs are drawn down, while Arrow maintains 227KAF and Duncan refills.

Comparison of Storage Magnitudes

Mica, Duncan, Libby and Dworshak reservoirs are operated within approximately the same storage range throughout the variable drawdown season, in both the 1994 and 1995 January - July studies (Figures 3.17, 3.20, 3.21, 3.23, 5.26, 5.29, 5.30 and 5.32). Consistently, HEC-PRM draws down Arrow reservoir to 227KAF and maintains this level from January to March, in both studies (Figures 3.18 and 5.27). All three months, HEC-PRM tends to draw Grand Coulee down lower in the 1995 study than the 1994 study (Figures 3.19 and 5.28).

Hungry Horse reservoir stores considerably more water in the 1994 study than the 1995 study (Figures 3.22 and 5.31). This is due to the use of 6% bank storage values in the 1994 study, and 3% bank storage values in the 1995 study. The 6% bank storage values include more bank elevation in the measurements for storage and, therefore, more water is considered.

Both HEC-PRM studies store more water in Mica than the respective AER operation in January, February and March (Figures 3.17 and 5.26). The HEC-PRM operation of Arrow reservoir is much less than the corresponding AER operation throughout the variable drawdown season for both studies (Figures 3.18 and 5.27). In fact, HEC-PRM draws Arrow down to its minimum allowable storage in both studies. In both the 1994 January - July study and the 1995 January - July study, HEC-PRM typically stores less water in Dworshak than the corresponding AER operation in January, February and March (Figures 3.23 and 5.32).

The HEC-PRM operations of Grand Coulee overlap with the respective AER operations in both the 1994 and 1995 studies (Figures 3.19 and 5.28). HEC-PRM operations for Duncan, Libby and Hungry Horse are not consistent between studies. HEC-PRM typically stores more water in Duncan, Libby and Hungry Horse reservoirs than the 1994 AER operation in January, February and March of the 1994 January - July study (Figures 5.29, 5.30 and 5.31). For the 1995 study, the HEC-PRM operation for Duncan, Libby and Hungry Horse reservoirs overlaps with the 1995 AER operation for January, February and March (Figures 3.20, 3.21 and 3.22).

Comparison of HEC-PRM Specific Quantitative Advice

HEC-PRM's specific quantitative advice is very consistent between the 1994 study and 1995 study (Table 5.6). Mica reservoir should release 603KAF (minimum allowable release) in January, February and March. The specific operation advice for Arrow is to drawdown to 227KAF (minimum allowable storage) during the variable drawdown season. This advice is stronger in the 1995 study, over 75% of the results always equal a storage of 227KAF. Grand Coulee reservoir should maintain 9107KAF (maximum allowable storage) in January, February and March. This advice is stronger in the 1994 study than in the 1995 study.

Table 5.6 Comparison of HEC-PRM Specific Advice (KAF) for 1994 and 1995 Jan- July Studies

Mica Reservoir	1994 Jan - July	%	1995 Jan - July	%
January	Release 603(Min)	25	SAME	50
February	Release 603	50	SAME	25
March	Release 603	50	SAME	50
Arrow Reservoir				
January	Store 227 (Min)-590	25	SAME	75
February	Store 227	75	SAME	75
March	Store 227	75	SAME	100
Grand Coulee Reservoir				
January	Store 9107 (Max)	100	SAME	50
February	Store 9107	50	Store 8200-9107	25
March	Store 8350-9107	25	Store 6750-8750	25
Duncan Reservoir				
January	Release 6 (Min)	75	SAME	75
February	Release 6	75	SAME	75
March	Release 6	75	SAME	75
Libby Reservoir				
January	Release 181 (Min)	100	SAME	75
February	Release 181	75	SAME	75
March	Release 181	25	SAME	75
Hungry Horse Reservoir				
January	Release 60	100	SAME	25
February	Release 60	100	SAME	75
March	Release 60	50	SAME	50
Dworshak Rsvr				
January	Release 300-350	50	Release 300-450	50
February	Release 230-300	50	Release 300-450	75
March	Release 200-300	50	Release 250-450	75

Duncan should release 6KAF (minimum allowable release) and refill the reservoir throughout the variable drawdown season. Similarly, a release of 60KAF is advised for Hungry Horse and the reservoir should refill. Libby reservoir should release the minimum allowable release, 181KAF, all three months of the variable drawdown season. HEC-PRM advises releases between 200KAF and 360KAF in the 1994 study, and discharges within the range of 250KAF to 450KAF in the 1995 study, throughout the variable drawdown season.

Comparison Conclusions

1. HEC-PRM's operation of Mica, Arrow, Grand Coulee, Duncan, Libby, Hungry Horse and Dworshak reservoirs is quite consistent between the 1994 and 1995 January - July studies. HEC-PRM's probability of refill, storage trends, storage magnitudes and specific advice compare well between the two studies.

2. The probability of refill is greater in the 1995 January - July study than the 1994 January - July study. Mica, Arrow, Grand Coulee and Libby reservoirs always refill to their targets in the 1995 study. Only Mica and Grand Coulee always meet their target storage in July. More reservoirs always meet their July target in the 1995 study because 1995 forecasted inflows are larger than the 1994 inflows.

3. In both studies, HEC-PRM draws down the system all three months of the variable drawdown season. The traditional operation for the Columbia River System in January, February and March is draw down. The 1994 AER operation follows this typical drawdown pattern, but the 1995 AER operation does not consistently drawdown the system. A dramatic refill is experienced in Grand Coulee in February 1995 that disrupts the system drawdown. The system storage, as a whole, draws down January 1995, then significantly refills in February. The system again draws down in March 1995.

4. Sixteen of the twenty-one comparisons between 1994 and 1995 HEC-PRM storage trends for the variable drawdown season matched. The HEC-PRM storage trends for the 1994 study compared better to the 1994 AER trends than the 1995 HEC-PRM trends did for the 1995 AER operation. Thirteen of the twenty-one comparisons matched in the 1994 study. Nine of HEC-PRM trends are the same as the AER trends in the 1995 study.

5. HEC-PRM stores more water in Mica than the AER operation throughout the variable drawdown season for both studies. HEC-PRM stores considerably less water in Arrow than the AER operation in January, February and March for both the 1994 and 1995 January - July studies. HEC-PRM stores less water in Dworshak in the variable drawdown season than the AER operation for both studies.

The HEC-PRM operation for Grand Coulee from January - March overlaps with the AER operation for both studies. The relationship between the HEC-PRM and AER operations for Duncan, Libby and Hungry Horse reservoirs in the variable drawdown season for the 1994 and 1995 studies are not similar. HEC-PRM operates Duncan, Libby and Hungry Horse with more water than the AER operation throughout the variable drawdown season for the 1994 study, but

HEC-PRM and AER operations for the 1995 study overlap.

6. The specific quantitative HEC-PRM advice for the 1994 and 1995 studies compare extremely well. Between the two studies, there is strong HEC-PRM specific advice available, for all seven reservoirs, for each month of the variable drawdown season. Mica should release 603KAF (minimum allowable release), Arrow should draw down to the minimum storage of 227KAF and Grand Coulee should aim to store 9107KAF (maximum allowable storage). Duncan releases should be the minimum, 6KAF, to encourage refill.

Libby reservoir should release 181KAF (minimum allowable release), and a release of 60KAF should be discharged from Hungry Horse. Dworshak releases vary slightly between studies. The 1994 study release advice is to release slightly less than the 1995 discharges. In 1994, the HEC-PRM releases are between ~200KAF and ~350KAF, while the 1995 releases range from ~250KAF and 450KAF. HEC-PRM's advice for Grand Coulee and Dworshak reservoirs is stronger in the 1994 study than the 1995 study.

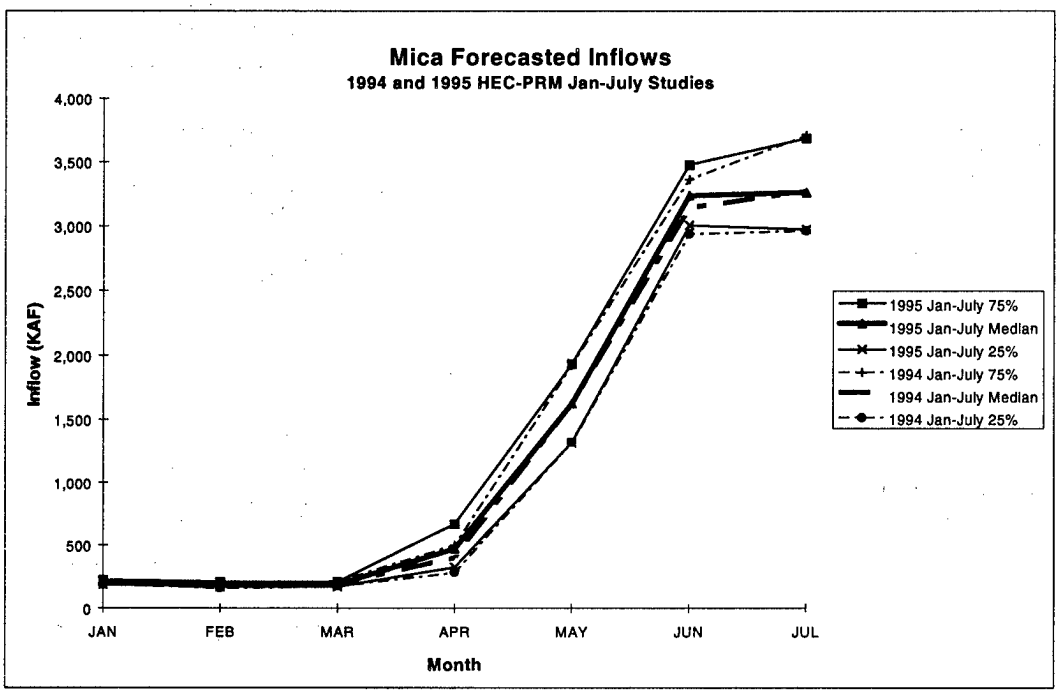


Figure 5.1 Comparison of Mica Forecasted Inflows for 1994 and 1995 Jan-July Studies

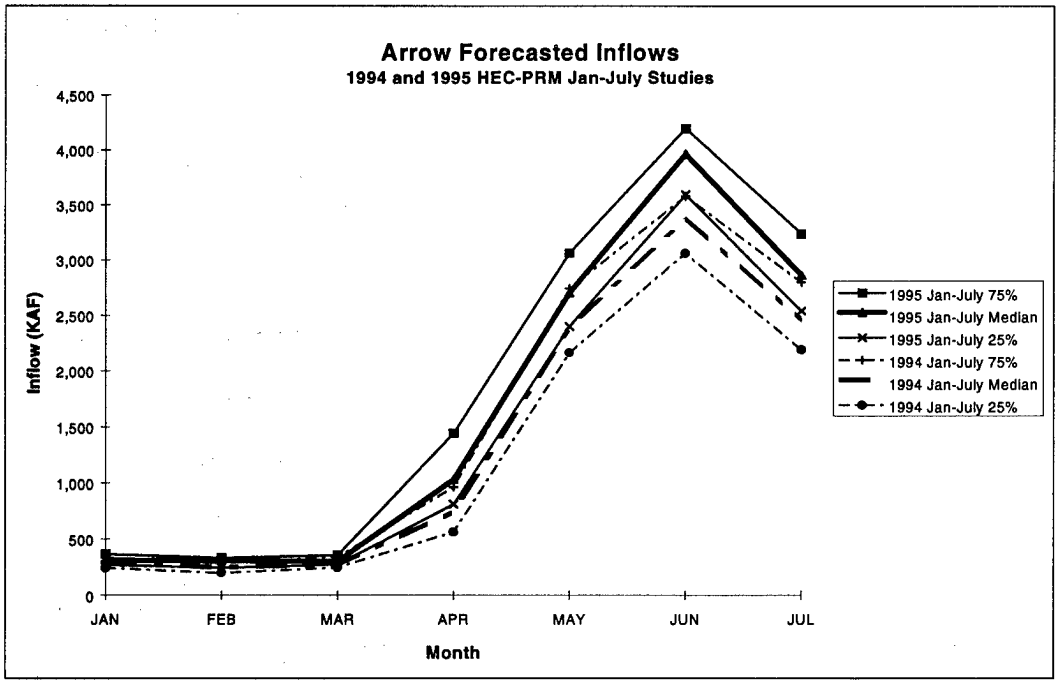


Figure 5.2 Comparison of Arrow Forecasted Inflows for 1994 and 1995 Jan-July Studies

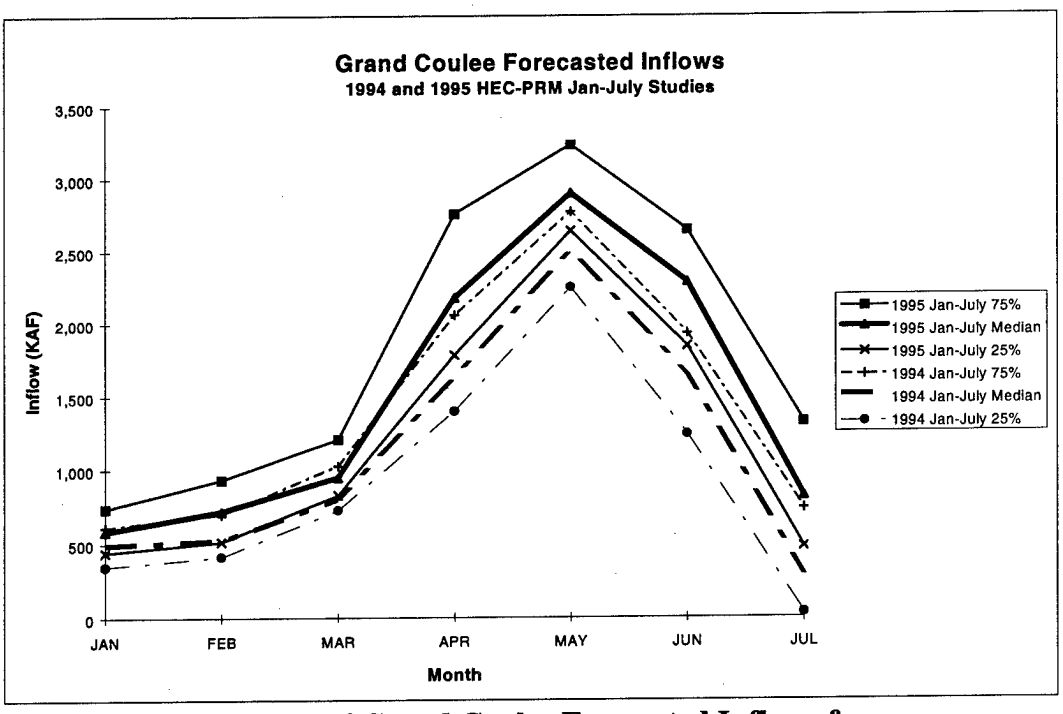


Figure 5.3 Comparison of Grand Coulee Forecasted Inflows for 1994 and 1995 Jan-July Studies

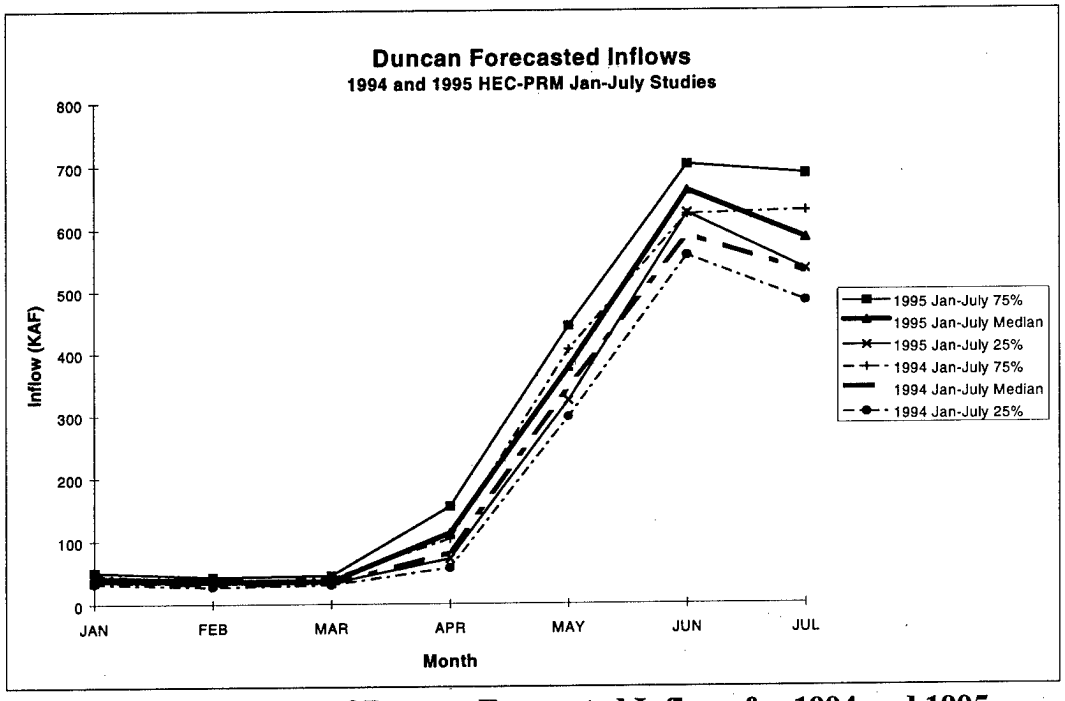


Figure 5.4 Comparison of Duncan Forecasted Inflows for 1994 and 1995 Jan-July Studies

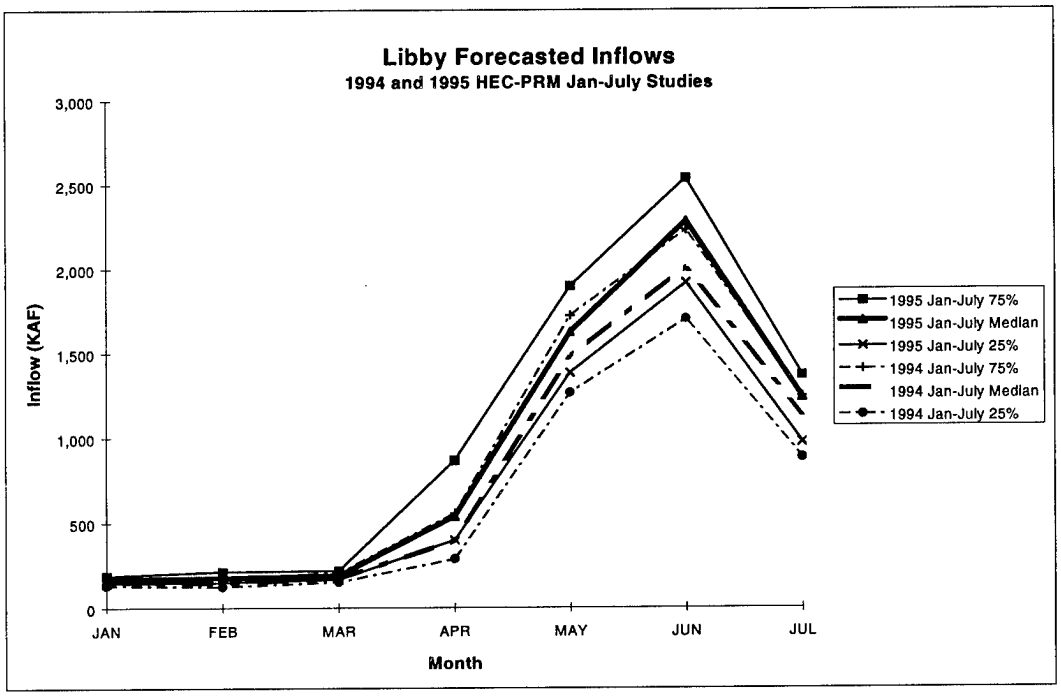


Figure 5.5 Comparison of Libby Forecasted Inflows for 1994 and 1995 Jan-July Studies

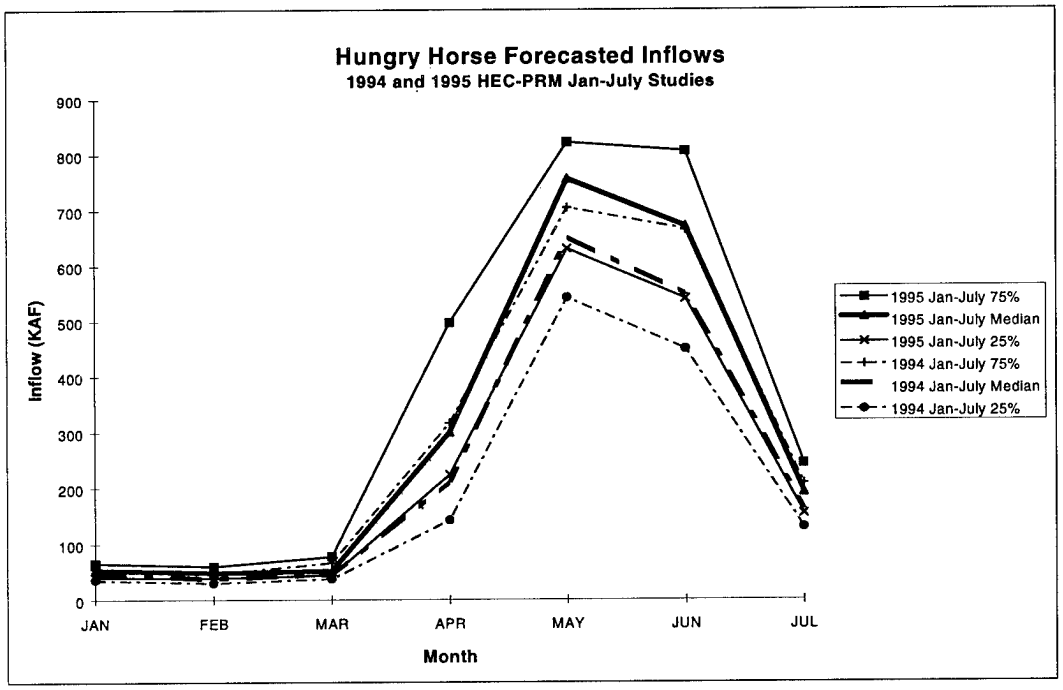


Figure 5.6 Comparison of Hungry Horse Forecasted Inflows for 1994 and 1995 Jan-July Studies

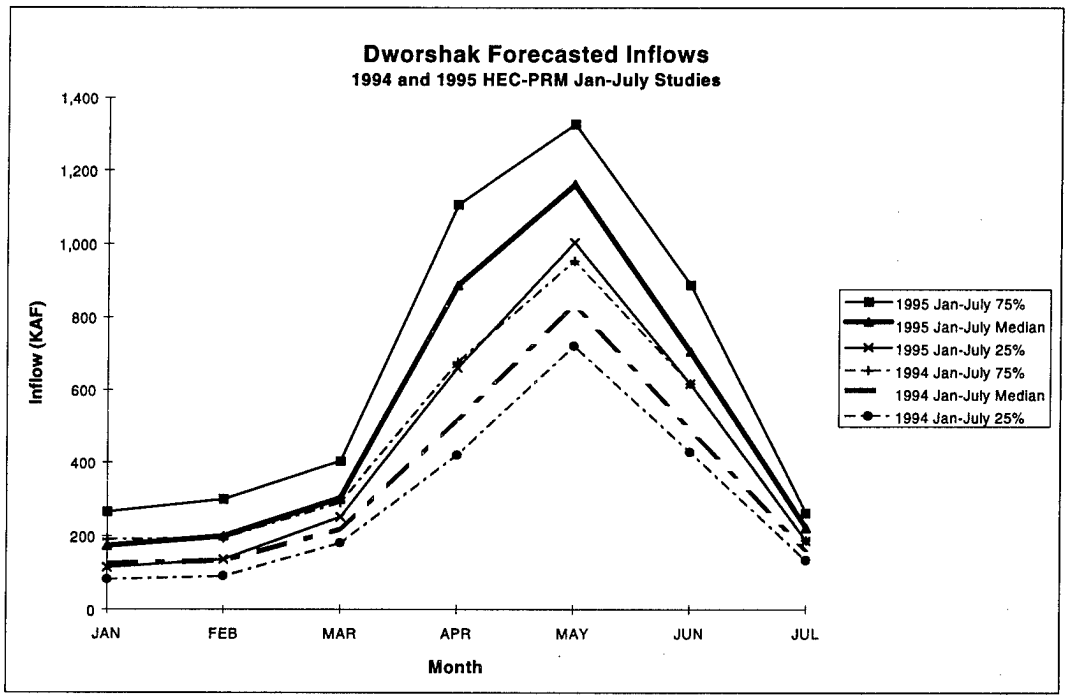


Figure 5.7 Comparison of Dworshak Forecasted Inflows for 1994 and 1995 Jan-July Studies

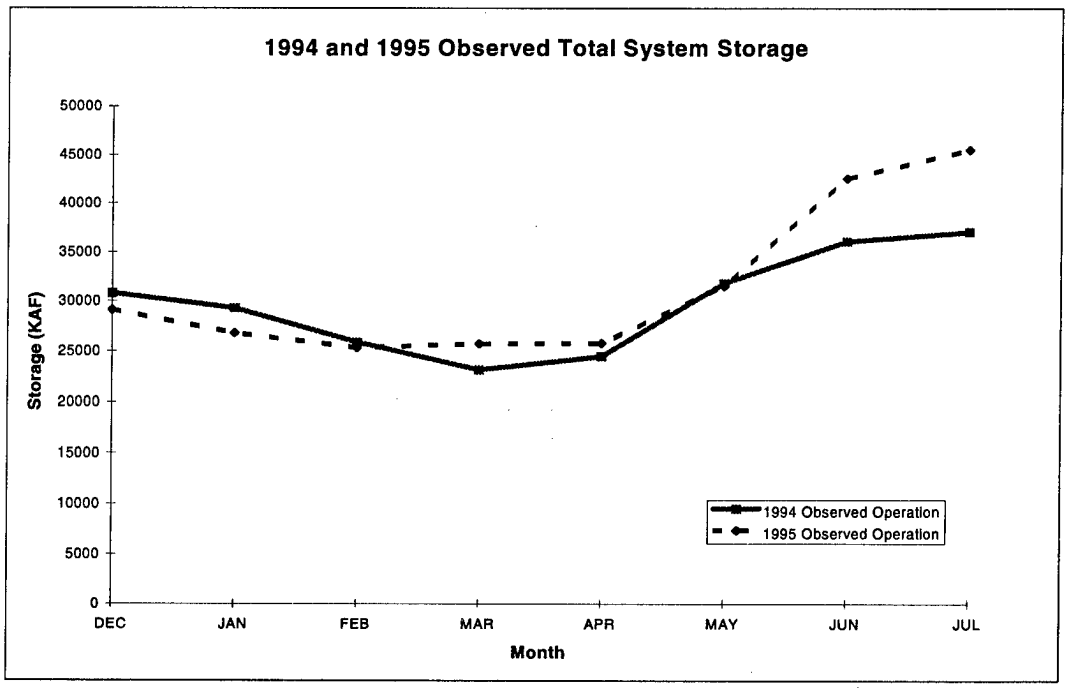
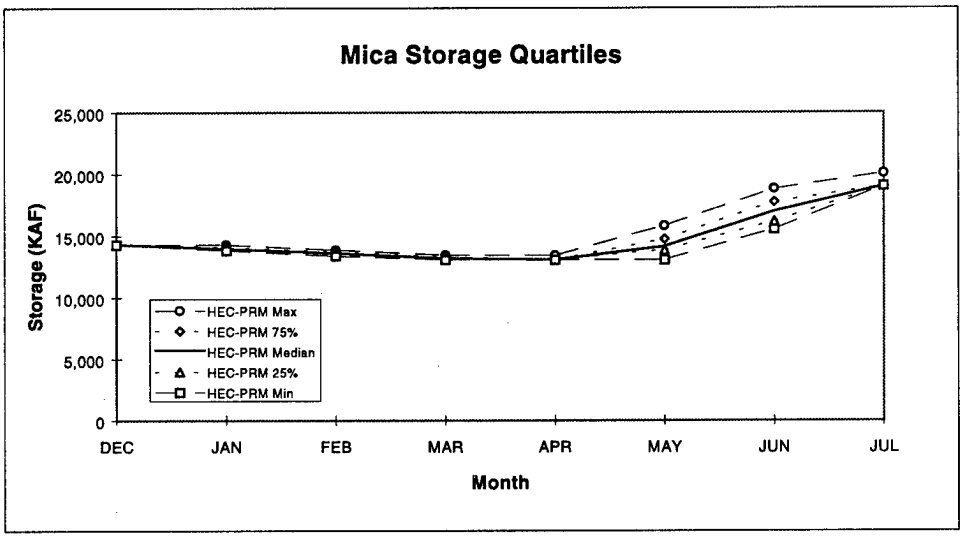
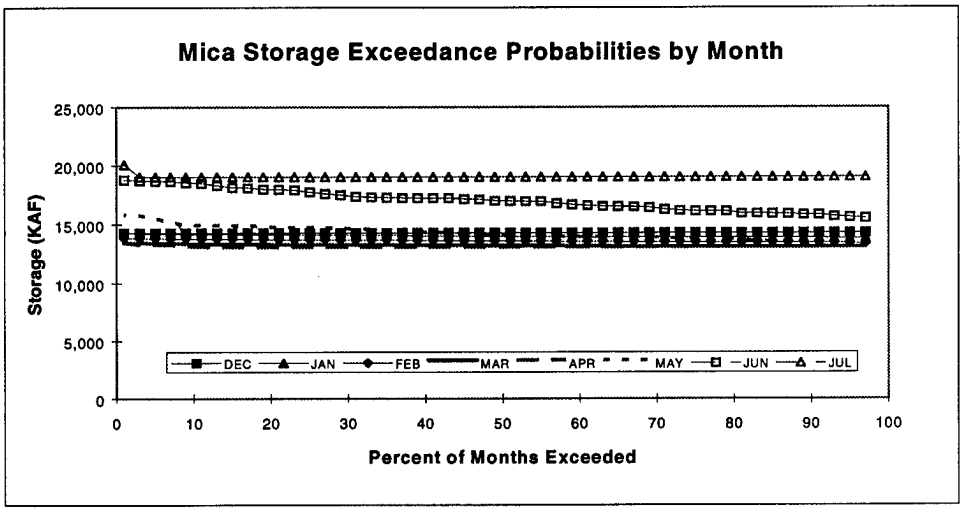


Figure 5.8 Comparison of 1994 and 1995 Observed Total System Storage





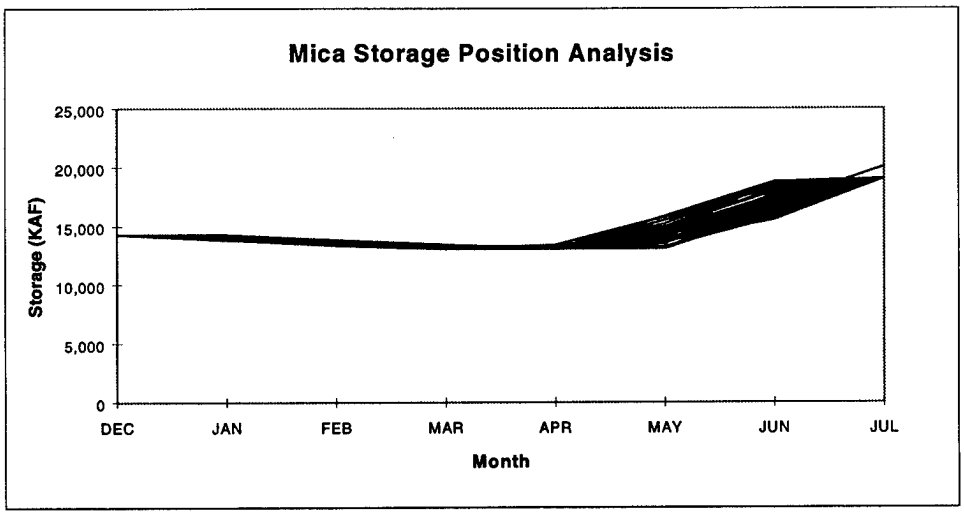
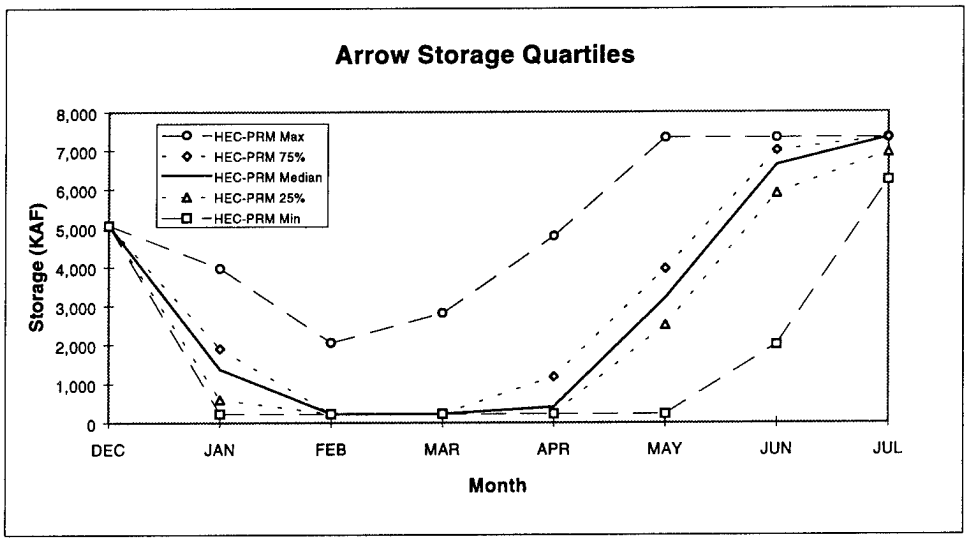
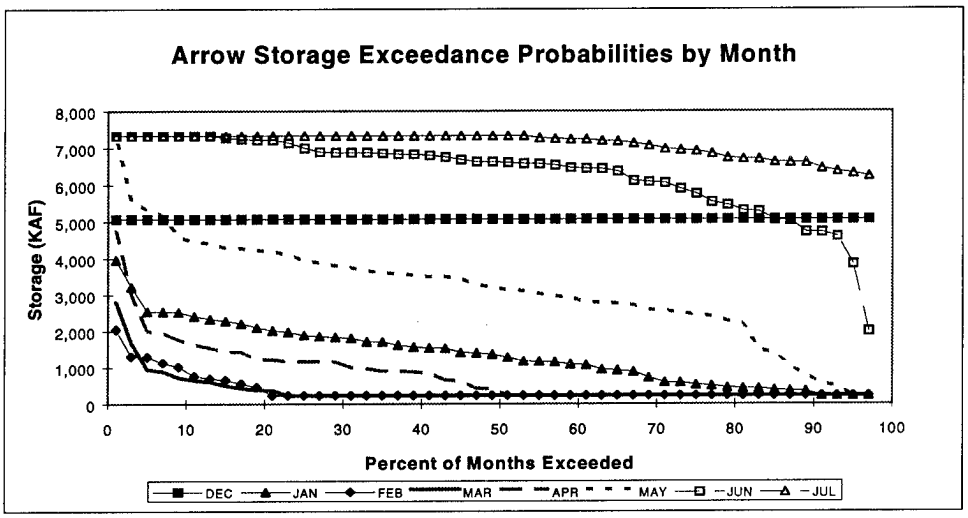


Figure 5.9 Mica Storage Results for HEC-PRM 1994 Jan-July Study





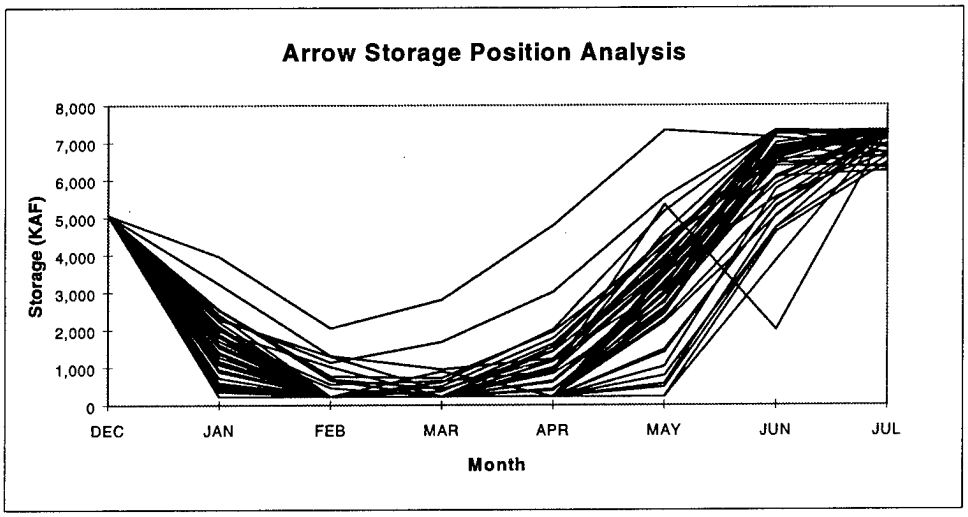
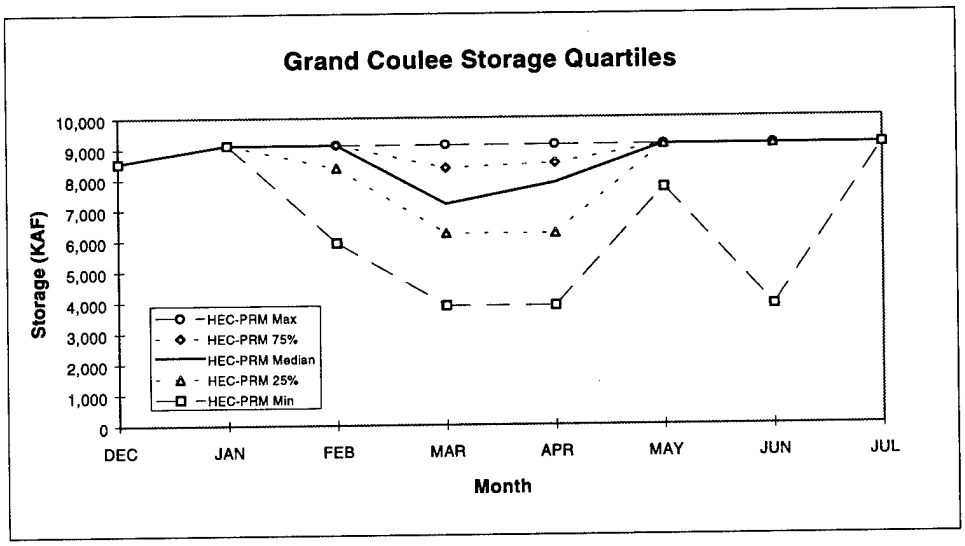
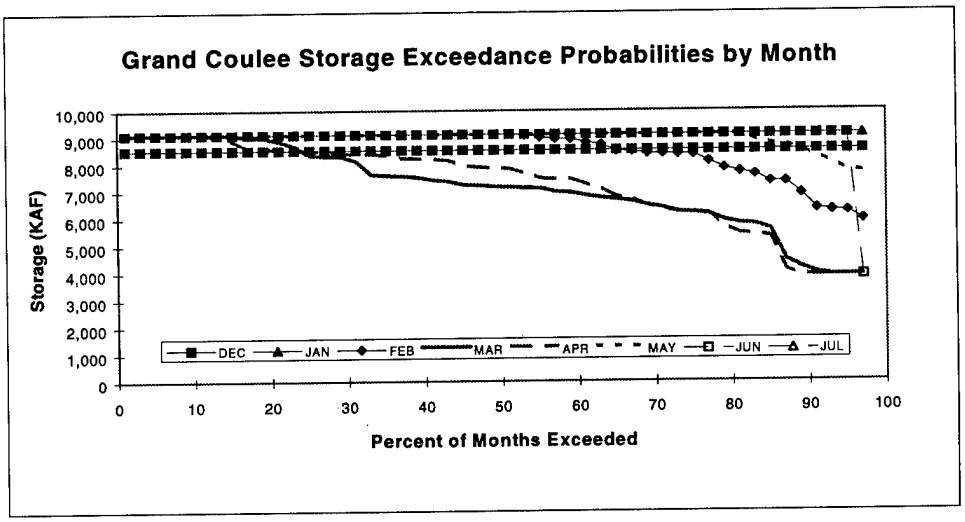


Figure 5.10 Arrow Storage Results for HEC-PRM 1994 Jan-July Study





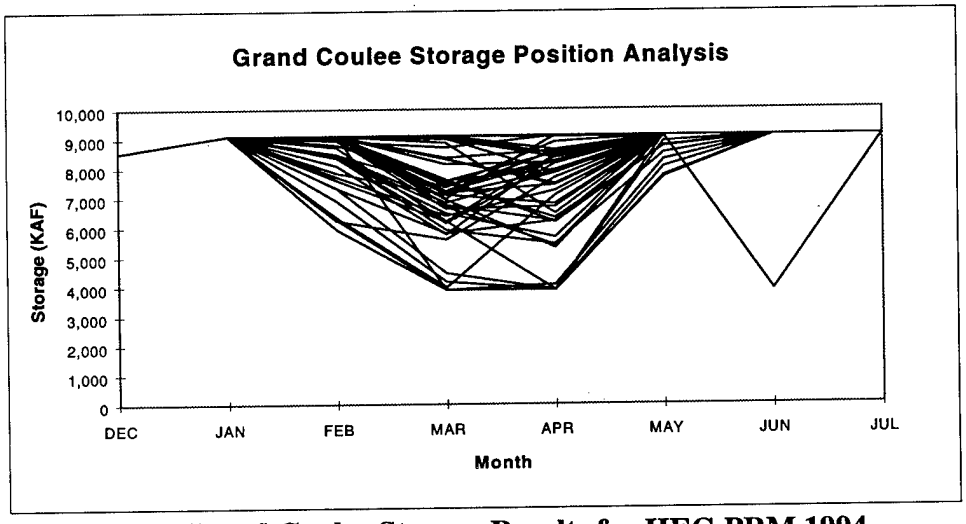
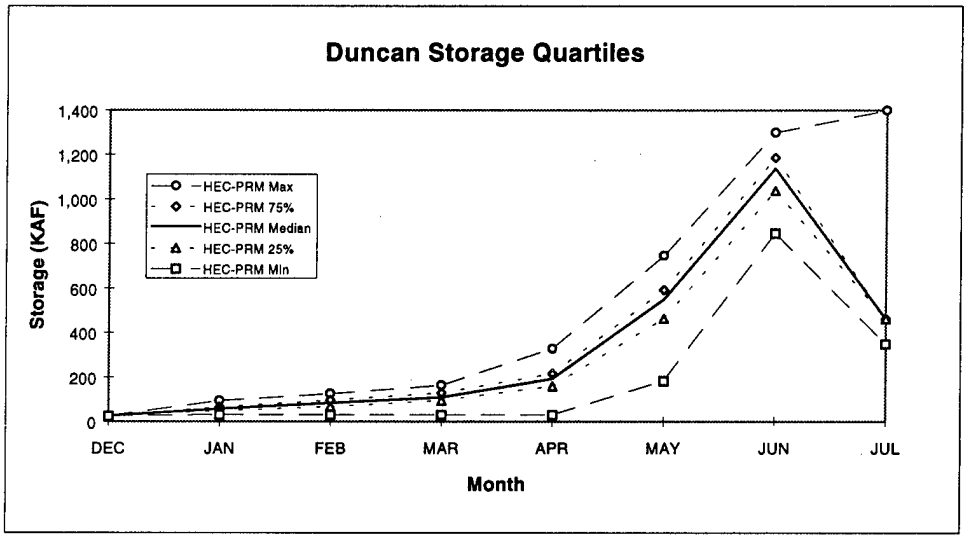
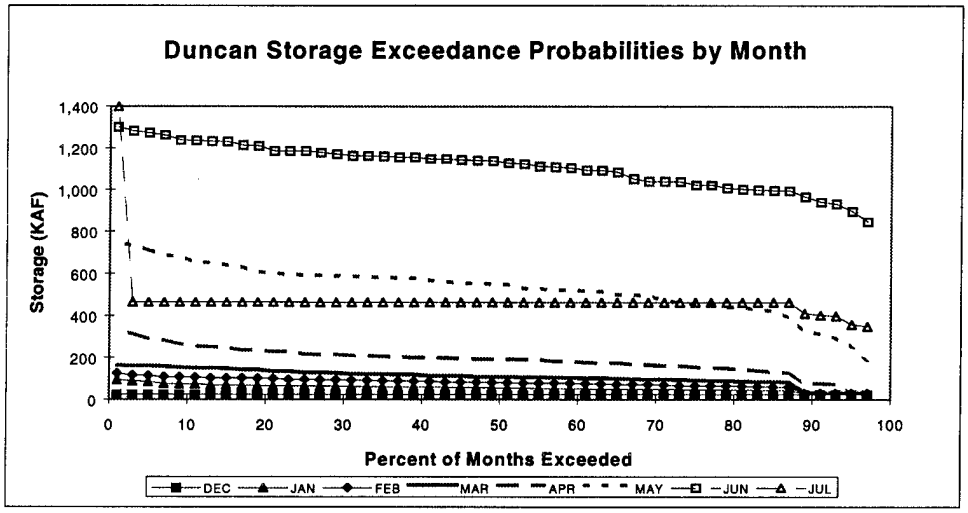


Figure 5.11 Grand Coulee Storage Results for HEC-PRM 1994 Jan-July Study





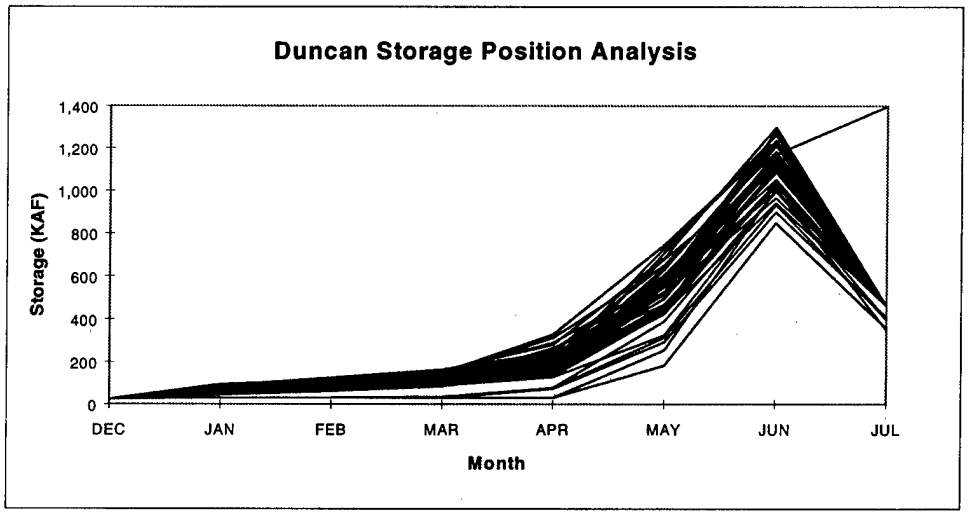
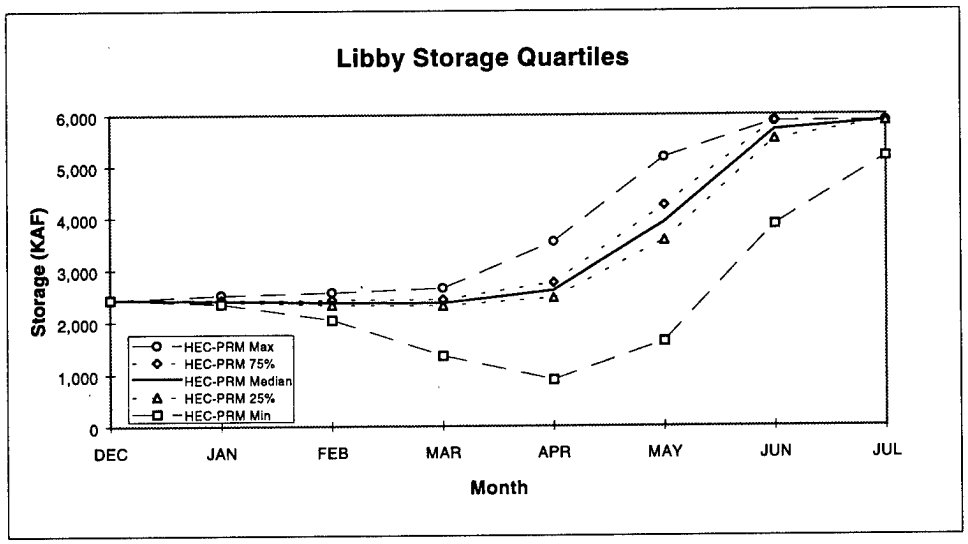
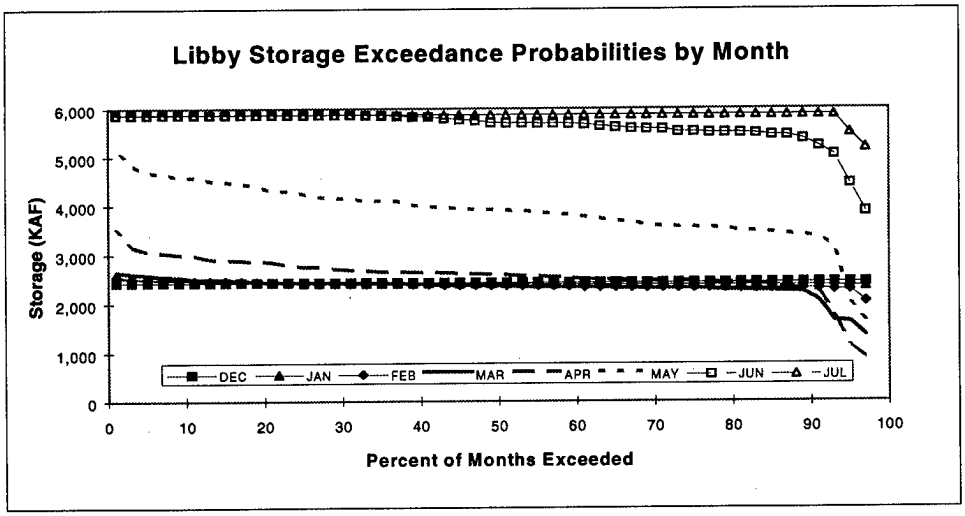


Figure 5.12 Duncan Storage Results for HEC-PRM 1994 Jan-July Study





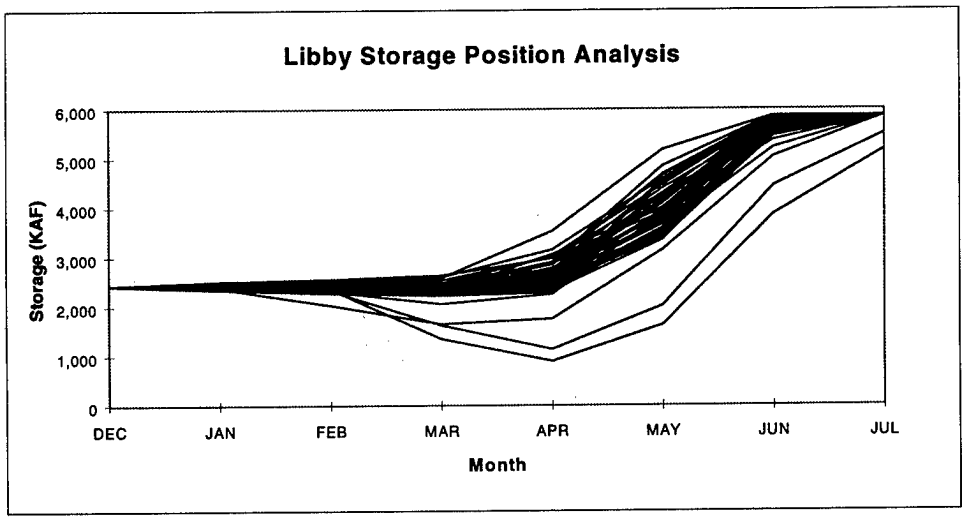
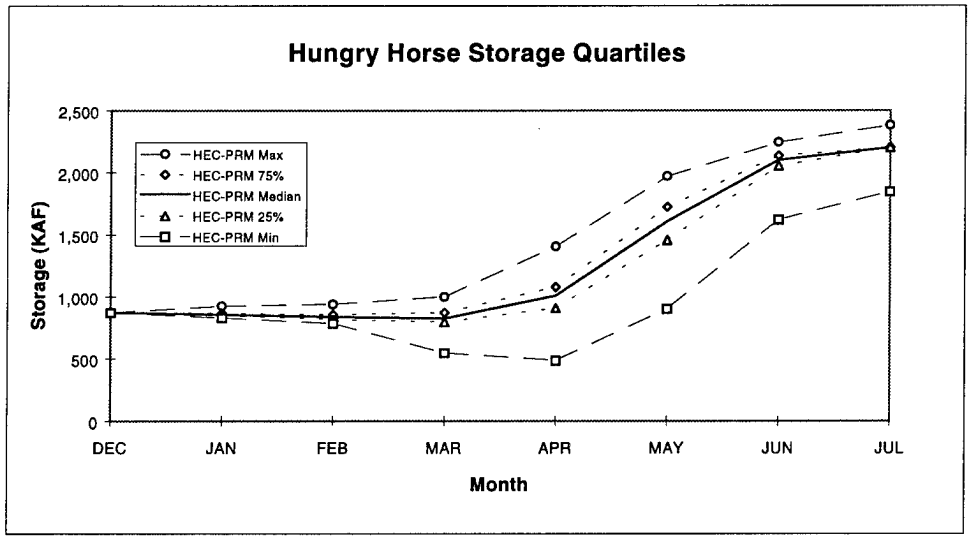
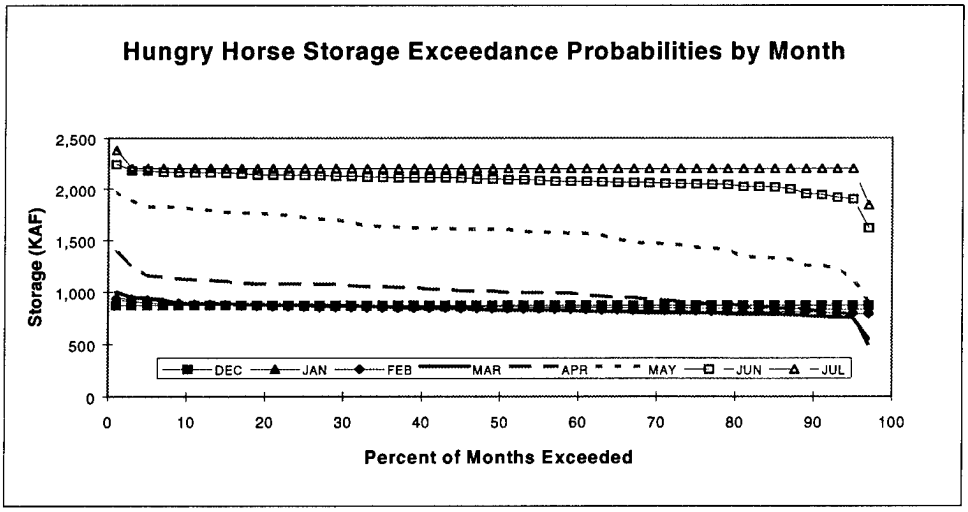


Figure 5.13 Libby Storage Results for HEC-PRM 1994 Jan-July Study





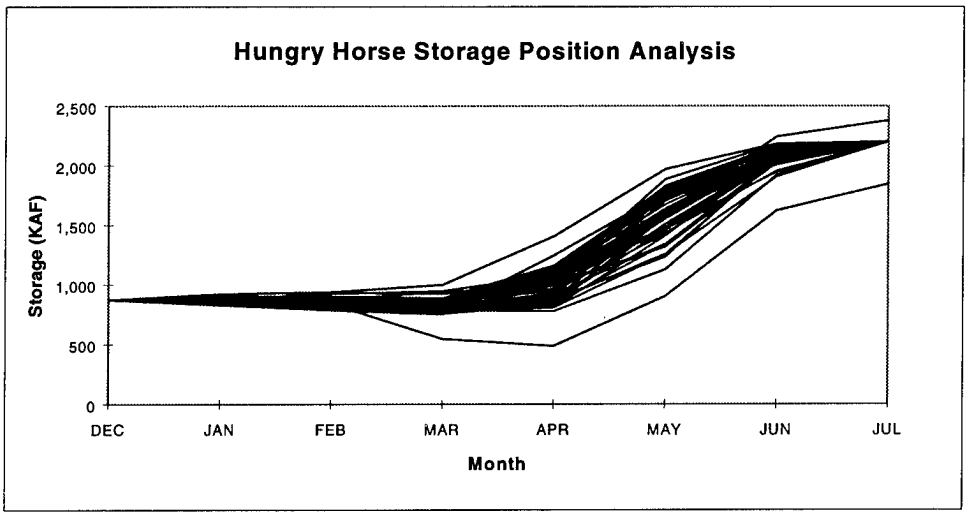
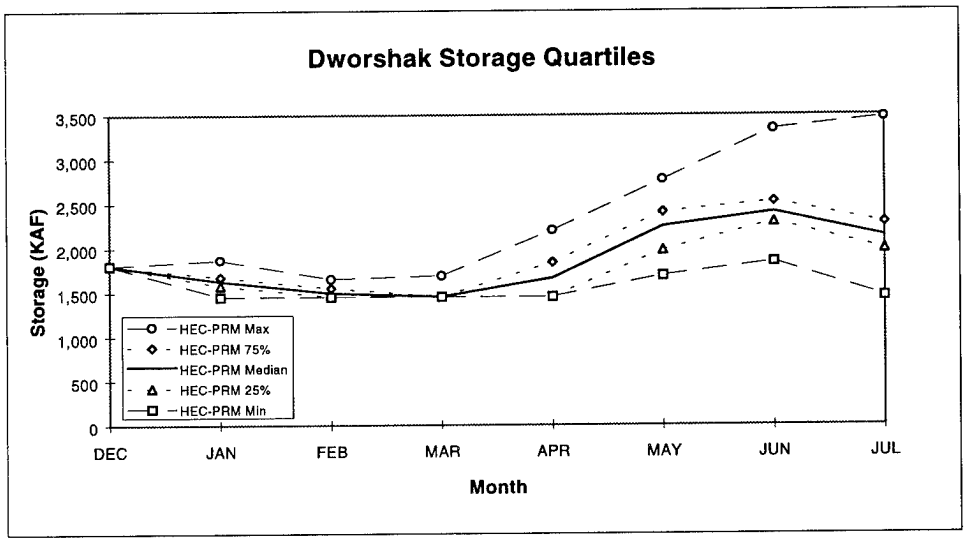
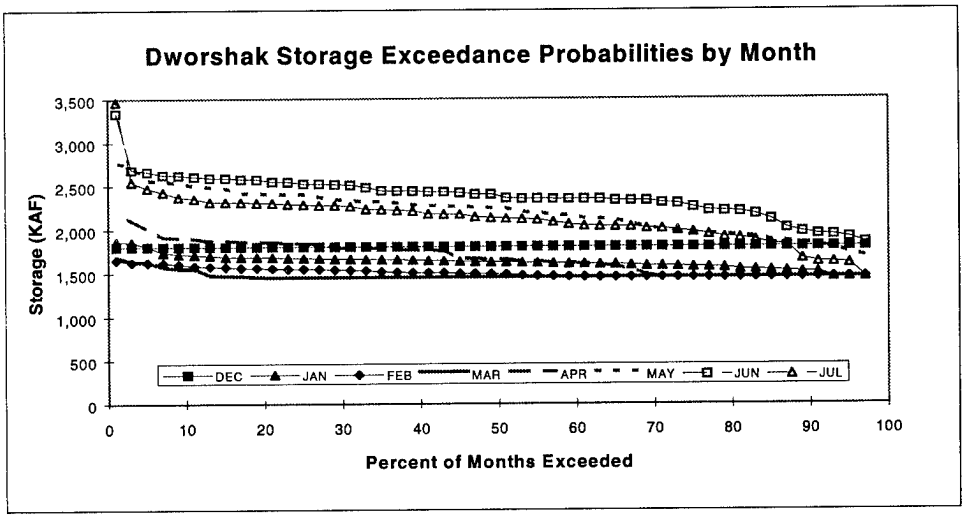


Figure 5.14 Hungry Horse Storage Results for HEC-PRM 1994 Jan-July Study





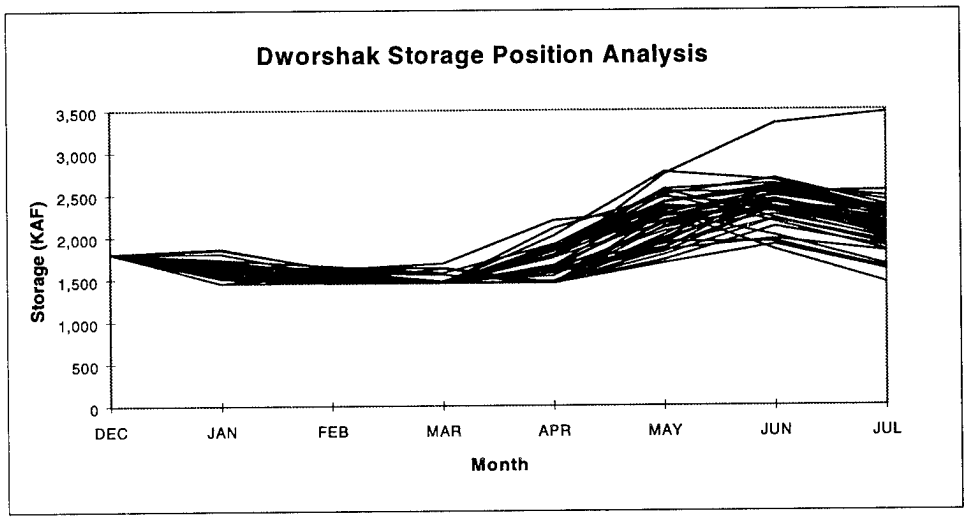


Figure 5.15 Dworshak Storage Results for HEC-PRM 1994 Jan-July Study

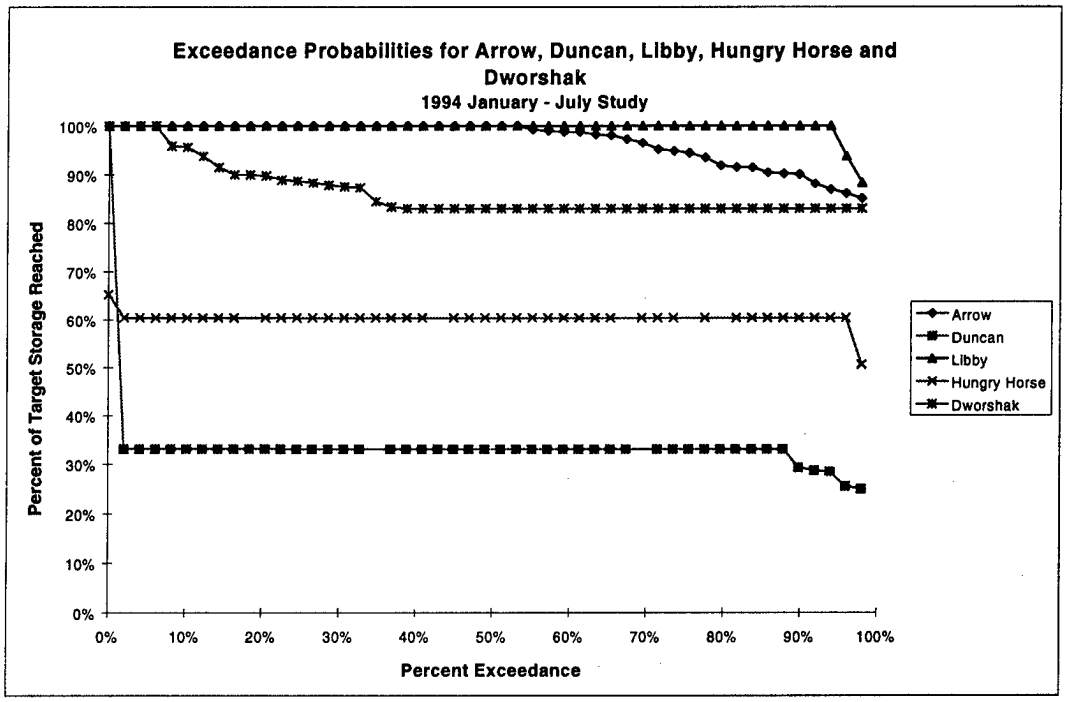


Figure 5.16 Exceedance Probabilities of Percent of Target Storage Reached for Arrow, Duncan, Libby, Hungry Horse and Dworshak for 1994 Jan-July Study

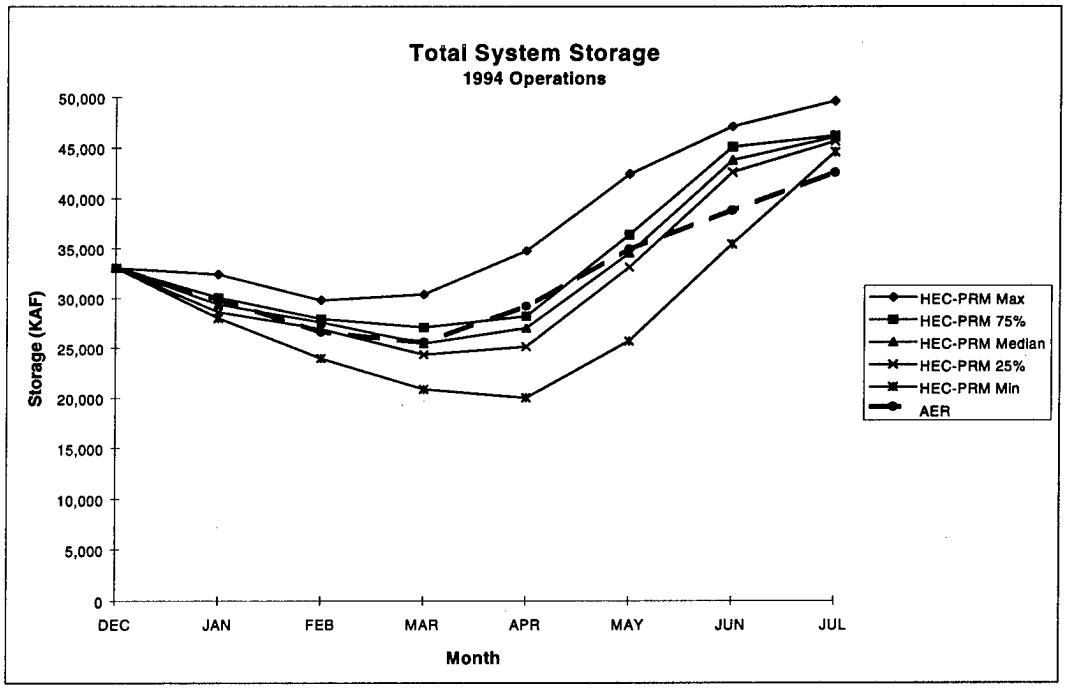


Figure 5.17 Comparison of Total System Storage for HEC-PRM 1994 Jan-July Study and 1994 AER Operations

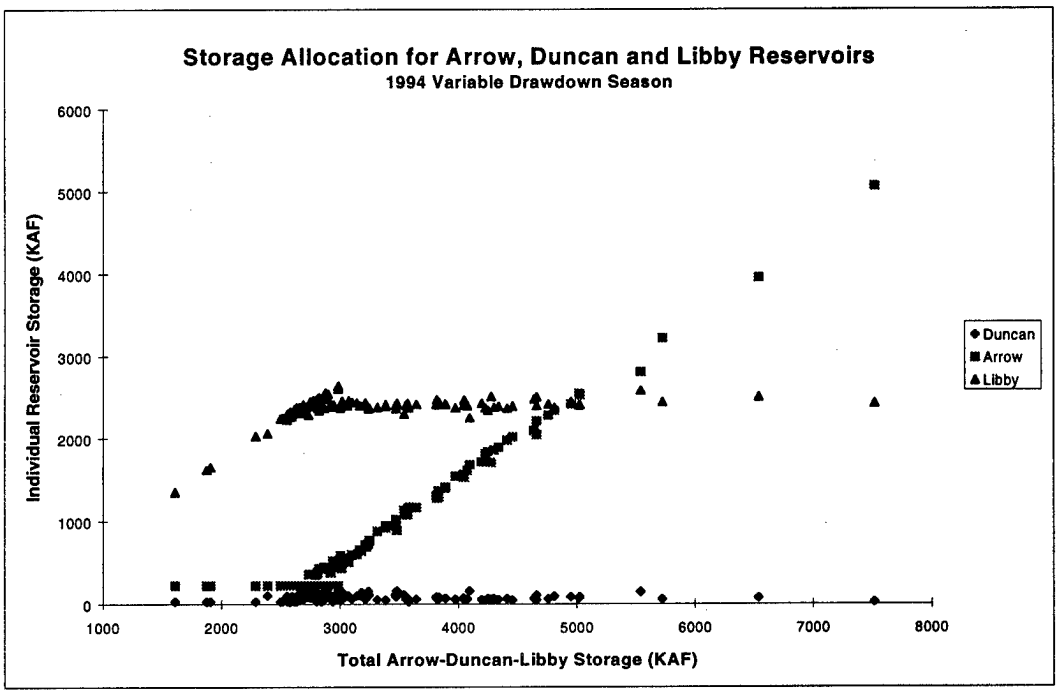


Figure 5.18 Storage Allocation for Arrow, Duncan and Libby for Variable Drawdown for 1994 Jan-July Study

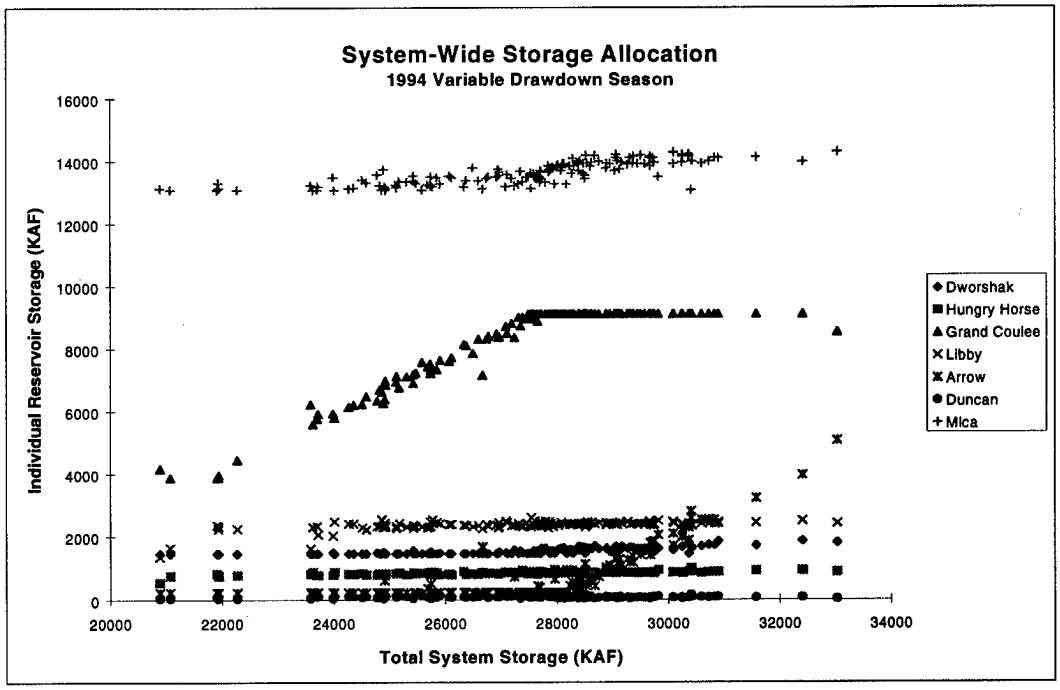


Figure 5.19 System-Wide Storage Allocation for Variable Drawdown for 1994 Jan-July Study

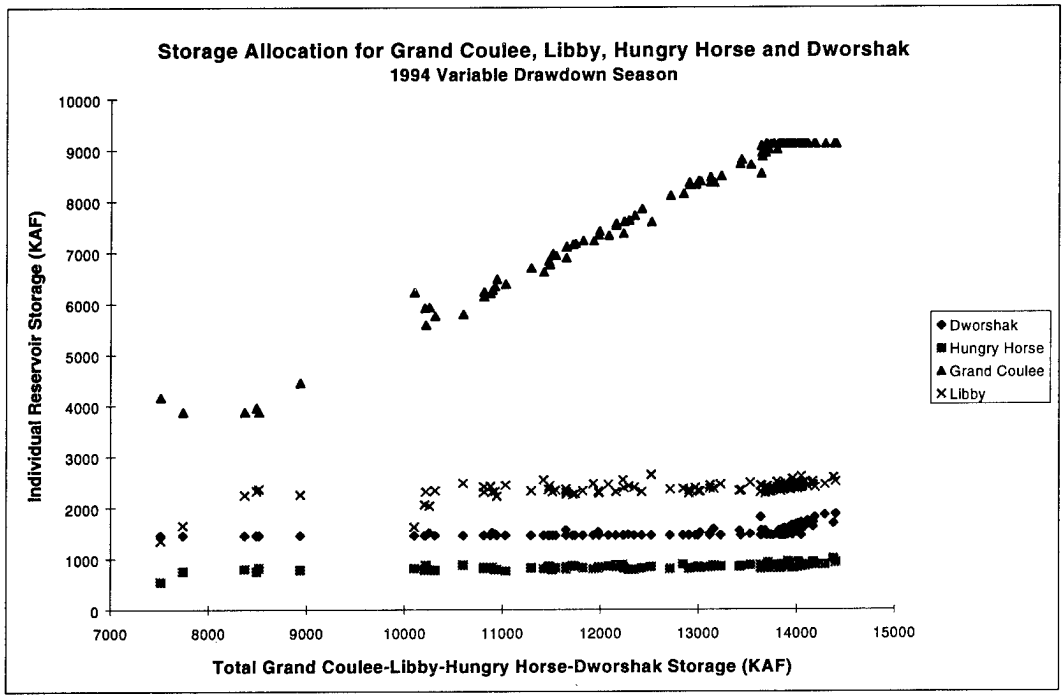


Figure 5.20 Storage Allocation for Grand Coulee, Libby, Hungry Horse and Dworshak for Variable Drawdown for 1994 Jan-July Study

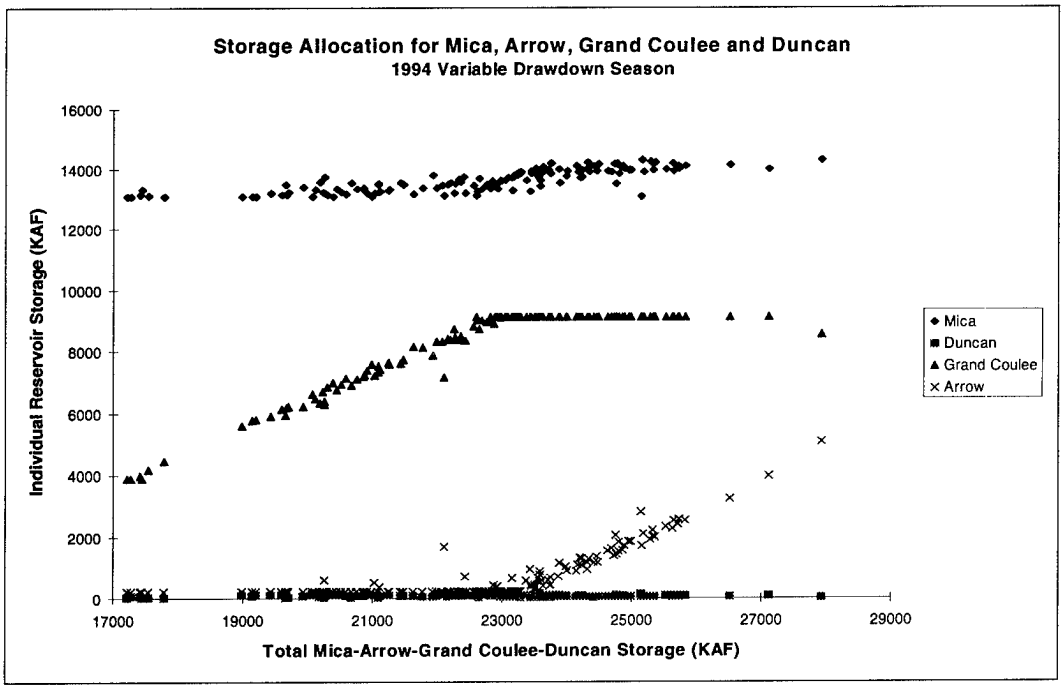


Figure 5.21 Storage Allocation for Mica, Arrow, Grand Coulee and Duncan for Variable Drawdown for 1994 Jan-July Study

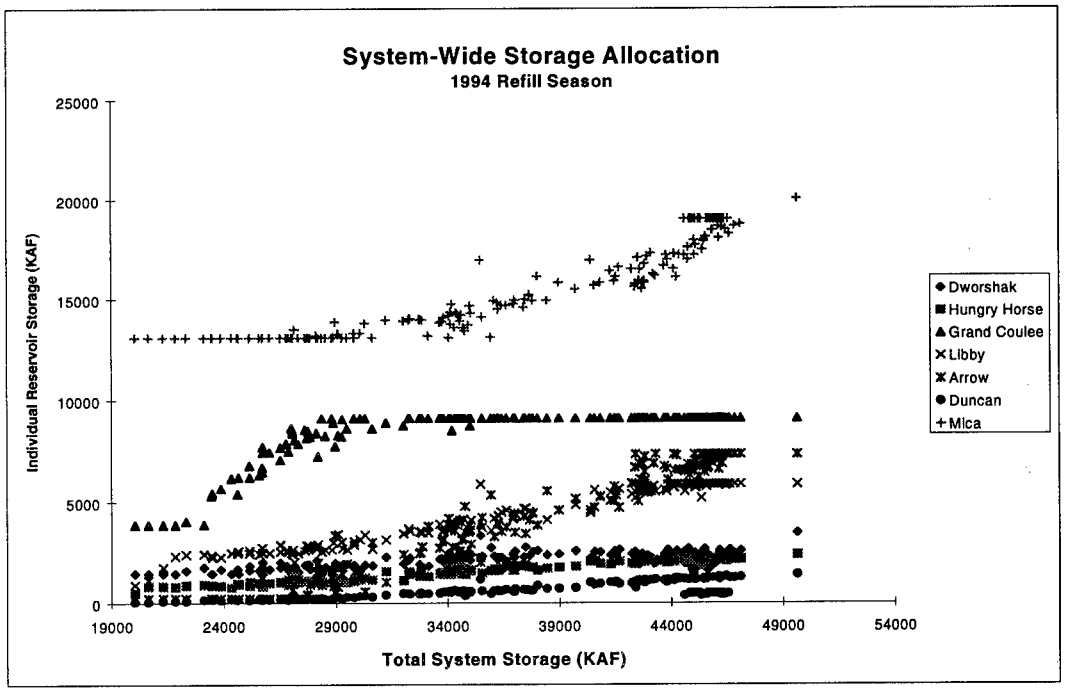


Figure 5.22 System-Wide Storage Allocation for Refill for 1994 Jan-July Study

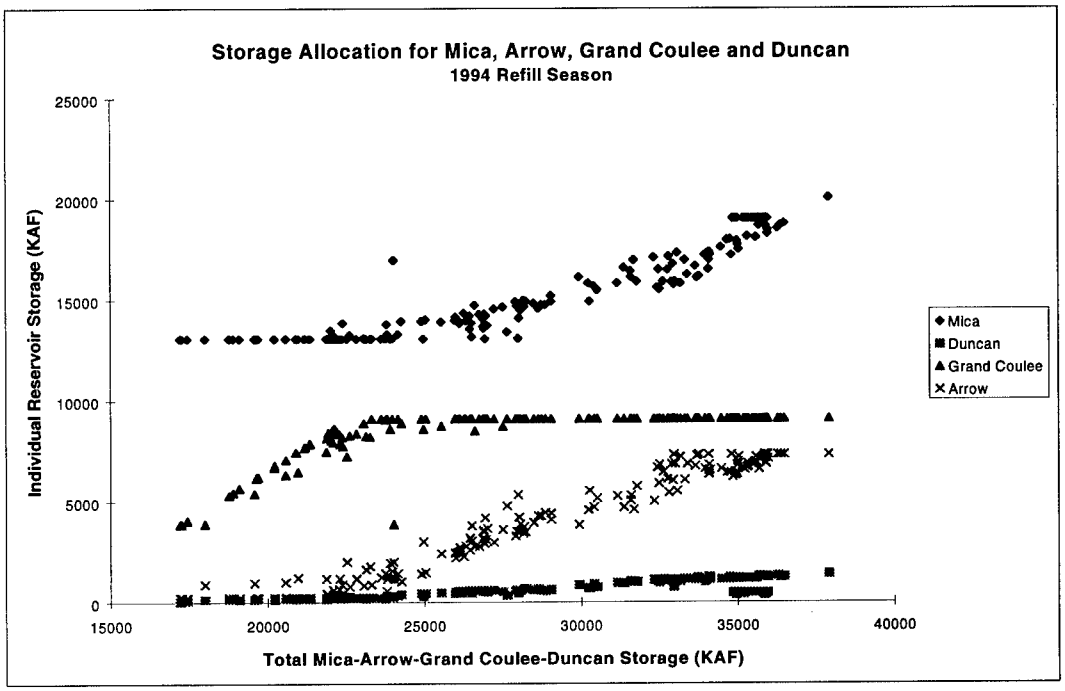


Figure 5.23 Storage Allocation for Mica, Arrow, Grand Coulee and Duncan for Refill for 1994 Jan-July Study

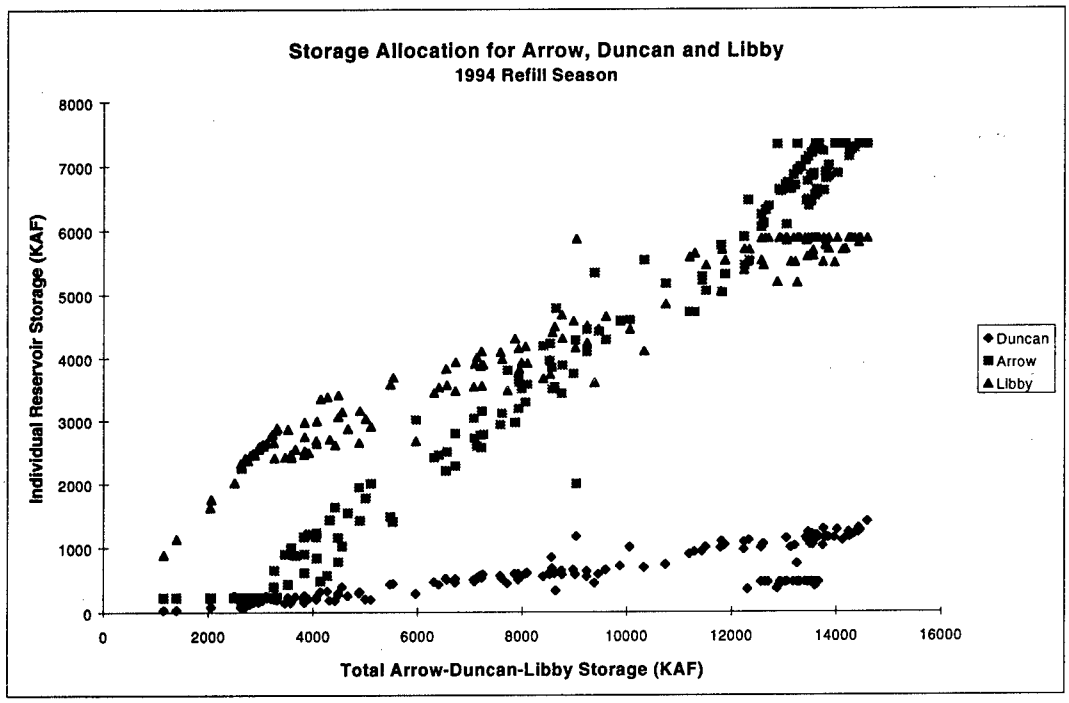


Figure 5.24 Storage Allocation for Arrow, Duncan and Libby for Refill for 1994 Jan-July Study

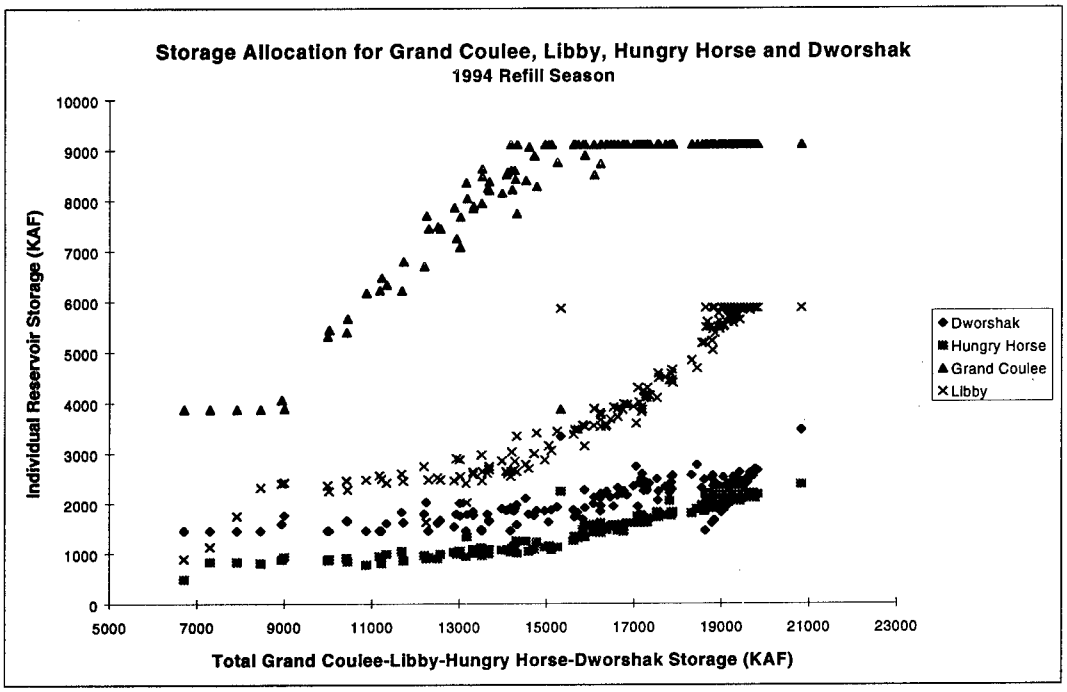


Figure 5.25 Storage Allocation for Grand Coulee, Libby, Hungry Horse and Dworshak for Refill for 1994 Jan-July Study

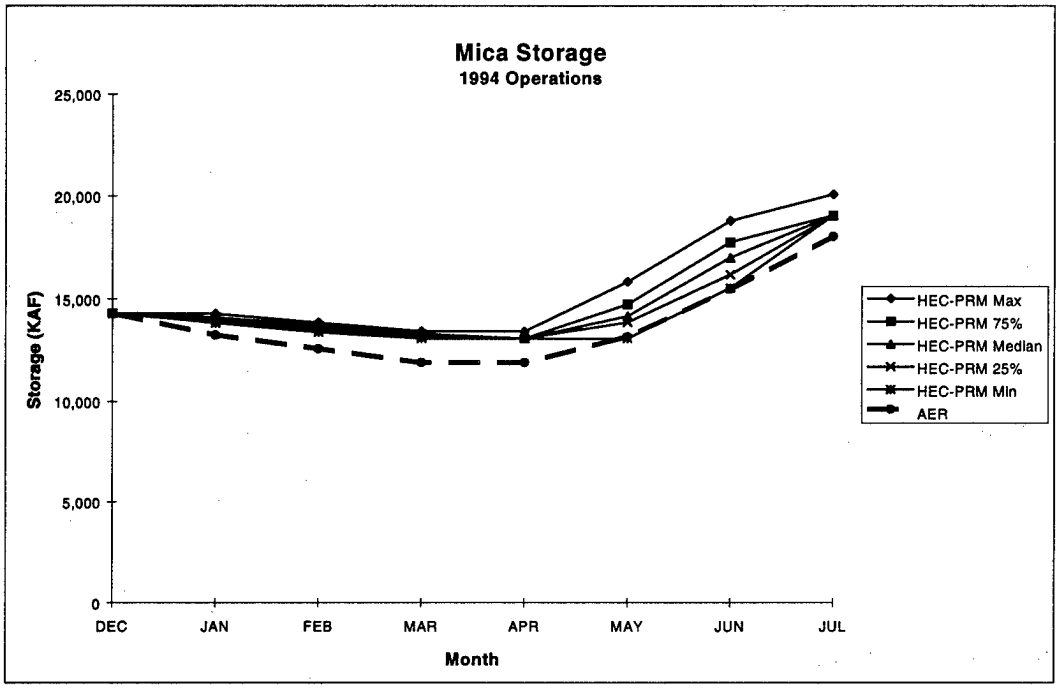


Figure 5.26 Comparison of Mica Storage for HEC-PRM 1994 Jan-July Study and 1994 AER Operation

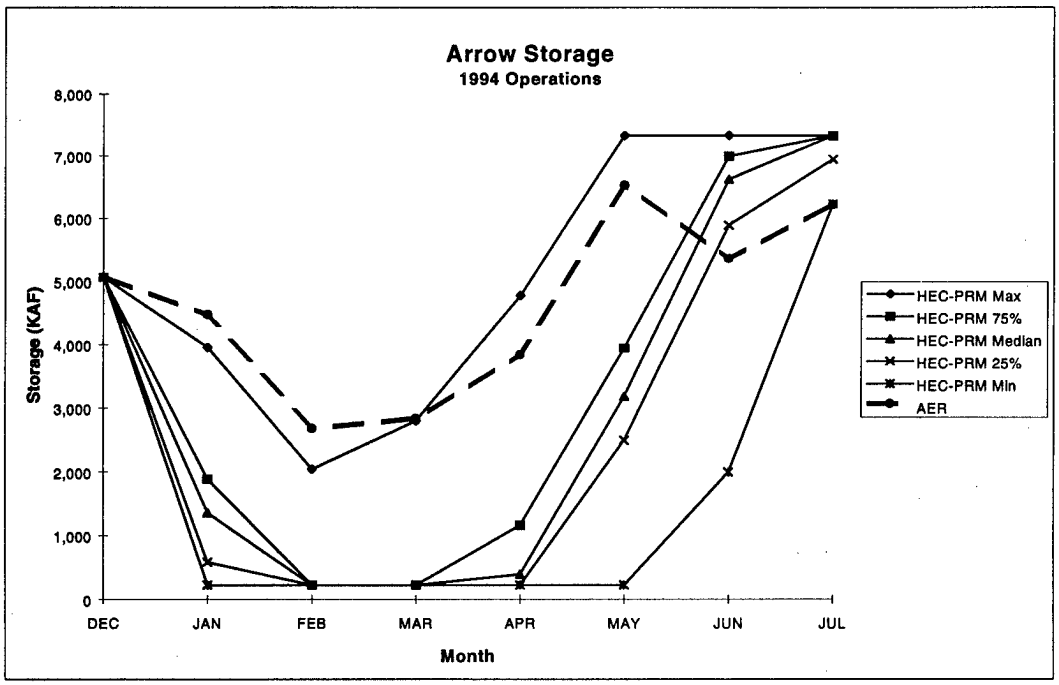


Figure 5.27 Comparison of Arrow Storage for HEC-PRM 1994 Jan-July Study and 1994 AER Operation

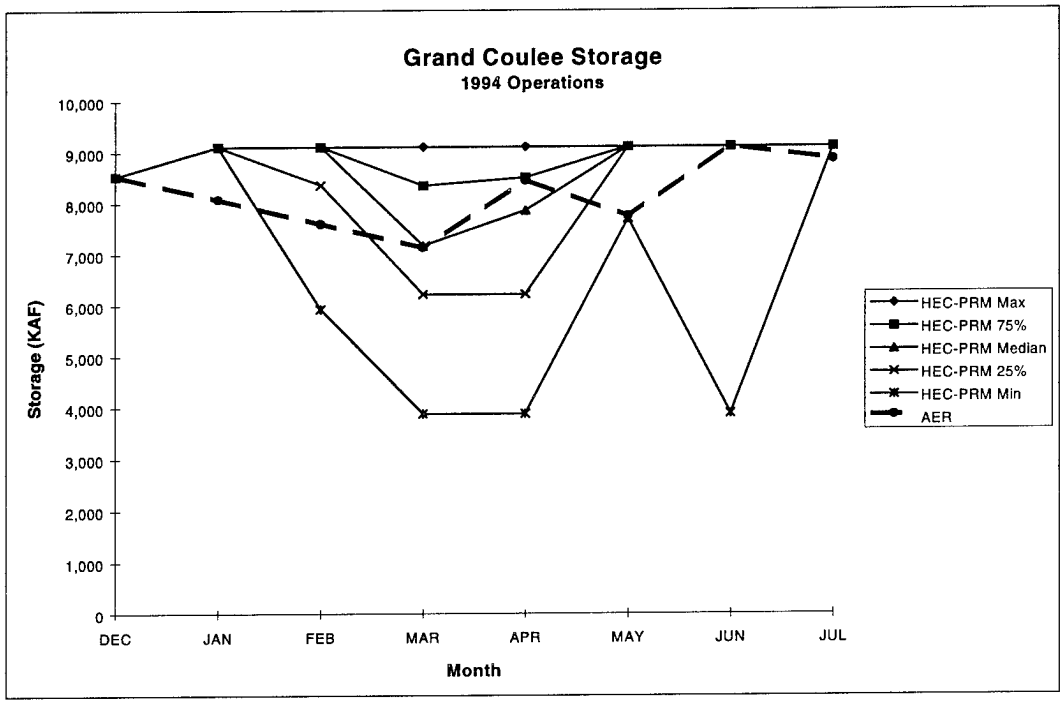


Figure 5.28 Comparison of Grand Coulee Storage for HEC-PRM 1994 Jan-July Study and 1994 AER Operation

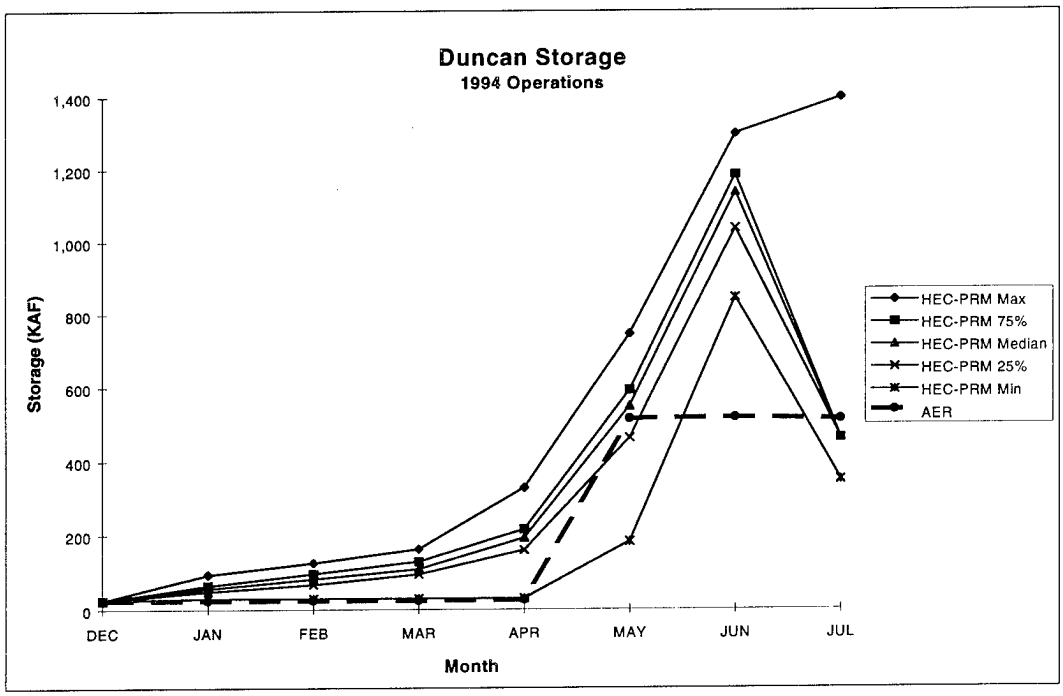


Figure 5.29 Comparison of Duncan Storage for HEC-PRM 1994 Jan-July Study and 1994 AER Operation

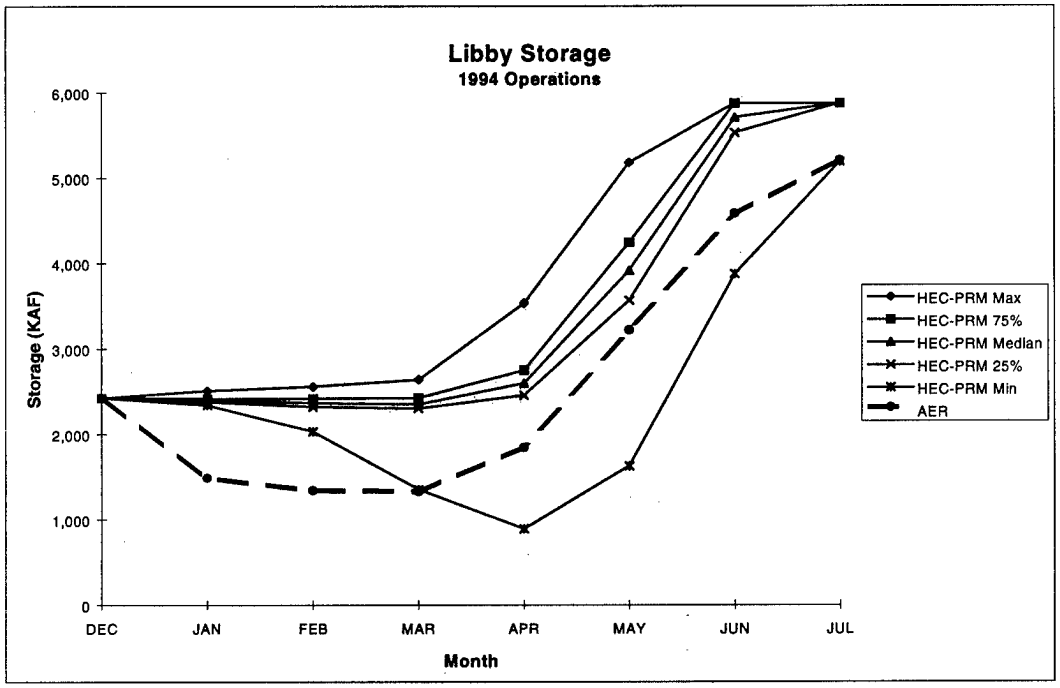


Figure 5.30 Comparison of Libby Storage for HEC-PRM 1994 Jan-July Study and 1994 AER Operation

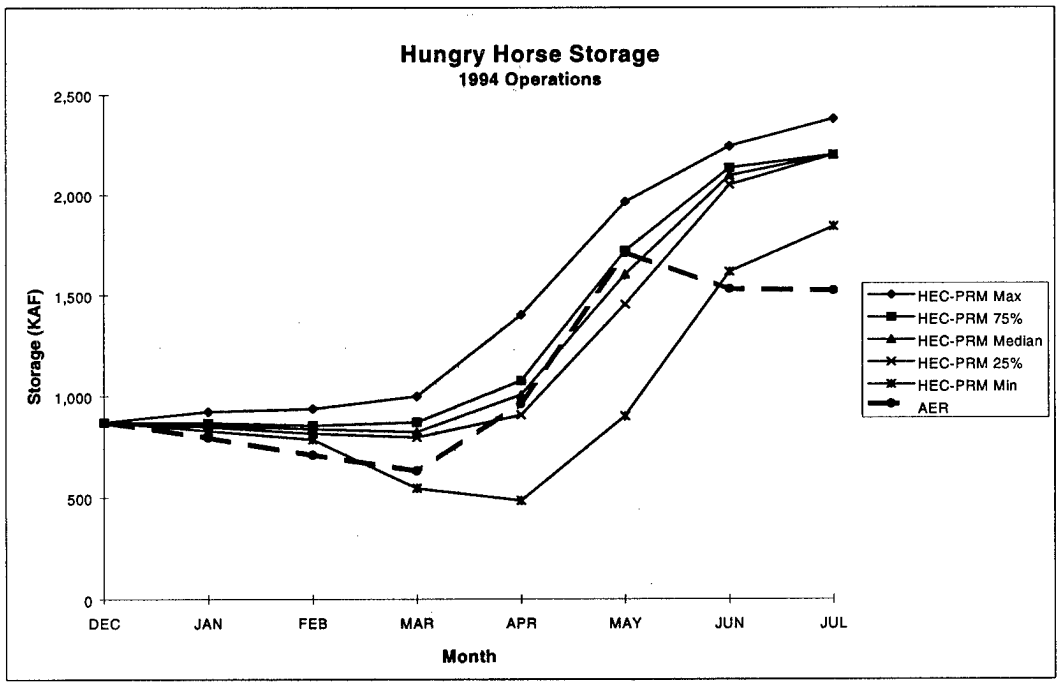


Figure 5.31 Comparison of Hungry Horse Storage of HEC-PRM 1994 Jan-July Study and 1994 AER Operation

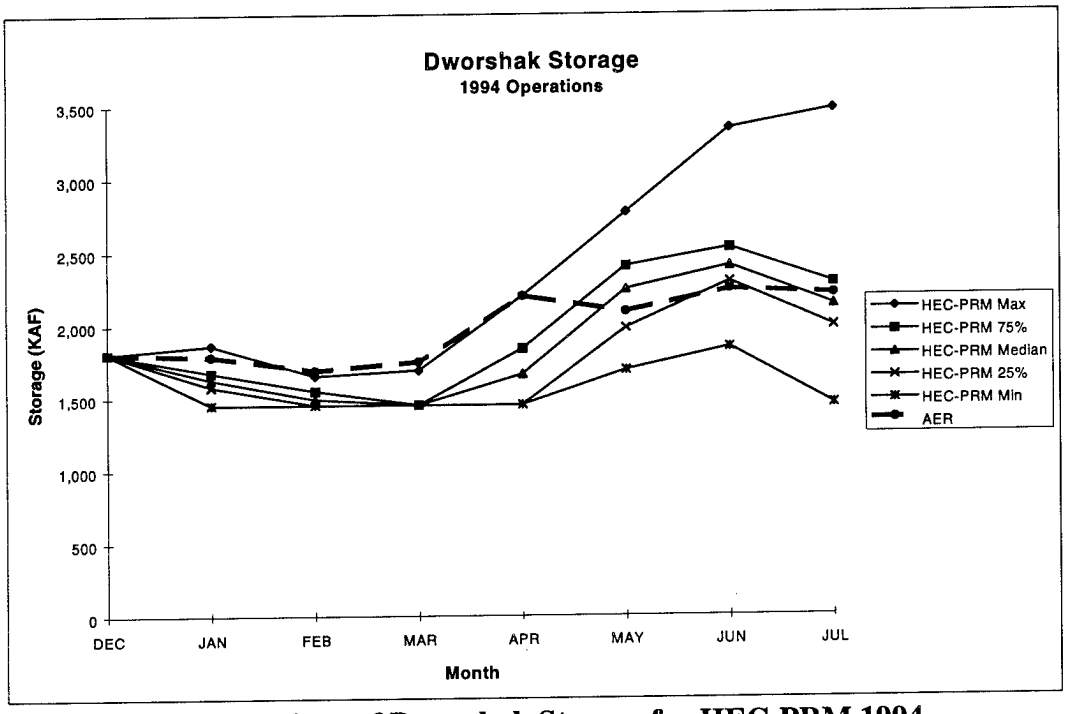


Figure 5.32 Comparison of Dworshak Storage for HEC-PRM 1994 Jan-July Study and 1994 AER Operation

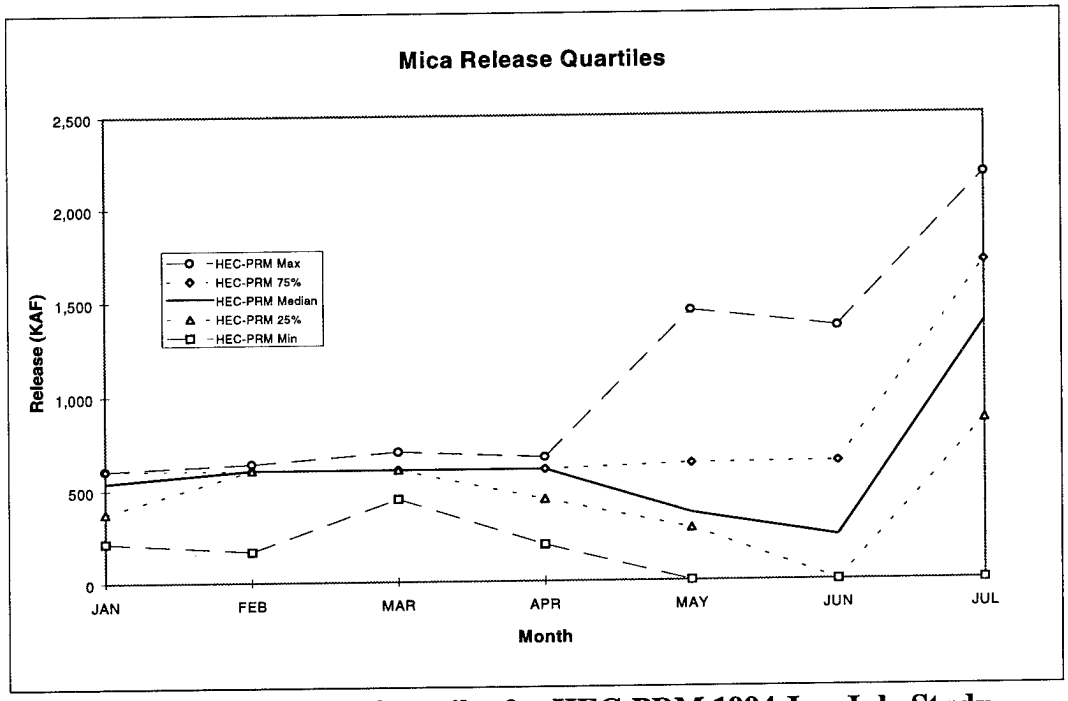


Figure 5.33 Mica Release Quartiles for HEC-PRM 1994 Jan-July Study

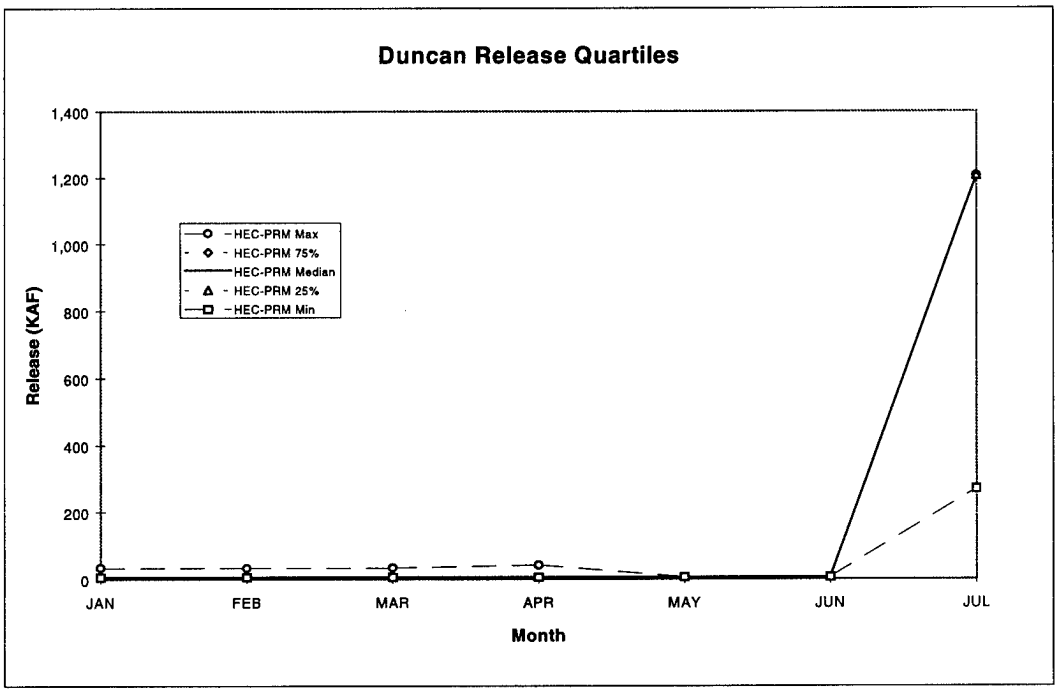


Figure 5.34 Duncan Release Quartiles for HEC-PRM 1994 Jan-July Study

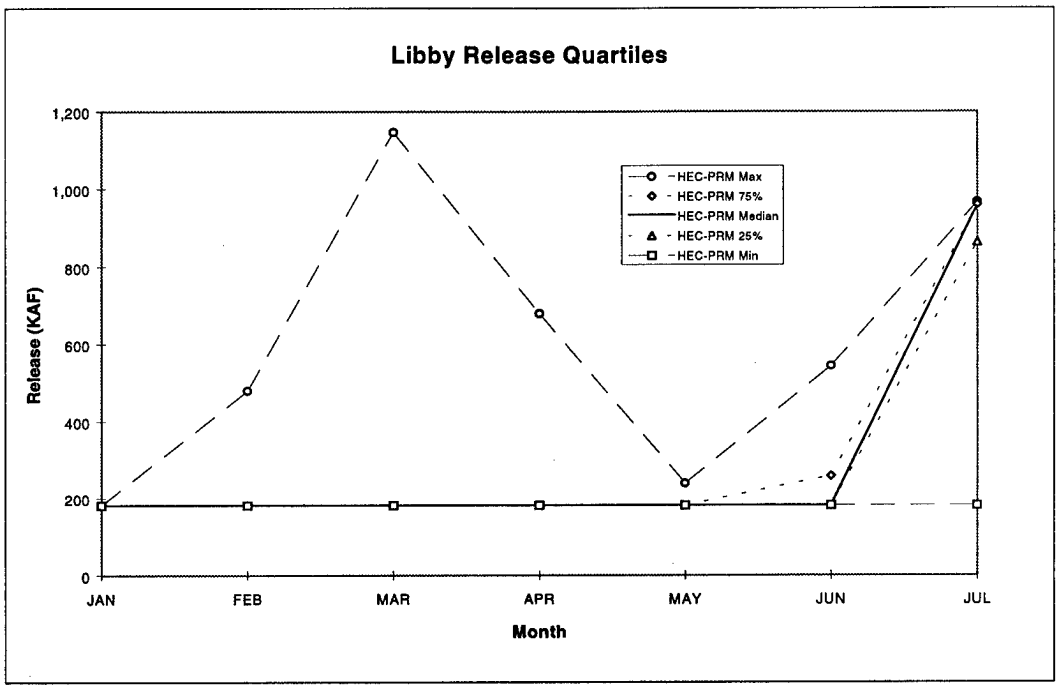


Figure 5.35 Libby Release Quartiles for HEC-PRM 1994 Jan-July Study

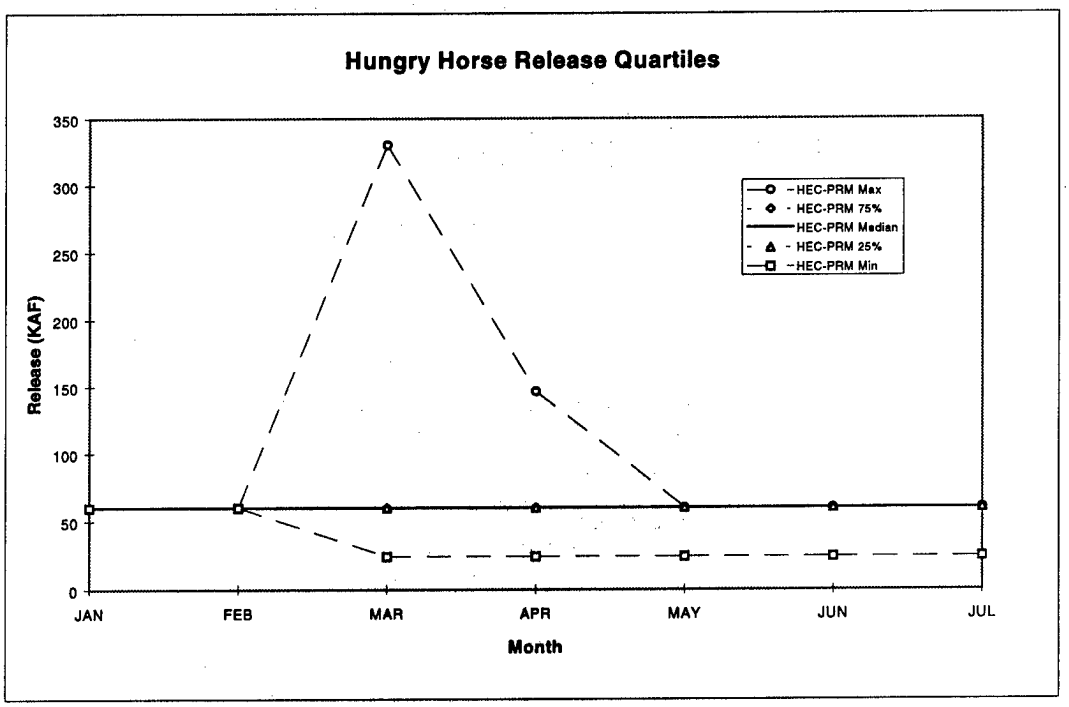


Figure 5.36 Hungry Horse Release Quartiles for HEC-PRM 1994 Jan-July Study

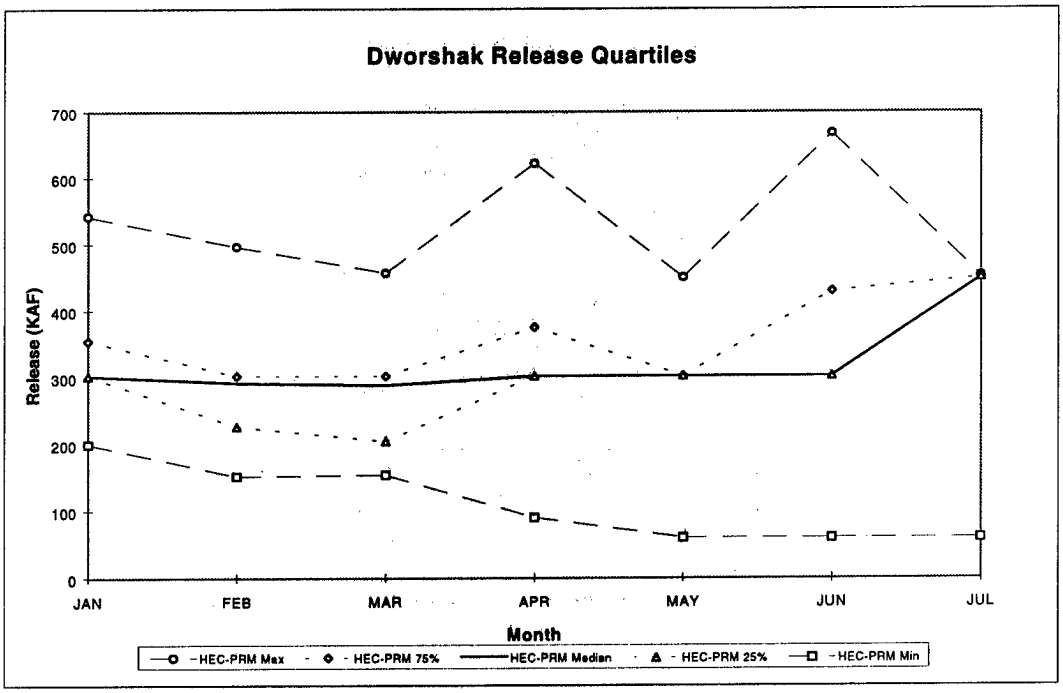


Figure 5.37 Dworshak Release Quartiles for HEC-PRM 1994 Jan-July Study

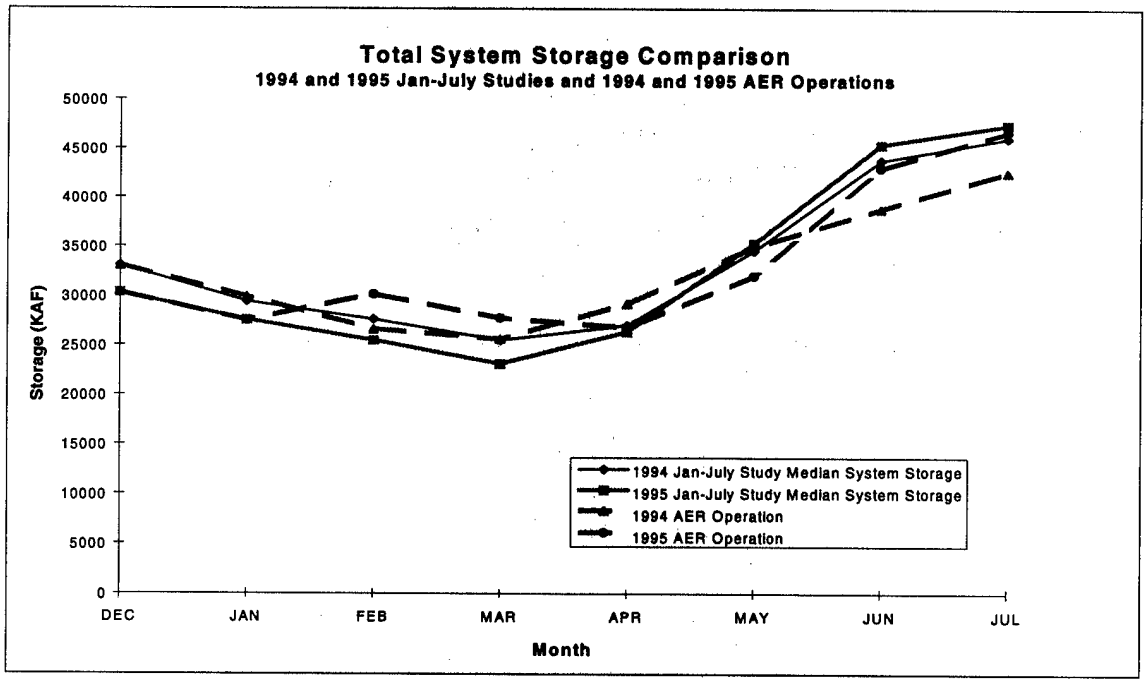


Figure 5.38 Comparison of Total System Storage for 1994 and 1995 Jan-July Studies and 1994 and 1995 AER Operations

Chapter 6

1994 Drawdown Season Study

Chapter 6 describes the HEC-PRM 1994 drawdown season study. This study includes two drawdown seasons, the fixed drawdown season (August - December) and the variable drawdown season (January - March). This is the only study in this report that considers the fixed drawdown season. Though modeling advice is not imperative for the fixed drawdown period because fixed rule curves usually are established, this drawdown study provides a perspective on HEC-PRM operations for the fixed drawdown season.

The first section of this chapter discusses the 1994 Drawdown season run. Section two presents a comparison of the results and advice between the 1994 Drawdown study and the 1995 January - July study.

Section 1 includes a discussion of the initial storage conditions, the study inflows, and the probability of drawing down to March targets for the 1994 Drawdown study. In addition, HEC-PRM results are compared to HYSSR results and the AER operation. The HEC-PRM near-term advice also is given. Section 2 presents the comparison of the 1995 variable drawdown season advice for both the 1994 Drawdown study and the 1995 January - July study.

6.1 The 1994 Drawdown Season Study

The 1994 Drawdown season study incorporates the fixed and variable drawdown seasons of the Columbia River System. This is the only study of the four in this report which includes the fixed drawdown season. HEC-PRM's advice for the fixed drawdown period completes the picture of HEC-PRM operation advice for an entire year.

The probabilities of reaching the drawdown targets in March 1995 are discussed. The initial storage values and inflows used in the drawdown season study are described. HEC-PRM operation is compared to both the AER operation and the HYSSR simulation results. HYSSR operation includes 49 inflow years, from 1929 - 1977. Lastly, HEC-PRM's near-term advice for the study period is presented.

6.1.1 Initial Storage and Forecasted Inflows

July Initial Storage Values

The HEC-PRM initial storage values for July 1, 1994 are listed in Table 6.1. The initial storages are Actual Energy Regulation (AER) values. AER storages are not the observed operation. Instead, the AER storage typically is the lowest draft level of a reservoir that allows

non-firm energy production in wet years (USDOE, 1991). In dry years, the AER result in firm energy production only.

Historical Inflows

The inflow sequences used for the 1994 Drawdown season study are historical inflows. Fifty years of historical inflow record, from 1929 to 1978, exist. Forecasted inflows are not used to run the 1994 Drawdown study because forecasts are unavailable in the fall. The 1994 fixed drawdown season extends from August 1, 1994 to January 1, 1995. Inflow forecasts start January 1st of each year, when the snowpack and soil moisture conditions are better known.

Table 6.1 July 1, 1994 Initial Storages (AER Values)

Reservoir	July 1 Initial Storage (KAF)
Mica	15474
Arrow	5363
Grand Coulee	9107 (Max)
Duncan	518
Libby	4578
Hungry Horse	1533
Dworshak	2237

6.1.2 Probability of Achieving Drawdown Targets in 1995

The storage reservoirs need to be drawn down by March to provide flood control space and to meet hydropower demands. HEC-PRM's advice is valuable when the operation can properly draw down the reservoirs from July to March. Drawdown is important to reduce flooding during the refill season.

The March target storage values are the median March HYSSR storage values from a past HYSSR simulation (USACE, 1995). The March targets, and HEC-PRM's success at reaching those targets, are given below in Table 6.2. All seven storage reservoirs always draw down to or below the March target storage (Figures 6.1 - 6.7).

For instance, Mica reservoir draws down below its target for 5 of 50 years. For 3 of the 5 years, Mica reaches its minimum allowable storage of 13075KAF. Arrow reservoir draws down to its target for 46 of 50 inflow sequences and reaches its minimum allowable storage of 227KAF in the remaining inflow sequences. Similarly, Grand Coulee draws down to its target storage, except for four years when the storage is 3879KAF, the minimum allowable storage. Duncan

reservoir draws down to its target in March for 47 of 50 years. For the other three years, Duncan drains to its minimum level of 30KAF.

Libby's March target storage is met for 96% of the inflow sequences. For the other inflow sequences, Libby stores the minimum allowable level of 890KAF. Hungry Horse draws down to its target storage for 40% of the inflow sequences. In 28 of the remaining 30

Table 6.2 March 1995 Target Storage Analysis for 1994 Drawdown Study

Reservoir	March 1995 Target Storage (KAF)	Percentage of Years Drawdown Storage Target Met (%)	March 1995 Median HEC-PRM Storage (KAF)	March 1995 AER Storage (KAF)
Mica	14000	100	14000	11950
Arrow	500	100	500	2226
Grand Coulee	4200	100	4200	7627
Duncan	40	100	40	131
Libby	1500	100	1500	2351
Hungry Horse	1800	100	1690	627
Dworshak	1750	100	1452 (Min)	2839

inflow sequences, the storage levels range from 1340KAF to 1795KAF. Hungry Horse reaches its minimum allowable storage of 486KAF in only one year. For 90% of the inflow years, HEC-PRM operates Dworshak reservoir below the target storage. In fact, Dworshak reservoir draws down to its minimum allowable storage of 1452KAF for 30 of the 45 years.

6.1.3 HEC-PRM System Operations for 1994 Drawdown Study

1994 Fixed Drawdown Period (August - January)

The fixed drawdown season in the Columbia River System is typically from August to December. The 1994 Drawdown season study begins in July, therefore, the HEC-PRM operation includes the end month of the refill period. HEC-PRM draws down the system from August to December during the fixed drawdown season (Figure 6.8). The AER operation draws down in August also (Figure 6.8). HYSSR draws down the system later in the season, starting in September rather than August (Figure 6.8).

HEC-PRM tends to store less water in the system by the end of December than HYSSR. Typically, HEC-PRM stores more water in the system than the AER operation. By January 1st, the AER operation stores less water than HEC-PRM and HYSSR.

Storage allocation plots provide a detailed look at HEC-PRM's drawdown advice. The order of drawdown among the individual reservoirs in the system is described in clear graphical form. The individual reservoir operations are plotted against the corresponding total system storage values. By reading the plot from one end to another, either the drawdown or refill pattern is represented. For the fixed drawdown season, start analysis from the right side and progress to the left. The storage allocation plots are an easy way to discover HEC-PRM's system operation in an integrated sense.

Using Figure 6.9 as a sample, HEC-PRM's near-term operation for Grand Coulee, Libby, Hungry Horse and Dworshak reservoirs can be studied for the fixed drawdown period. Analyzing the plot from the right, Dworshak is the first of the four reservoirs to draw down in the fixed drawdown period. Next, Hungry Horse begins to drawdown. Grand Coulee reservoir is level at 9107KAF (maximum allowable storage) and maintains this level throughout the season. Dworshak reservoir continues to drawdown. When the water in the reservoir system is ~8500KAF, Libby draws down significantly. Hungry Horse and Dworshak level out and, ultimately, Libby is the last reservoir to draw down.

The storage allocation plot for the seven reservoirs in the fixed drawdown period is shown in Figure 6.10. Mica, Duncan and Dworshak drawdown first. Arrow and Hungry Horse seems to fluctuate up and down relatively small amounts. Grand Coulee and Libby stay level. As soon as ~3000KAF is released from the system, Arrow begins to draw down dramatically. Mica, Duncan, Hungry Horse and Dworshak reservoirs draw down considerable amounts also. Grand Coulee's storage remains constant. Arrow reaches its minimum allowable storage at 227KAF and Grand Coulee's storage takes a slight, temporary dip. Grand Coulee returns to 9107KAF. Libby is the last reservoir to draw down. Mica, Duncan, Hungry Horse and Dworshak reservoirs stay fairly constant at this time.

1995 Variable Drawdown Period

In practice, the variable drawdown season is operated on a different basis than the fixed drawdown season. The January 1 inflow forecasts are used to operate reservoir storage during the variable drawdown season, whereas a fairly consistent drawdown procedure is employed for the fixed drawdown season. For the HEC-PRM 1994 Drawdown season study, though, HEC-PRM is not given the January forecast information. Typically, a HEC-PRM variable drawdown season study would not be conducted this way, but would be repeated on January 1st using updated initial storages and inflow forecasts. However, since the information is available, HEC-PRM's variable drawdown season operation using historical flows is studied anyway to determine if any useful operations are suggested.

HEC-PRM's storage allocation advice for January - March 1995 is shown graphically in Figure 6.11. Mica, Arrow, Duncan, Libby and Dworshak reservoirs drawdown initially. Grand Coulee operates at 9107KAF. Hungry Horse appears level also. After ~3000KAF is released

from the system, Grand Coulee begins to draw down. Arrow and Duncan reached their minimum allowable storages. Mica and Libby fluctuate up and down as they gradually draw down overall (Figures 6.1 and 6.5).

An additional ~2000KAF decrease in system storage occurs and Grand Coulee dramatically draws down, while the other six reservoirs continue their previous operations. When the system storage drops to ~24000KAF, Mica, Grand Coulee, Arrow, Duncan, Libby and Dworshak level out. Hungry Horse, on the other hand, draws down. Eventually, Grand Coulee reaches its minimum allowable storage level of 3879KAF. Hungry Horse is the last reservoir to draw down; the other reservoirs are at constant storages.

6.1.4 Comparison of HEC-PRM with HYSSR and AER Operations for July - September

HEC-PRM seasonal studies are used mainly to discover near-term operations. The near-term period is defined as the first three months of a study. As a result, July to September is the near-term period for the 1994 Drawdown season study. The intent of the 1994 - 1995 study is to capture the drawdown seasons, but July actually incorporates the end of the refill season. Despite this discrepancy, HEC-PRM's July operations are considered in the near-term operation to be consistent with the "near-term" definition. The HEC-PRM near-term operations are compared to HYSSR results and the AER operations on the basis of storage trends and storage magnitudes.

Near-Term Storage Trend Comparison

The storage trends for HEC-PRM, HYSSR and the AER operation are listed in Table 6.3. The comparisons are favorable. HEC-PRM trends matched the HYSSR results for 12 of 21 possible comparisons. HEC-PRM trends are the same as the AER operations for 10 of 21 comparisons. HYSSR matched AER 12 of 21 instances. All three operations agreed for 7 of 21 comparisons. It is encouraging that HEC-PRM's storage trend results compare well with two other operation standards.

<u>July</u>

The three operations have the same storage trends for 2 of 7 reservoirs, Arrow and Libby, in July. Both reservoirs are refilled. In addition, HEC-PRM operations agree with HYSSR trends for 4 of 7 reservoirs, Grand Coulee, Duncan, Hungry Horse and Dworshak. Grand Coulee maintains 9107KAF, and Duncan, Hungry Horse and Dworshak are refilled. Lastly, HEC-PRM matches the AER operation of refill for once in July, for Mica reservoir.

Table 6.3 Near-Term Comparison of Storage Trends for HEC-PRM 1994 Drawdown Study, 1994 HYSSR and 1994 AER Operation

RESERVOIR	HEC-PRM	HYSSR	AER
July			
Mica	Refill	Drawdown	Refill
Arrow	Refill	Refill	Refill
Grand Coulee	Maintain 9107KAF	Maintain 9107KAF	Drawdown
Duncan	Refill	Refill	Drawdown
Libby	Refill	Refill	Refill
Hungry Horse	Refill	Refill	Drawdown
Dworshak	Refill	Refill	Drawdown
August			
Mica	Refill	Refill	Refill
Arrow	Drawdown	Drawdown	Drawdown
Grand Coulee	Maintain 9107KAF	Drawdown	Drawdown
Duncan	Refill	Drawdown	Drawdown
Libby	Refill	Drawdown	Drawdown
Hungry Horse	Refill	Refill	Drawdown
Dworshak	Drawdown	Refill	Drawdown
September			
Mica	Drawdown	Mtn 14830KAF	Drawdown
Arrow	Drawdown	Drawdown	Drawdown
Grand Coulee	Maintain 9107KAF	Drawdown	Mtn 8760KAF
Duncan	Variable	Drawdown	Drawdown
Libby	Variable	Drawdown	Drawdown
Hungry Horse	Drawdown	Drawdown	Drawdown
Dworshak	Drawdown	Drawdown	Drawdown

August

HEC-PRM, HYSSR and AER operations agree for 2 of 7 reservoirs, Mica and Arrow, in August. Mica is refilled, while Arrow is drawn down. In addition, HEC-PRM matches the HYSSR trend of refill for Hungry Horse. HEC-PRM draws down Dworshak in August similarly to the AER operation also. The HYSSR and AER operations are the same for 3 reservoirs, Grand Coulee, Duncan and Libby reservoirs; all drawdown.

September

HEC-PRM, HYSSR and AER have the same trend of drawdown for 3 reservoirs, Arrow, Hungry Horse and Dworshak. The HEC-PRM trend for Mica reservoir is the same as the AER operation. Mica is drawn down by both in September, and Grand Coulee maintains its high storage level. The HYSSR operation matches the AER trends for Duncan and Libby in September. Both Duncan and Libby are drawn down.

Near-Term Storage Magnitude Comparison

HEC-PRM results, HYSSR results and the AER operations are compared for storage magnitude differences. The comparisons are made for the near-term period, July, August and September.

Figures 6.12 - 6.18 show the storage operations. The HYSSR storage results for June 30 are not shown on the plots because this information is unavailable. For the HEC-PRM and HYSSR results, only the 25th - 75th percentile curves are graphed, for clarity. The magnitude differences are comparisons between the median HEC-PRM storage and the AER operation, and the median HYSSR storage with the AER operation. The magnitude differences also are measured relative to the total storage capacity of the given reservoir for perspective.

System-Wide

Comparing the median HEC-PRM and HYSSR storage values with the AER operation, HEC-PRM typically stores more water in the total system than both HYSSR and AER in July, August and September (Figure 6.8). For Duncan, Libby and Hungry Horse reservoirs specifically, HEC-PRM and HYSSR median storages are greater than the AER storage (Figures 6.15 - 6.17). HEC-PRM and AER operate Mica similarly, but, notably, HEC-PRM and AER operations both store significantly more water than HYSSR in Mica reservoir (Figure 6.12).

HEC-PRM stores the least amount of water in Arrow; both HYSSR and AER operations store more than the median HEC-PRM storage (Figure 6.13). HEC-PRM, HYSSR and AER operations store approximately the same amount of water in Grand Coulee in July, August and September (Figure 6.14). Lastly, HEC-PRM, HYSSR and AER operations in Dworshak are similar in July, August and September (Figure 6.18).

Mica Reservoir

The basic storage trajectories of HEC-PRM, HYSSR and the AER operations are similar (Figure 6.12). Notably, the HYSSR operation curves are considerably less than the HEC-PRM and AER curves. Typically, HEC-PRM and AER operations in July, August and September are very similar. During these three months, the difference between the median HEC-PRM storage value and the AER storage is ~600KAF, less than 3% of Mica's total storage capacity. In July, the median HEC-PRM storage is greater than the AER. Conversely, in August and September, the median HEC-PRM value is less than the AER.

HEC-PRM stores more water in Mica in July, August and September than HYSSR. In July, the magnitude difference is over ~5MAF, about 25% of Mica's total storage capacity. The differences decrease in August and September to ~4MAF and ~2.8MAF, respectively. By September, the magnitude difference between median values is ~14% of the total storage of Mica.

Arrow Reservoir

The HEC-PRM and AER operations for Arrow in July, August and September are similar, but the HYSSR storages are considerably greater than both HEC-PRM and AER operations (Figure 6.13). The median HEC-PRM values are very close to the AER storages in July and August, approximately 300KAF less than AER, ~4% of Arrow's total storage capacity. In September, the median HEC-PRM value is ~1.3MAF less than the AER operation, an increase to ~18% of the total storage capacity of Arrow reservoir.

HEC-PRM typically stores considerably less water in Arrow than HYSSR. In July, the difference between median values is ~1.5MAF, ~20% of Arrow's total storage capacity. The difference increases in August and September to ~2.5MAF and ~4MAF, respectively. By September, the magnitude difference is more than 50% of Arrow's total storage capacity. HEC-PRM usually stores minimal water in Arrow, permitted by the lack of penalty functions on Arrow's operation.

Grand Coulee Reservoir

HEC-PRM, HYSSR and AER operations are essentially the same for Grand Coulee in July, August and September (Figure 6.14). Grand Coulee is kept high during this period likely for hydropower. HEC-PRM typically stores ~300KAF more water in Grand Coulee than the AER operation. This difference is only ~3% of Grand Coulee's total storage capacity.

HEC-PRM and HYSSR operations are nearly identical in July and August, keeping Grand Coulee around 9107KAF (maximum allowable storage). HYSSR storage dropped slightly in September, approximately 100KAF. This difference is less than 2% change relative to the total storage capacity of Grand Coulee.

Duncan Reservoir

The HEC-PRM and HYSSR operation curves overlap each other and are wide spread, but the AER operation is always lower than both HEC-PRM and HYSSR (Figure 6.15). The magnitude difference between HEC-PRM and AER operations increases from July to September. In July, the median HEC-PRM storage is ~450KAF greater than the AER operation, over 30% of Duncan's total storage capacity. The difference doubled in August to ~900KAF, almost 65% of the total storage capacity of Duncan. The difference in September is ~1MAF, more than 70% of Duncan's capacity. AER operations typically are the lowest storage draft limit for a reservoir.

For two of the three months, the median HEC-PRM storage is greater than the median HYSSR storage. In August and September, the median HEC-PRM storage is ~200KAF and 450KAF larger than HYSSR, ~14% and ~32% of Duncan's capacity, respectively. For the July difference, the median HEC-PRM storage is ~100KAF less than the median HYSSR value.

Libby Reservoir

The storage trajectories of HEC-PRM, HYSSR and AER operations are very similar (Figure 6.16). The AER operation stores less water throughout the July - September period. The median HEC-PRM is ~375KAF greater than AER operation, ~6% of Libby's total storage capacity. This difference increases to ~850KAF in August and ~1.5MAF in September, with the median HEC-PRM value greater. The maximum difference is ~25% of Libby's capacity.

The median HEC-PRM is less than the median HYSSR in July, 125KAF less. In August, the median HEC-PRM value is ~200KAF greater than the median HYSSR storage. The September difference is ~500KAF, with the median HEC-PRM value still larger than the median HYSSR. The maximum magnitude difference is ~8.5% of Libby's capacity.

Hungry Horse Reservoir

The HEC-PRM and HYSSR operation are very similar in July, August and September (Figure 6.17). The AER operation is always less than the HEC-PRM and HYSSR operations. In July, the median HEC-PRM storage is ~150KAF greater than the AER operation, less than 5% of Hungry Horse's total storage capacity. By August, the median HEC-PRM operation is ~500KAF greater than AER. The September difference is ~700KAF, almost 20% of Hungry Horse's total storage capacity.

The difference between the median values for HEC-PRM and HYSSR is minimal throughout July, August and September. In July and August, the median HYSSR values are ~50KAF greater than the median HEC-PRM storages, a mere 1% of the total storage capacity of Hungry Horse. The median HEC-PRM and HYSSR values are the same in September.

Dworshak Reservoir

The storage trajectories for HEC-PRM, HYSSR and the AER operation are similar in July, August and September (Figure 6.18). The median HEC-PRM value is ~100KAF greater

than the AER operation in July. The median HEC-PRM storage and the AER storage are basically the same in August. The AER operation is greater than the median HEC-PRM storage by ~50KAF in September. The maximum difference is less than 3% of Dworshak's total storage capacity.

The median HEC-PRM and HYSSR storages are the same in July. The median HYSSR value in August is ~125KAF larger than the median HEC-PRM storage, less than 4% of the total capacity of Dworshak reservoir. Lastly, in September, the difference increased to ~350KAF, with the HYSSR value greater than the HEC-PRM storage. This difference is ~10% of Dworshak's total storage capacity.

6.1.5 HEC-PRM Near-Term Advice for 1994 Drawdown Study

The HEC-PRM near-term advice for the 1994 variable drawdown period is discussed in this section. The near-term advice covers July, August and September. The 1994 - 1995 study is run through March 1995 to include the variable drawdown targets in the HEC-PRM optimization process. Advice is given both for the entire seven reservoir system, and for each reservoir separately. Both general qualitative advice and specific quantitative advice is presented.

Near-Term HEC-PRM System-Wide Operation Advice

HEC-PRM advises refilling the system in July, and drawing it down in August and September (Figure 6.8). The AER operation is in agreement, but the HYSSR operation does not draw down until September. Simulation testing should be used to discover the possibilities of starting the fixed drawdown season earlier than in the HYSSR operation, in August, as HEC-PRM suggests.

For the storage allocation from August to December, HEC-PRM advises drawing down Mica, Duncan and Dworshak first (Figure 6.10). At the same time, Arrow and Hungry Horse can fluctuate small amounts, while Grand Coulee and Libby reservoir stay constant (Figures 6.10 and 6.19). As additional water is discharged from the system, Arrow reservoir should be drawn down to its minimum storage of 227KAF. Simultaneously, Mica, Duncan, Libby, Hungry Horse and Dworshak reservoirs should draw down significantly also. Grand Coulee should maintain 9107KAF (maximum storage). HEC-PRM's last advice is to draw down Libby reservoir last when Arrow reaches 227KAF.

Arrow, Mica and Libby reservoirs draw down the greatest amounts in sheer volume. The minimal constraints placed on Arrow's operation makes the reservoir ideal for large changes in storage. Grand Coulee is kept at or near 9107KAF throughout the fixed drawdown period. Clearly, HEC-PRM views this operation as a priority.

Near-Term HEC-PRM Individual Reservoir Storage Trend and Magnitude Advice

Mica Reservoir

HEC-PRM advises that Mica should refill in July and August, and the fixed drawdown period should not begin until September (Figure 6.12). HEC-PRM advises storing more water in Mica than presented in the HYSSR results in July, August and September. In fact, HEC-PRM should store a considerable amount more, ~4KAF. In addition, HEC-PRM's operation should be similar to the AER operation.

Arrow Reservoir

HEC-PRM advises drawdown starting in August and September (Figure 6.13). The fixed drawdown season should be planned to ensure Arrow reservoir reaches its minimum allowable storage of 227KAF by the beginning of the variable drawdown season in January. HEC-PRM suggests a very large drawdown for Arrow early in the fixed drawdown season, while HYSSR waits until November and December to drawdown Arrow significantly. The HEC-PRM operation draws down similarly to the AER operation in August and September, but the AER operation does not draw down Arrow to its minimum storage by the beginning of the variable drawdown season. HEC-PRM's advice for August and September drawdown should be explored with simulation testing.

Grand Coulee Reservoir

HEC-PRM's advice for Grand Coulee in July, August and September is extremely clear. Consistently store the maximum allowable storage of 9107KAF in Grand Coulee reservoir (Figure 6.14). The AER operation maintains Grand Coulee between ~8750KAF and ~8850KAF in July, August and September. The HYSSR results concur with the HEC-PRM advice as the HYSSR operation maintains approximately 9107KAF in July and August, and slightly less in September. HYSSR and AER operations in July, August and September support HEC-PRM's operation to keep Grand Coulee near its maximum allowable level.

Duncan Reservoir

HEC-PRM advises refilling Duncan in July and August, but the advice for September is variable (Figure 6.15). HEC-PRM does suggest storing more water in July, August and September than the AER operation. The HEC-PRM advice is different from the HYSSR operation; the HYSSR operation is scattered.

Libby Reservoir

HEC-PRM's advice for Libby reservoir is refill in July and August, and draw down in September (Figure 6.16). HEC-PRM should store more water than the AER operation throughout the three months. The HYSSR operation is essentially the same as the HEC-PRM operation in July and August. In September, HEC-PRM advises storing more water in September than HYSSR.

Hungry Horse Reservoir

HEC-PRM's advice for Hungry Horse is refill in July and drawdown in August and September (Figure 6.17). HEC-PRM advises storing more water in Hungry Horse than the AER operation. HYSSR straddles the HEC-PRM operation, showing some higher and lower storage curves throughout July, August and September, but, otherwise, the two operations are quite similar.

Dworshak Reservoir

Dworshak reservoir should refill in July and draw down in August and September, according to HEC-PRM (Figure 6.18). HEC-PRM should store a similar quantity of water in Dworshak as provided in the AER operation. HEC-PRM should store roughly the same amount of water in Dworshak reservoir as HYSSR in July, but HEC-PRM draws down Dworshak more than HYSSR in August and September. In fact, when HEC-PRM advises drawdown to begin in August, HYSSR is still refilling Dworshak.

Near-Term HEC-PRM Individual Reservoir Specific Storage and Release Operations Advice

Strong, specific quantitative advice is available in the HEC-PRM results. HEC-PRM results qualify as specific advice when HEC-PRM operates at least 25% or more of the inflow sequences in a similar manner. For instance, at least 25% of the release results for Duncan in July, August and September equal 60KAF. Table 6.4 lists the specific advice.

Mica Reservoir

Mica should store between ~18080KAF and 20000KAF, according to 75% of the results (Figure 6.1). HEC-PRM advises releases between 2420KAF and 2520KAF in August (Figure 6.20). In September, Mica should release 2420KAF. For both the August and September advice, at least 50% of the results equaled the values.

Arrow Reservoir

HEC-PRM advises releasing between 2000KAF and 3500KAF in July (Figure 6.21). Fifty percent of the results are in this range. Fifty percent of the August results fall within the range of 4100KAF and 5620KAF. At least 50% of the September releases should be 3960KAF to 4640KAF.

Grand Coulee Reservoir

HEC-PRM's specific advice for Grand Coulee clearly is store the maximum, 9107KAF, in July, August and September (Figure 6.3). All of the HEC-PRM storage results equaled 9107KAF.

Table 6.4 HEC-PRM Specific Quantitative Advice for 1994 Fixed Drawdown Season

Reservoir	Month	Operation	HEC-PRM Advice (KAF)	Percentage of Results (%)
Mica	July	Storage	18080-20000	75
	August	Release	2420-2520	50
	September	Release	2420	50
Arrow	July	Release	2000-3500	50
	August	Release	4100-5620	50
	September	Release	3960-4640	50
Grand Coulee	July	Storage	9107 (Max)	100
	August	Storage	9107	100
	September	Storage	9107	100
Duncan	July	Release	6 (Min)	25
	August	Release	6	25
	September	Release	6	25
Libby	July	Release	181 (Min) -210	50
	August	Release	181-270	25
	September	Release	181-320	25
Hungry Horse	July	Release	60	100
	August	Release	60	100
	September	Release	60	100
Dworshak	July	Release	60-300	100
	August	Release	100-210	75
	September	Release	60-380	100

Duncan Reservoir

Duncan should release 6KAF, the minimum allowable release, all three months (Figure 6.22). At least 25% of the release results equaled 6KAF.

Libby Reservoir

In July, HEC-PRM advises releasing between 181KAF, the minimum allowable release, and 210KAF (Figure 6.23). At least half of the release results fall within this range. In August, at least 25% of the releases suggested are from 181KAF to 270KAF. September releases should be similar. Release between 181KAF to 320KAF, as discovered in 25% of the release results.

Hungry Horse Reservoir

Always release 60KAF from Hungry Horse in July, August and September (Figure 6.24). All of the results equaled 60KAF.

Dworshak Reservoir

Release between 60KAF and 300KAF from Dworshak in July (Figure 6.25). This range includes all of the July release results. The range of August releases should be from 100KAF to 210KAF to facilitate this operation. Seventy-five percent of the results fall within this release range. Lastly, in September, releases should be between 60KAF and 380KAF. This range incorporates all the release results.

6.1.6 Conclusions for 1994 Drawdown Season Study

1. Overall, HEC-PRM operations for the 1994 Drawdown study compare well with HYSSR results and the AER operation. All March 1995 reservoir drawdown targets are met by HEC-PRM. The storage trend comparisons between HEC-PRM, HYSSR and AER operations are favorable. HEC-PRM also provides strong, specific quantitative advice. New operations proposed by HEC-PRM should be tested with simulation to explore the possibilities.

2. HEC-PRM operations successfully reach the variable drawdown targets. All seven reservoirs always met their March target storages with the HEC-PRM operation.

3. HEC-PRM begins drawing down the system the same month that the Columbia River System is typically drawn down, in August. The AER operation is the same, but HYSSR starts the drawdown season one month later in September. Since the HEC-PRM 1994 Drawdown study begins in the month of July, the last month of the refill season, HEC-PRM refills the system in July.

HEC-PRM typically stores more water in the system than the AER operation in July, August and September. HEC-PRM and HYSSR operations overlap, but HEC-PRM tends to store a small amount more water than HYSSR.

4. Mica, Duncan and Dworshak should be the first reservoirs to draw down in the 1994 fixed drawdown season. HEC-PRM's advice for the initial operation of Grand Coulee and Libby is maintain a constant storage. Arrow and Hungry Horse fluctuate until additional water leaves the system. After a considerable amount of water, ~3000KAF, is released from the system, Arrow should draw down dramatically. Grand Coulee still should remain constant at 9107KAF (maximum allowable storage). Mica, Duncan, Libby, Hungry Horse and Dworshak all should draw down significantly. Arrow reservoir should drain to 227KAF, its minimum storage, and Libby reservoir should be the last reservoir to draw down.

5. The storage trend comparisons are quite favorable. HEC-PRM agreed with the AER operation for 10 of the 21 comparisons. HEC-PRM matched 12 of the 21 instances compared

with HYSSR. HEC-PRM, HYSSR and the AER operation all had the same storage trend for 7 of 21 instances. Clearly, HEC-PRM is capable of matching HYSSR and the AER storage trends.

6. HEC-PRM typically stores more water than HYSSR, and an amount similar to the AER operation, in Mica reservoir. HEC-PRM typically stores the least amount of water in Arrow reservoir because HEC-PRM encourages dramatic drawdown in Arrow to reach 227KAF by January 1st. HEC-PRM, HYSSR and AER operations all operate Grand Coulee near its maximum allowable storage.

In Duncan, Libby and Hungry Horse reservoirs, HEC-PRM stores more water than the AER operation, while HEC-PRM and HYSSR operations overlap. HEC-PRM tends to store less water in Dworshak than AER and HYSSR operations.

7. HEC-PRM provides good specific quantitative advice for the 1994 Drawdown season. For example, Grand Coulee should always store 9107KAF in July, August and September. HEC-PRM advises that Hungry Horse always release 60KAF all three months. In addition, Duncan should release 6KAF (minimum allowable release) from July to September. HEC-PRM's specific advice should be tested further with simulation to explore its usefulness.

6.2 Comparison of Variable Drawdown Operations for 1994 Drawdown Season Study and 1995 January - July Season Study

Section 6.2 describes the comparison of the 1995 variable drawdown season common to the 1994 Drawdown season study and the 1995 January - July season study. The HEC-PRM fixed drawdown results from the 1994 Drawdown study are not compared because there are no other HEC-PRM studies available for comparison purposes for this period. The issues of study inflows, probability of March drawdown, storage allocation, storage trends and magnitudes and HEC-PRM advice are compared in this section.

Comparison of Inflows

The 1995 January - July study uses 48 years of inflow, from 1929 to 1976. Fifty inflow sequences, 1929 - 1978, are available for the 1994 Drawdown study. The assumption is made that the two year difference in inflow years will not negatively affect the comparison of the two studies. The most significant difference in study inflows is that no forecasted inflows are used in the 1994 Drawdown study. Forecasted inflows are unavailable in July. It is assumed that this discrepancy is not detrimental for study comparison.

The inflows for the 1995 January - July study and 1994 Drawdown study are similar for January to March (Figures 6.26 - 6.32). Specifically, the forecasted inflows of the 1995 January - July for Grand Coulee, Duncan and Dworshak typically are larger than the historical inflows of the 1994 Drawdown study (Figure 6.28, 6.29 and 6.32).

Comparison of March Drawdown Probability

In the 1994 Drawdown study, all reservoirs always reach the target storages for March specified in the 1994 Drawdown season. In fact, all the reservoirs draw down below the target to their minimum allowable storages at least once. The March targets are the median HYSSR storage values from a previous simulation study of the Columbia River System (USACE, 1995).

Only three reservoirs in the 1995 January - July study always reach the March targets specified in the 1994 Drawdown study. The three reservoirs are Mica, Arrow and Hungry Horse reservoir (Figures 3.1, 3.2 and 3.6). Eighty-six percent of the March storage results for Dworshak meet the target. Grand Coulee meets its target for nine of fifty inflow sequences. Only for three years do Duncan and Libby meet their drawdown targets.

Comparison of System-Wide Operation

The HEC-PRM 1994 Drawdown study tends to store more water in the system in January and February, and typically less in March, than the 1995 January - July study (Figures 3.11 and 6.8). In the 1994 Drawdown study, all seven reservoirs draw down to or below their March targets for every inflow year. Therefore, in the 1994 Drawdown study, HEC-PRM appears to keep the system storage higher and longer given that the March draw down targets are met.

In February and March, the AER operation typically stores more water in the system than HEC-PRM, for both the 1994 Drawdown study and the 1995 January - July study (Figure 6.33). In January, HEC-PRM stores more water in the 1994 Drawdown study for the total system than the AER system storage. The 1995 January - July study system operation is approximately the same as the AER storage in January.

Comparison of Storage Allocation Plots

HEC-PRM allocates the storage among the reservoirs similarly between the 1994 Drawdown (July - March) study and the 1995 January - July study. For both studies, Mica, Arrow and Dworshak are among the first reservoirs for HEC-PRM to draw down (Figures 3.13 and 6.11). In the 1994 Drawdown study, Duncan and Libby are also drawn down initially. In both studies, HEC-PRM advises that Grand Coulee should stay level at the maximum, 9107KAF, in the beginning. Hungry Horse remains fairly level in both studies, and Duncan and Libby are relatively constant in the 1995 January - July study.

Arrow reservoir drains to 227KAF (minimum allowable storage) in both studies. Duncan reaches its minimum allowable storage of 30KAF at the same time in the 1994 Drawdown study. Given Arrow is at its minimum storage, Grand Coulee dramatically draws down, while Mica, Libby , Hungry Horse and Dworshak continue to draw down in both studies. Duncan stores the minimum, 30KAF, in the 1994 Drawdown study, but Duncan fluctuates in the 1995 January - July study (Figures 3.13 and 6.34). In the 1994 Drawdown study only, as the system is approaching its minimum total storage, suddenly, Mica, Grand Coulee and Libby level as they draw down. On the other hand, Arrow levels once it refills slightly and Hungry Horse draws down significantly. Eventually, in the 1995 January - July study, Libby is the final reservoir to draw down and the other six reservoirs level. Hungry Horse is the last reservoir to draw down in the 1994 Drawdown study.

HEC-PRM uses Arrow and Grand Coulee to release the greatest volume of water. Arrow reservoir has no penalties assigned to its operation, therefore, it is advantageous to operate Arrow with large changes in storage. Grand Coulee is ideal for considerable drawdown because the reservoir can make large releases.

Comparison of Storage Trends

For both the 1994 Drawdown study and the 1995 January - July study, HEC-PRM storage trends matched the AER storage trends for 6 of the 21 comparisons (Table 6.5). The two HEC-PRM studies have the same trends for 12 of the 21 instances. Nine of twenty-one comparisons between 1995 January - July study and the AER operation for the variable drawdown period match. The trends for the 1994 Drawdown study and the AER operation for January, February and March 1995 agree for 8 of 21 comparisons.

<u>January</u>

The dominant storage trend among the two HEC-PRM runs and the AER operation for January 1995 is drawdown. The trends for all three operations match for three of the seven

Table 6.5 Comparison of Storage Trends for 1995 Variable Drawdown Season

RESERVOIR	1995 Jan - July Study	1994 Drawdown Study	1995 AER
January			
Mica	Drawdown	Drawdown	Drawdown
Arrow	Drawdown	Drawdown to 227KAF	Drawdown
Grand Coulee	Refill	Maintain 9107KAF	Drawdown
Duncan	Refill	Drawdown to 30KAF	Refill
Libby	Drawdown	Drawdown	Drawdown
Hungry Horse	Refill	Drawdown	Drawdown
Dworshak	Drawdown	Drawdown	Refill
February			
Mica	Drawdown	Drawdown	Drawdown
Arrow	Maintain 227KAF	Maintain 227KAF	Refill
Grand Coulee	Drawdown	Drawdown	Refill
Duncan	Refill	Maintain 30KAF	Refill
Libby	Variable	Drawdown	Drawdown
Hungry Horse	Drawdown	Drawdown	Refill
Dworshak	Drawdown	Drawdown	Refill
March			
Mica	Drawdown	Drawdown	Drawdown
Arrow	Maintain 227KAF	Refill	Drawdown
Grand Coulee	Drawdown	Drawdown	Drawdown
Duncan	Refill	Maintain 30KAF	Refill
Libby	Drawdown	Drawdown	Refill
Hungry Horse	Variable	Drawdown	Refill
Dworshak	Drawdown	Maintain 1452KAF	Refill

reservoirs. Mica, Arrow and Libby reservoirs are drawn down in January.

February

The dominant trend for the 1995 January - July study remains drawdown, but the 1994 Drawdown study and the AER operation mainly refill in February 1995. All three operations agree only for one reservoir, Mica. Mica is still drawn down in February by all three operations.

March

The 1995 January - July study predominantly draws down reservoirs in the system in March, while the trends for the 1994 Drawdown study and the AER operation are refill. Mica and Grand Coulee are drawn down by all three operations in March.

Comparison of Storage Magnitudes

For both the 1994 Drawdown study and the 1995 January - July study, HEC-PRM operates Mica reservoir with more water than the AER operation (Figures 3.17 and 6.12). HEC-PRM stores more water in Mica in the 1994 Drawdown study than the 1995 January - July study. In the 1994 Drawdown study, HEC-PRM also stores more water in Mica than HYSSR (Figure 6.12).

HEC-PRM operates Arrow reservoir the same in both studies during the 1995 variable drawdown season (Figures 3.18 and 6.13). HEC-PRM aims to store 227KAF in Arrow reservoir throughout January, February and March 1995. Given this operation, HEC-PRM stores less water in Arrow reservoir than the AER operation in both studies and HYSSR in the 1994 Drawdown study. HEC-PRM can drain Arrow because there are no penalties on its operation.

For both studies, HEC-PRM operations for Grand Coulee overlap the AER operation (Figures 3.19 and 6.14). Both HEC-PRM operations begin to draw down Grand Coulee reservoir in January. Only the 1994 Drawdown study operations always draw down Grand Coulee to a low level of ~4400KAF in March. The HEC-PRM operations for March in the 1995 January - July study spans from ~4000KAF to ~8800KAF. The 1994 Drawdown study always draws Grand Coulee down low in March because the March target storage is clearly defined in end-of-period penalty functions.

The 1995 January - July study stores more water in Duncan than the 1994 Drawdown study (Figures 3.20 and 6.15). The two HEC-PRM studies operate fairly similarly to the AER operations. In the 1995 January - July study, the AER operation follows the median HEC-PRM storage curve. For the 1994 Drawdown study, HEC-PRM operates Duncan with less water than the AER operation.

Both studies show that HEC-PRM typically stores more water in Libby reservoir than the AER operation (Figures 3.21 and 6.16). An exception exists in the 1994 Drawdown study; HEC-PRM stores significantly less water in Libby in March than the AER operation. HEC-PRM changes Libby reservoir more dramatically in the 1994 Drawdown study than the 1995 January - July study. Libby is drawn down from ~4000KAF to less than ~2000KAF from January to

March in the 1994 Drawdown study, while the range of Libby storage in the 1995 January to July study is mainly between ~2000KAF and ~2800KAF.

HEC-PRM stores considerably more water, ~1MAF, in Hungry Horse in the 1994 Drawdown study than the 1995 January - July study (Figures 3.22 and 6.17). The AER operation is very similar to the 1995 January - July study. As a result, the AER operation is significantly lower than HEC-PRM operation in the variable drawdown season of the 1994 Drawdown season study.

HEC-PRM operates Dworshak similarly in the two studies (Figures 3.23 and 6.18). The AER operation typically stores more water than the HEC-PRM operation for both studies. This is the second reservoir that HEC-PRM operates lower than the AER operation; the first is Arrow reservoir. HEC-PRM appears to be using Arrow and Dworshak water to keep other reservoirs in the system at high storage levels.

Comparison of HEC-PRM Specific Quantitative Advice

HEC-PRM advises strong specific quantitative advice for both the 1994 Drawdown study and the 1995 January - July study. The specific advice for the two studies is similar for five of the seven reservoirs, Mica, Arrow, Grand Coulee, Hungry Horse and Dworshak. HEC-PRM's specific advice for Duncan and Libby reservoirs differs for the two studies.

Mica reservoir should release 603KAF, the minimum allowable release, in January, February and March according to both the 1994 Drawdown study and the 1995 January - July study (Figures 3.24 and 6.20). This advice is stronger for the 1994 Drawdown study, as a higher percentage of results suggest 603KAF (Table 6.6). HEC-PRM clearly advises operating Arrow reservoir at 227KAF throughout the variable drawdown season for both studies (Figures 3.2 and 6.2).

Grand Coulee should store 9107KAF in January, as seen in at least 50% of the storage results for both studies (Figures 3.3 and 6.3). In both studies, HEC-PRM advises slight drawdown from 9107KAF in February. By March, Grand Coulee should be drawn down considerably lower, according to both studies. Seventy-five percent of the storage results for the 1994 Drawdown season study equal 4200KAF. Similarly, in the 1995 January - July study, at least 50% of the results show that Grand Coulee should draw down between 3879KAF and 5350KAF.

The specific operation advice for Duncan is quite different between the two studies. In the 1994 Drawdown study, Duncan reservoir is advised to draw down and store 30KAF (minimum storage) in January and February, and 40KAF in March (Figure 6.4). On the other hand, the 1995 January - July study advice is to refill Duncan and release 6KAF throughout the variable drawdown season (Figures 3.4 and 3.25).

Libby advice varies between the two studies also. The 1995 January - July study primarily advises releases of 181KAF (minimum allowable release) in January, February and March (Figure 3.26). The advice for the 1994 Drawdown study is to store decreasing amounts of

Table 6.6 Comparison of HEC-PRM Specific Advice (KAF) for 1994 Drawdown and 1995 Jan-July Studies

Mica Reservoir	1994 Drawdown	%	1995 Jan - July	%
January	Release 603(Min)	75	SAME	50
February	Release 603	50	SAME	25
March	Release 603	75	SAME	50
Arrow Reservoir				
January	Store 227(Min)	75	SAME	75
February	Store 227	100	SAME	75
March	Store 227	50	SAME	100
Grand Coulee Reservoir				
January	Store 9107(Max)	50	SAME	50
February	Store 8380-9107	50	SAME	25
March	Store 4200	75	Store 3879(Min)-5350	50
Duncan Reservoir				
January	Store 30(Min)	75	Release 6(Min)	75
February	Store 30	100	Release 6	75
March	Store 40	75	Release 6	75
Libby Reservoir				
January	Store 3270-3500	25	Release 181(Min)	75
February	Store 2690-3020	75	Release 181	75
March	Store 1500	75	Release 181-225	75
Hungry Horse Reservoir				
January	Release 60	75	SAME	25
February	Release 60	50	SAME	75
March	Release 60	50	SAME	50
Dworshak Reservoir				
January	Release 200-300	75	Release 300-450	50
February	Release 190-300 Store 1452(Min)	75 75	Release 300-450	75
March	Release 120-300 Store 1452	75 50	Release 250-450	75

water as the variable drawdown season progresses. In January, 3270KAF - 3500KAF should be stored in Libby (Figure 6.5). The range decreases in February to 2690KAF - 3020KAF. Lastly, in March, store a level 1500KAF. HEC-PRM's advice is direct for Hungry Horse; release 60KAF all three months, for both studies (Figures 3.10 and 6.24).

For Dworshak reservoir, similar release ranges are suggested in the two studies (Figure 3.27 and 6.25). For the 1994 Drawdown study, releases approximately between 120KAF - 300KAF are suggested for each month. The release range advised in the 1995 January - July study is slightly larger than for the 1994 Drawdown study.

Dworshak releases from 250KAF to 450KAF are advised for each month in the variable drawdown study. There is strong storage advice given in the 1994 Drawdown season study in February and March. In February, HEC-PRM advises a storage range between 1452KAF (minimum allowable storage), over 75% of the storage results fall in this range. The constant storage level of 1452KAF is suggested for Dworshak in March.

Comparison Conclusions

1. HEC-PRM storage trends compare well between studies and with the AER operation. HEC-PRM offers strong quantitative advice. HEC-PRM's storage allocation process for the 1994 Drawdown study and the 1995 January - July study are similar. The probability of drawdown for the 1994 Drawdown study is higher than for the 1995 January - July study. HEC-PRM's advice from both studies should be studied with simulation to discover new seasonal operation ideas.

2. More reservoirs meet the March drawdown target storage in the 1994 Drawdown study than the 1995 January - July study. All seven reservoirs meet their March drawdown targets in the 1994 Drawdown study. Only Mica, Arrow and Hungry Horse reservoirs always meet these March drawdown target storage in the 1995 January - July study. The probability of drawdown is distinctly higher in the 1994 Drawdown study than the 1995 January - July study because specific end-of-period penalty functions are defined for the 1994 Drawdown study to encourage March drawdown target storage.

3. From a system-wide perspective, HEC-PRM stores more water in the system in the 1994 Drawdown study in January and February and less water in March than the HEC-PRM 1995 January - July study. The median HEC-PRM operation tends to store less water than the AER operation in the total system in February and March. In January, in the 1994 Drawdown study, HEC-PRM's median operation stores more water than the AER operation. In the 1995 January - July study, HEC-PRM's median January total system storage operation is approximately the same as the AER operation.

4. A comparison of the storage allocation in HEC-PRM studies shows that Mica, Arrow and Dworshak reservoirs are drawn down first in both HEC-PRM studies. Both HEC-PRM studies agree that Grand Coulee should stay high at 9107KAF (maximum allowable storage) initially. Duncan and Libby draw down in the 1994 Drawdown study, but remain level in the 1995

January - July study, in the beginning.

For both HEC-PRM studies, Hungry Horse operates at a fairly constant storage level throughout the system-wide drawdown. Both studies show that Grand Coulee should be drawn down dramatically once Arrow reaches its minimum storage level. Mica, Libby, Hungry Horse and Dworshak gradually draw down at this time in both HEC-PRM studies. Libby is the last reservoir to draw down in the 1995 January - July study, while Hungry Horse is the final reservoir to draw down in the 1994 Drawdown study.

5. The AER operation and both HEC-PRM studies agree on the same storage trends for 6 of 21 comparisons. The two HEC-PRM studies have matching storage trends for 12 of 21 instances. Nine of twenty-one instances match for the 1995 January - July study and the AER operation, while only eight agree for the 1994 Drawdown study and the AER operation.

HEC-PRM and AER operations mainly draw down the reservoirs in January. In February and March, HEC-PRM draws down most of the reservoirs in the 1995 January - July study, but HEC-PRM refills the majority of the reservoirs in the 1995 January - July study. The AER operation refills a majority of the reservoirs in February and March also. All three operations agree on the drawing down Mica reservoir each month of the variable drawdown season.

6. HEC-PRM operates Mica reservoir with more water in both studies than the AER operation in January, February and March. HEC-PRM stores more water in Mica in the 1994 Drawdown study than the 1995 January - July study all three months. Both HEC-PRM studies typically store 227KAF (minimum allowable storage) in Arrow throughout the variable drawdown season, which is considerably less than the AER operation. HEC-PRM typically operates Dworshak with less water than the AER operation in both studies.

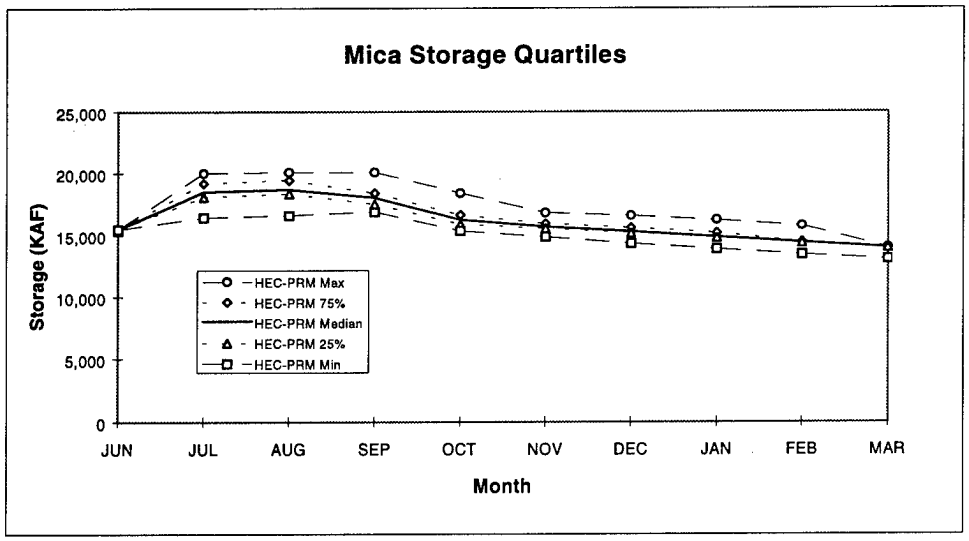
The HEC-PRM operations in both studies for Grand Coulee reservoir overlap with the AER operation, but there is no clear pattern to this relationship. The 1994 Drawdown HEC-PRM study neatly draws down Grand Coulee in March, unlike the operation in the 1995 January - July study. HEC-PRM stores more water in Duncan in the 1995 January - July study than the 1994 Drawdown study. Despite this difference, HEC-PRM and AER operations for Duncan are fairly similar throughout the variable drawdown season.

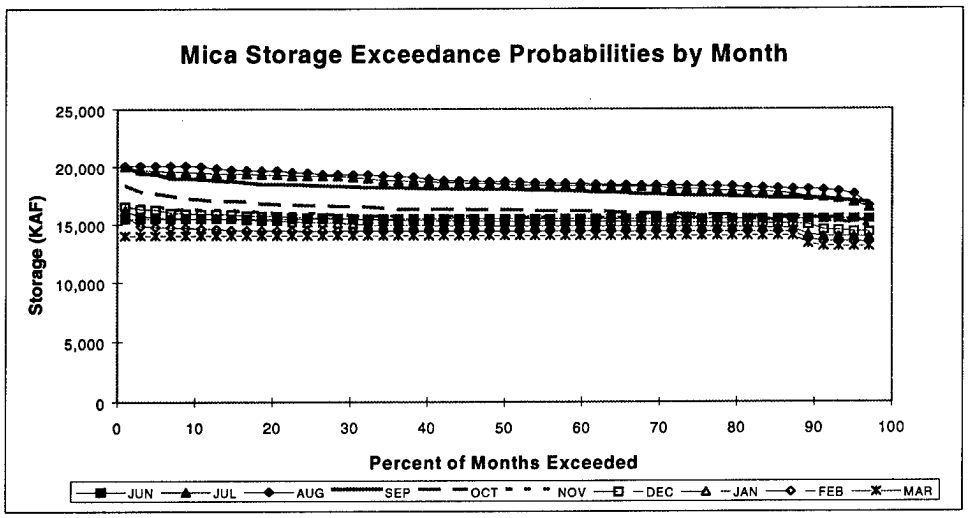
HEC-PRM's storage operation of Libby in the 1995 January - July study is relatively level compared to the 1994 Drawdown study. Both HEC-PRM studies are similar to the AER operations. HEC-PRM stores considerably more water in Hungry Horse in the 1994 Drawdown study than the 1995 January - July study. The AER operation is very similar to the 1995 January - July study, and, consequently, much lower than the HEC-PRM 1994 Drawdown study operations.

7. Both the 1994 Drawdown study and the 1995 January - July study offer consistent specific HEC-PRM advice. Mica should release 603KAF (minimum allowable release) per month throughout the variable drawdown season. HEC-PRM advises keeping Arrow at its minimum allowable storage of 227KAF in January, February and March. Grand Coulee should store 9107KAF in January and draw down around 4200KAF or lower by March.

The specific advice for Duncan and Libby reservoirs varies between the two studies. The 1994 Drawdown study stores ~30KAF (minimum allowable storage) - 40KAF per month in January, February and March, while Duncan should release 6KAF (minimum release) each month according to the 1995 January - July study. For Libby, the 1994 Drawdown season study advises ~3300KAF in January and a drawdown to 1500KAF in March. On the other hand, the specific advice from the 1995 January - July study is to release 181KAF (minimum allowable release), on average.

Hungry Horse should release 60KAF consistently each month throughout the variable drawdown season. On average, Dworshak reservoir should release between 200KAF and 450KAF each month, or, as suggested in the 1994 Drawdown study, store ~1452KAF in February and March.





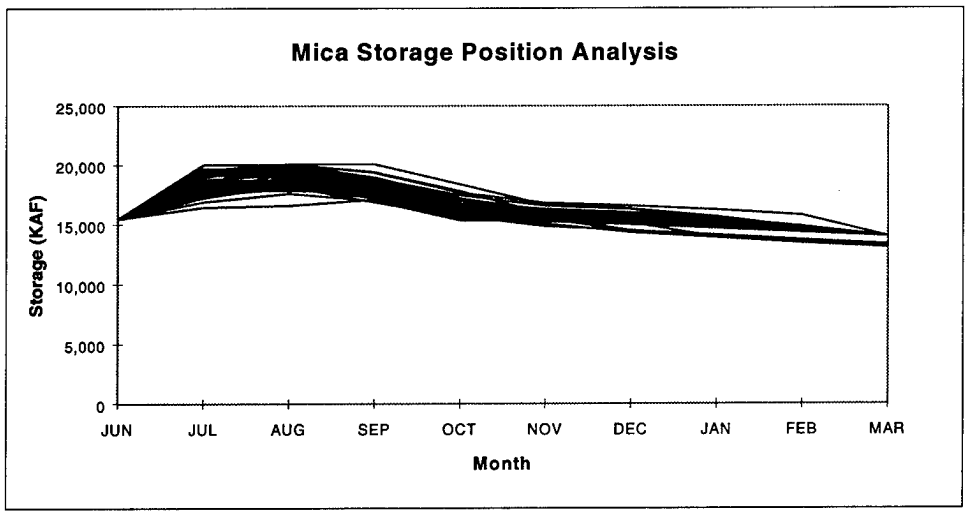
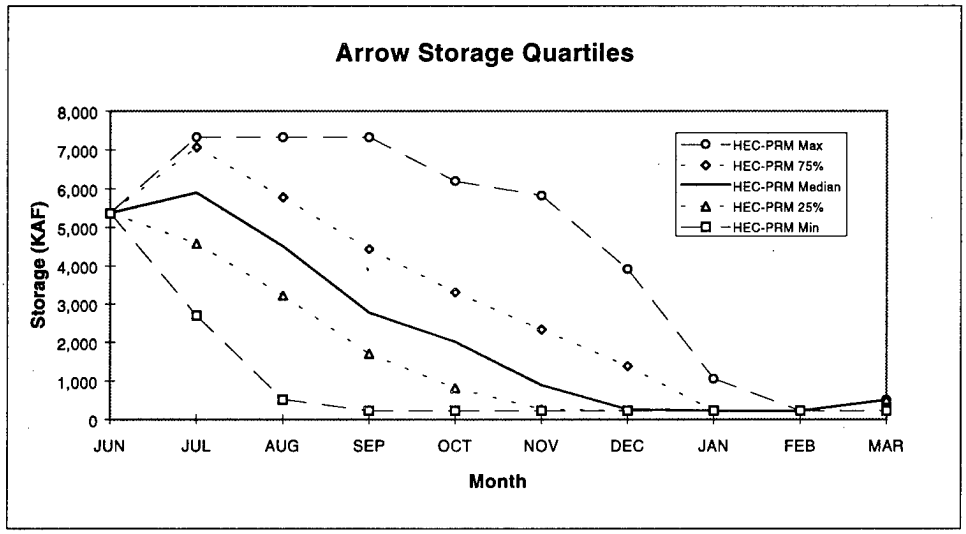
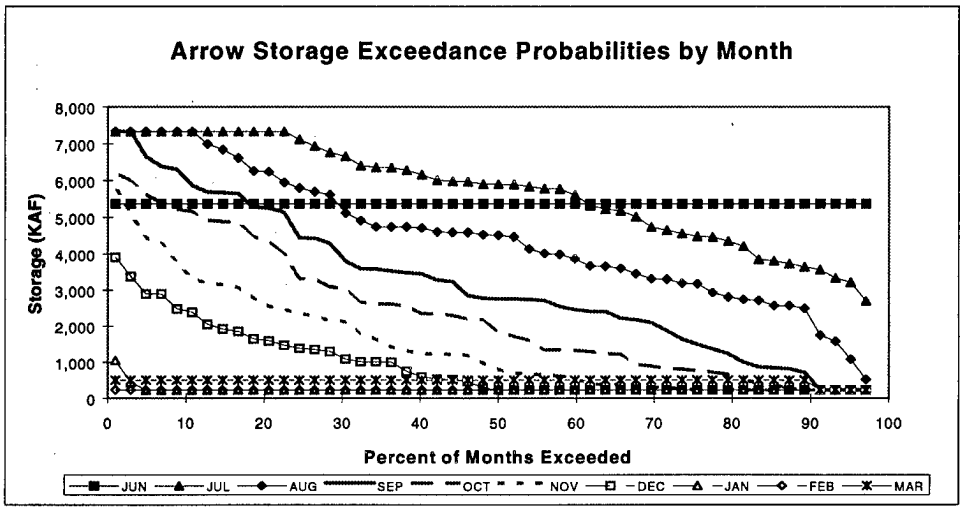


Figure 6.1 Mica Storage Results for HEC-PRM 1994 Drawdown Study





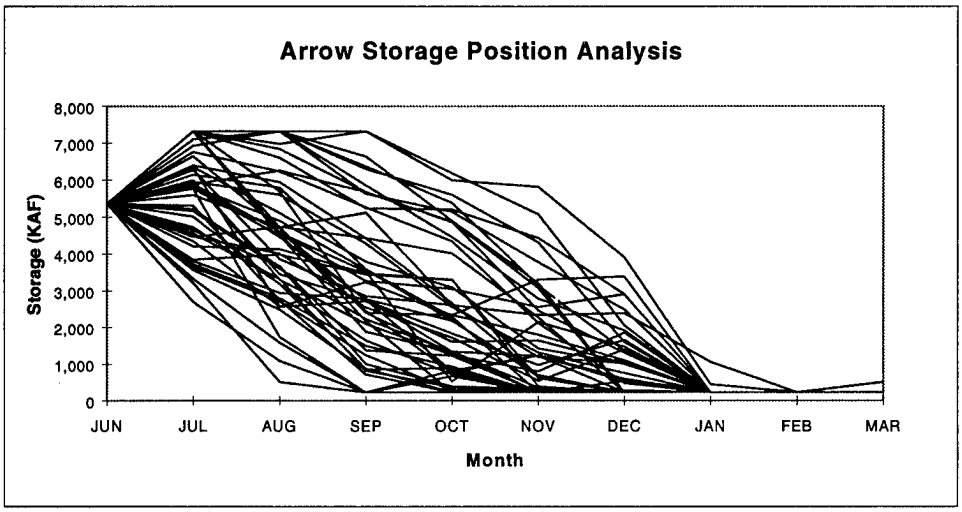
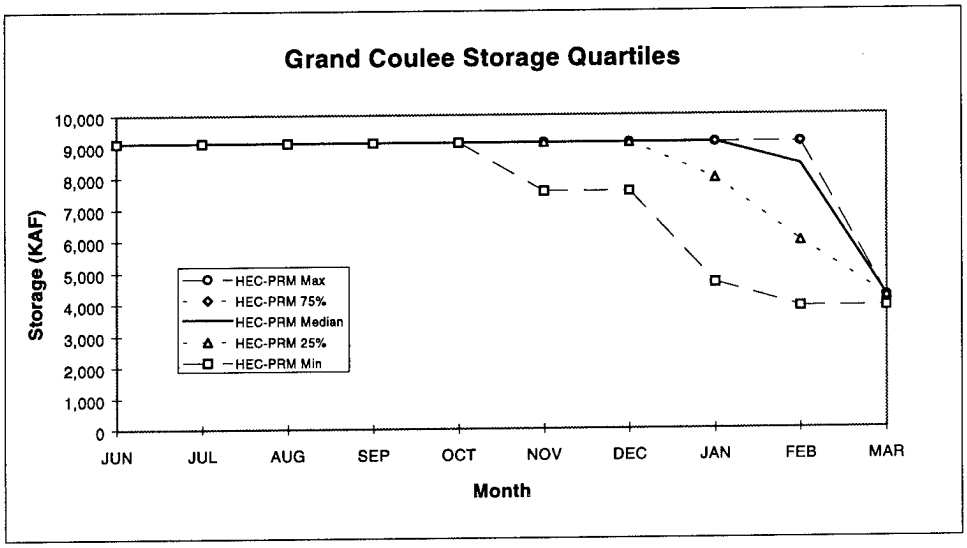
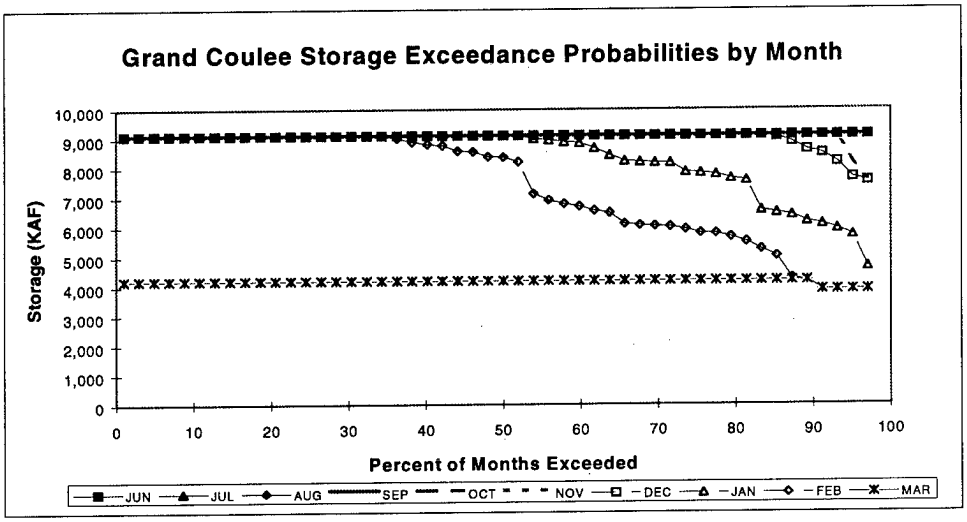


Figure 6.2 Arrow Storage Results for HEC-PRM 1994 Drawdown Study





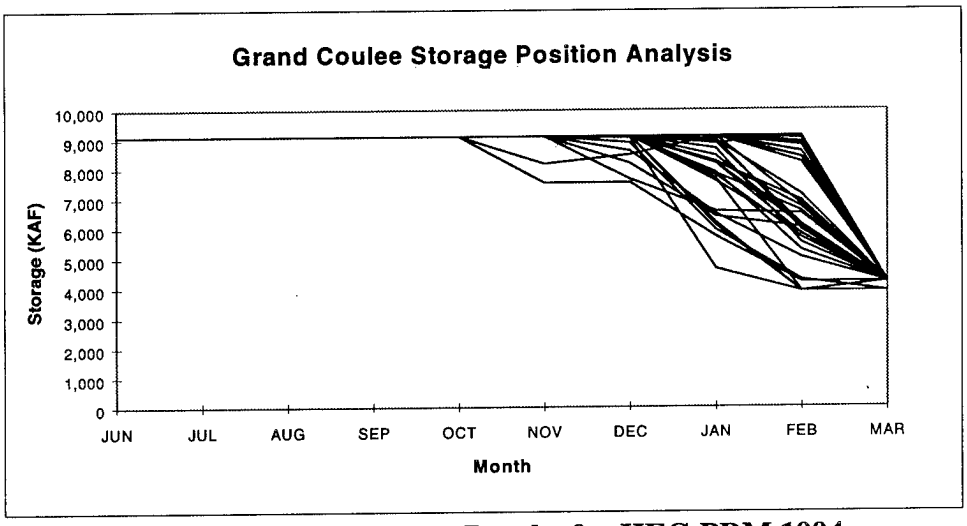
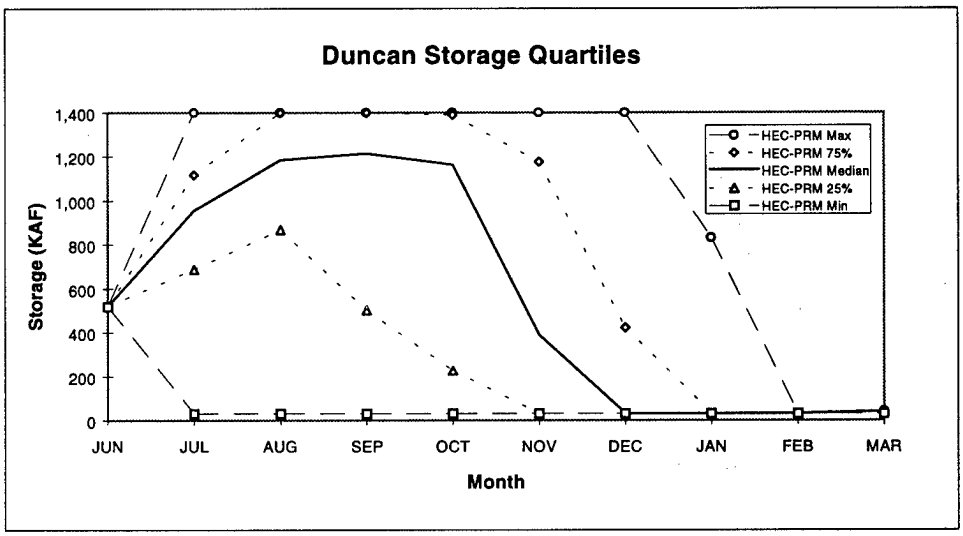
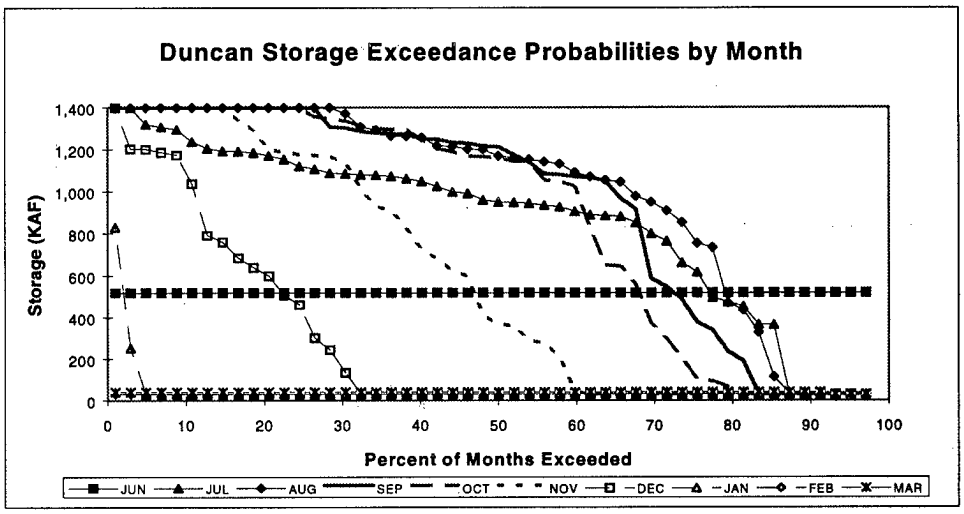


Figure 6.3 Grand Coulee Storage Results for HEC-PRM 1994 Drawdown Study





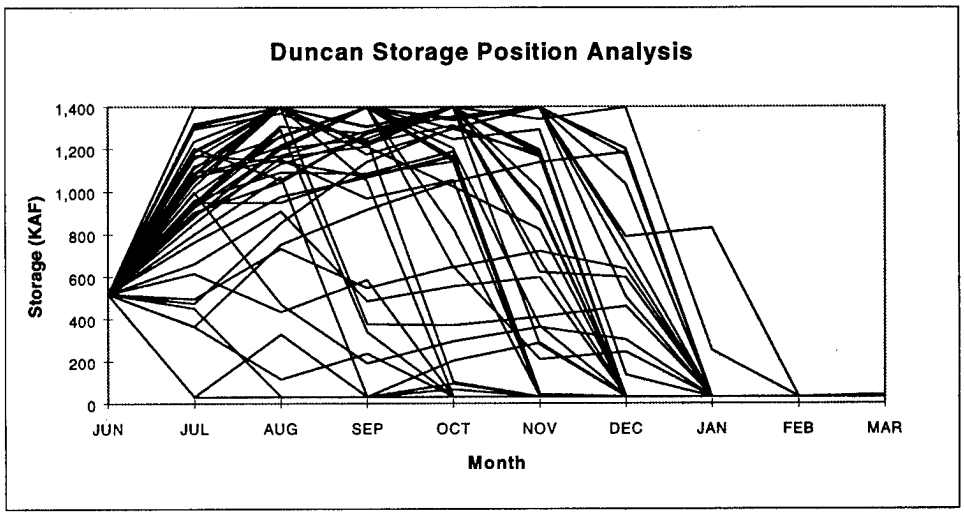
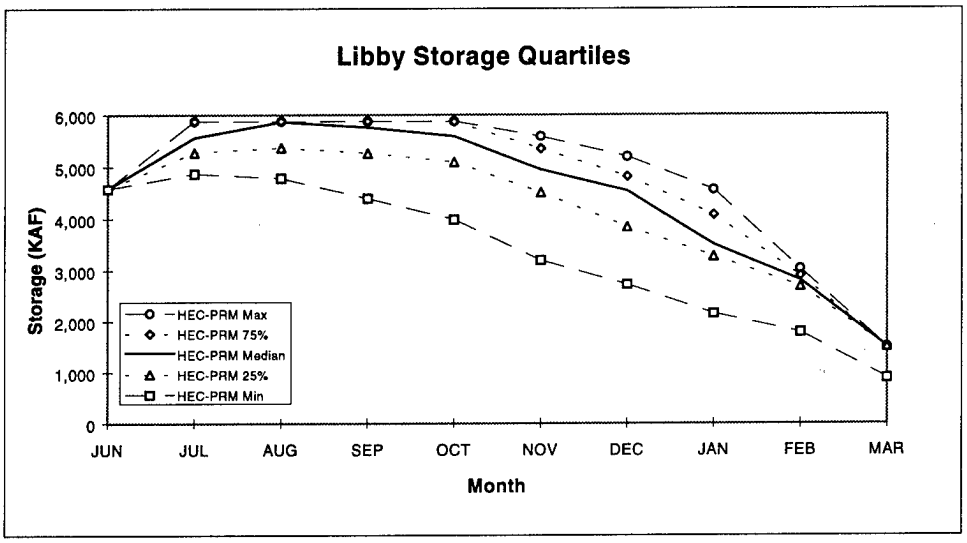
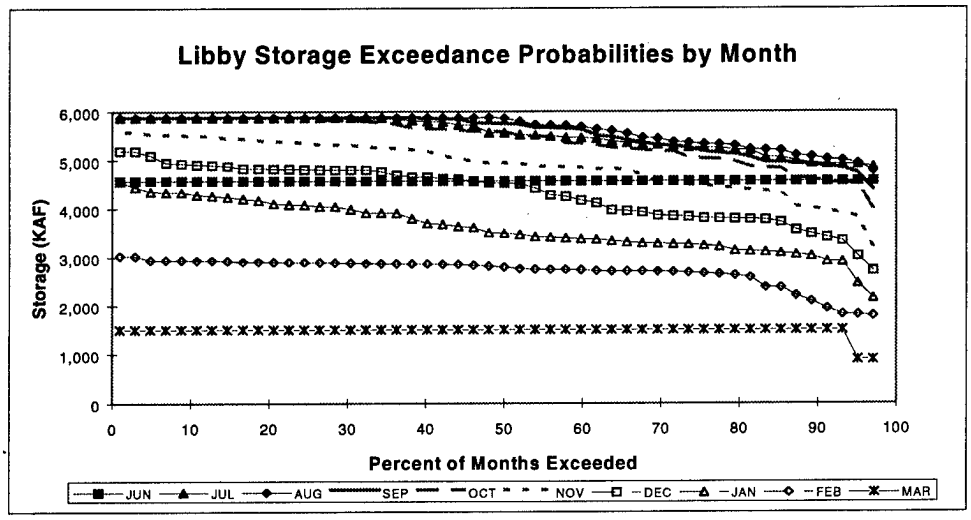


Figure 6.4 Duncan Storage Results for HEC-PRM 1994 Drawdown Study





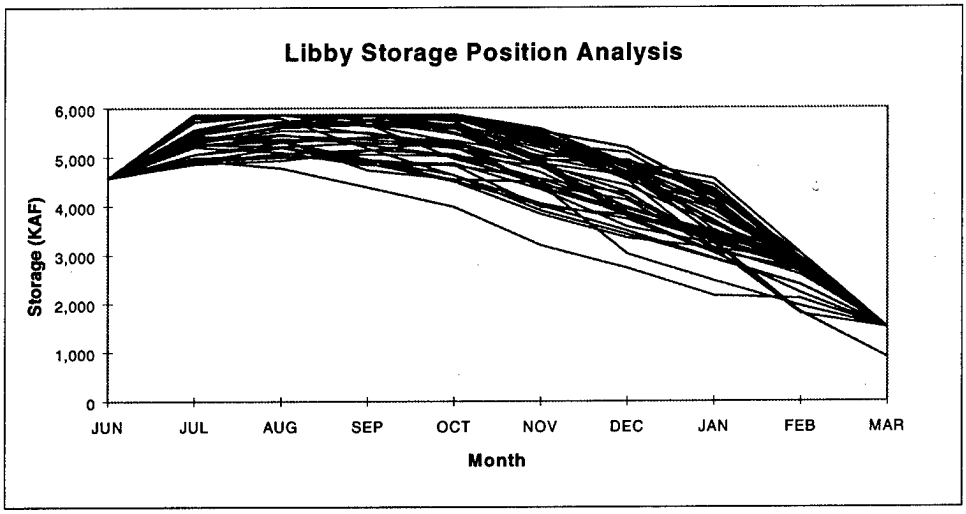
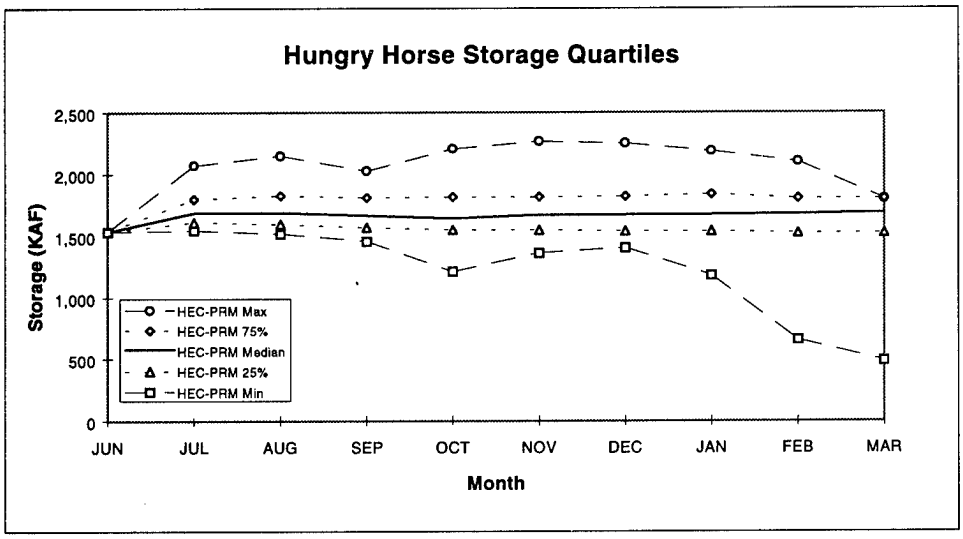
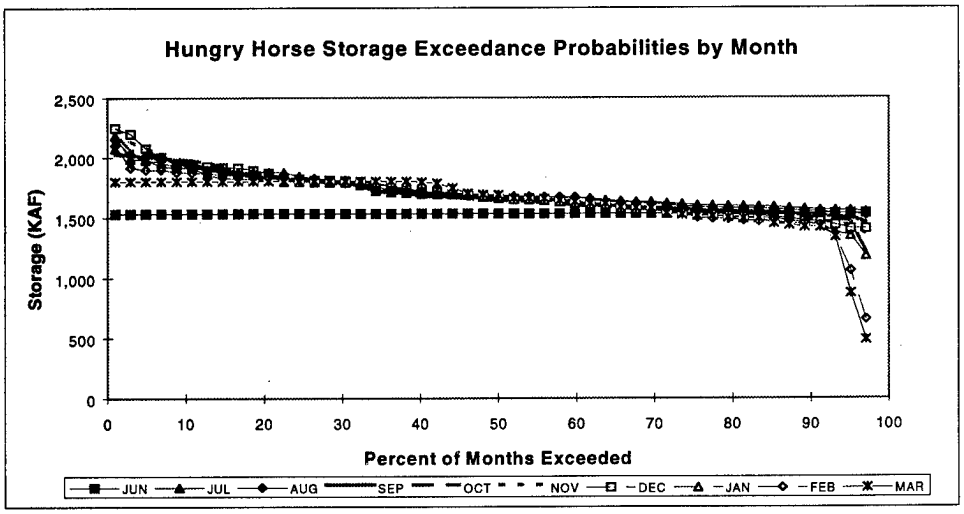


Figure 6.5 Libby Storage Results for HEC-PRM 1994 Drawdown Study





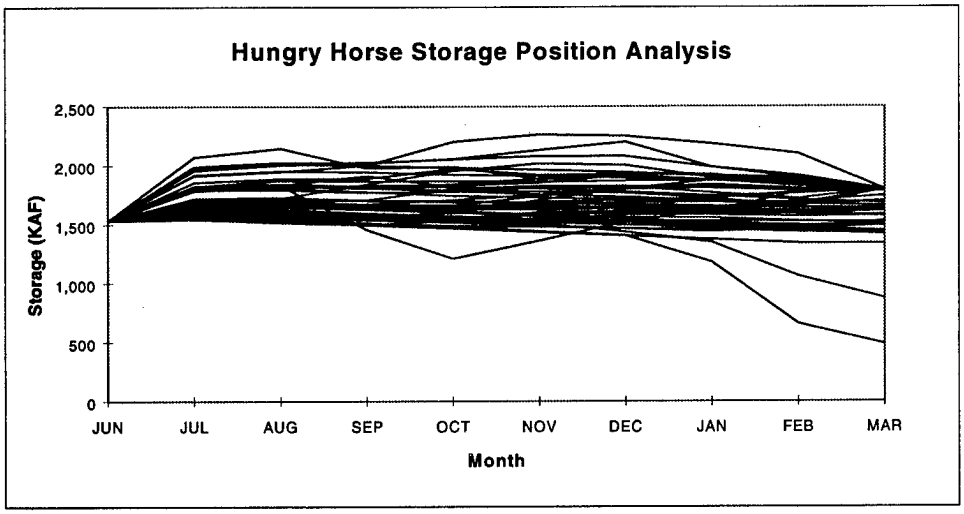
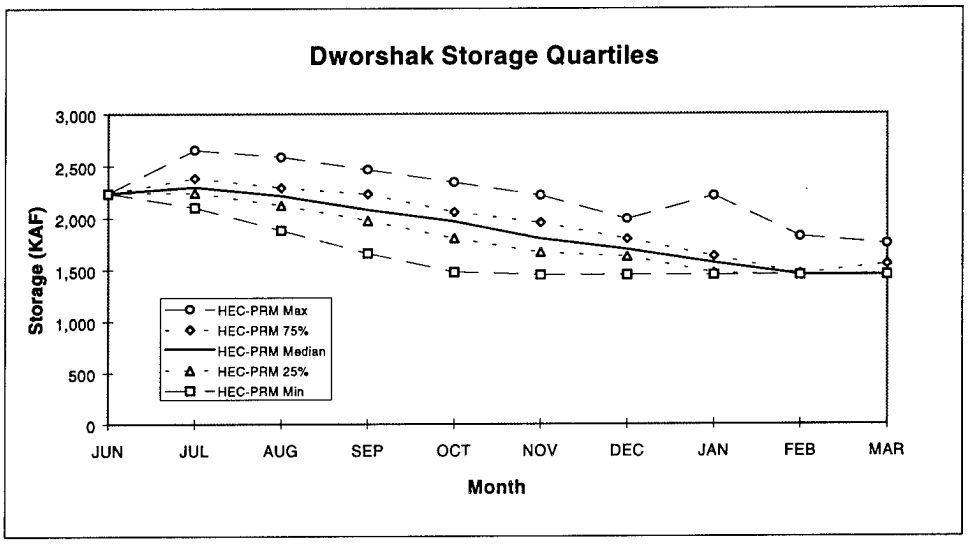
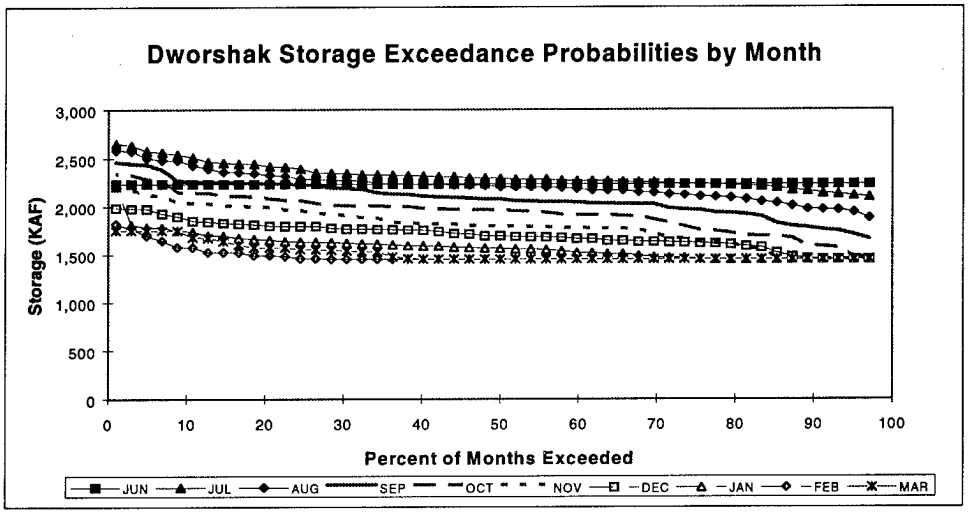


Figure 6.6 Hungry Horse Storage Results for HEC-PRM 1994 Drawdown Study





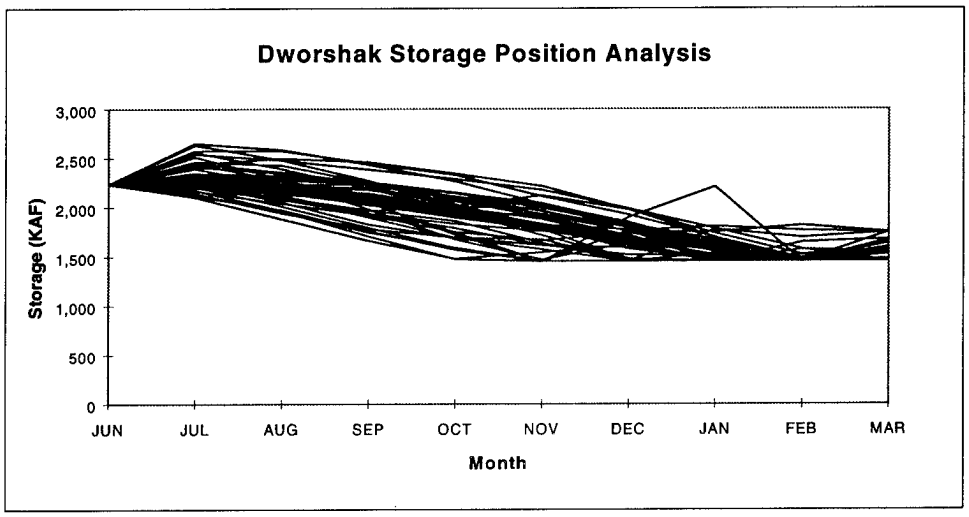


Figure 6.7 Dworshak Storage Results for HEC-PRM 1994 Drawdown Study

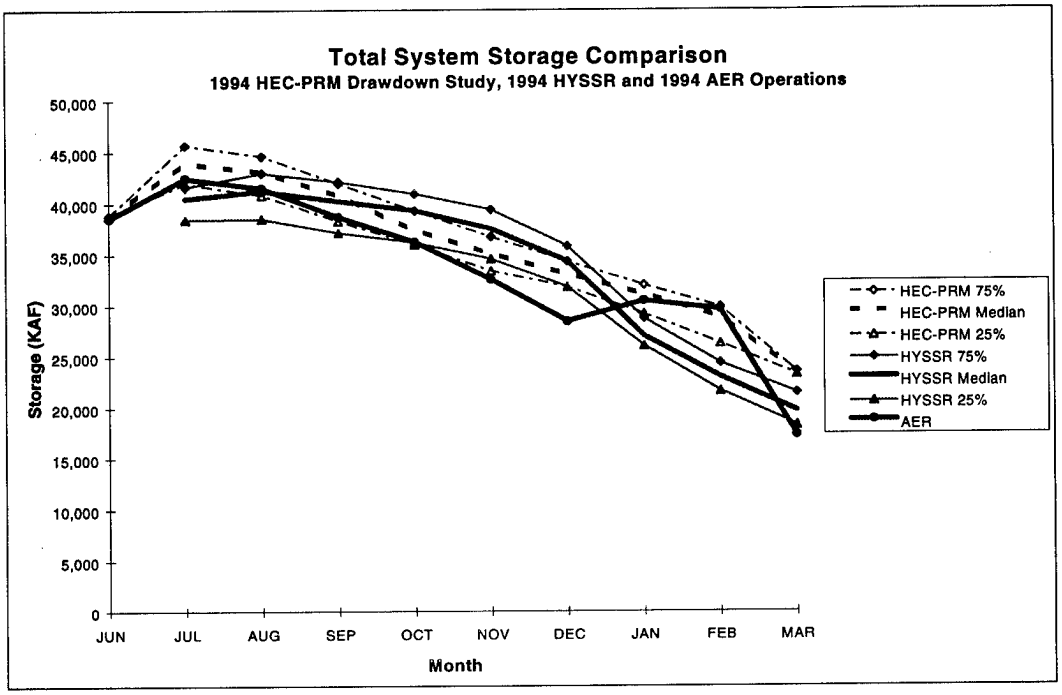


Figure 6.8 Comparison of Total System Storage for HEC-PRM 1994 Drawdown Study, 1994 HYSSR and 1994 AER Operations

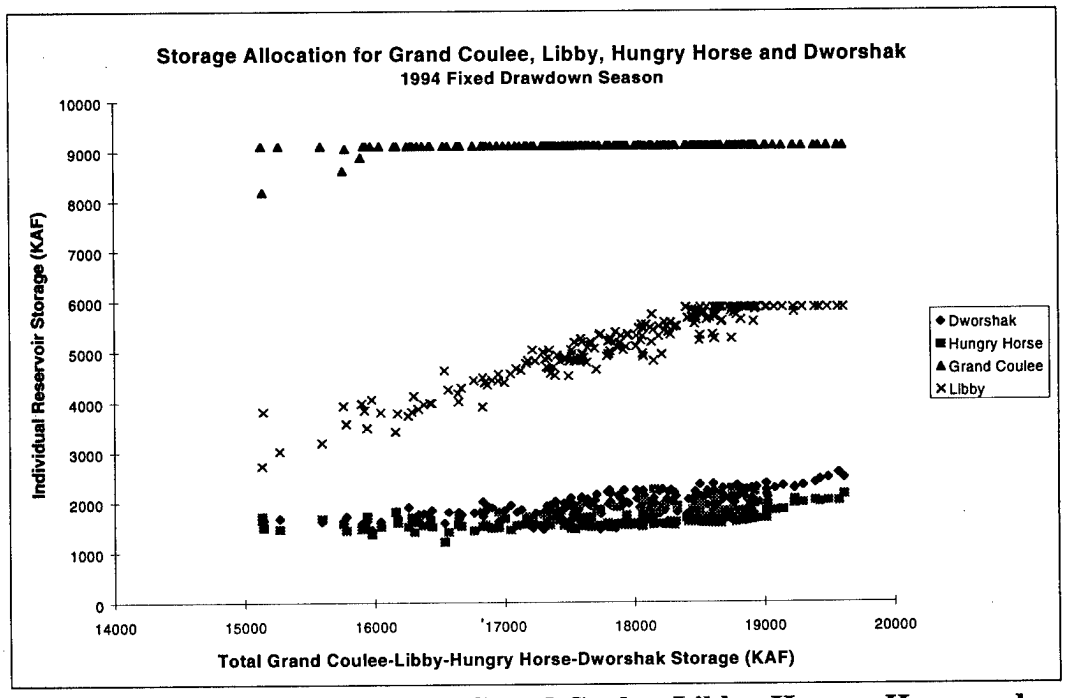


Figure 6.9 Storage Allocation for Grand Coulee, Libby, Hungry Horse and Dworshak for Fixed Drawdown for 1994 Drawdown Study

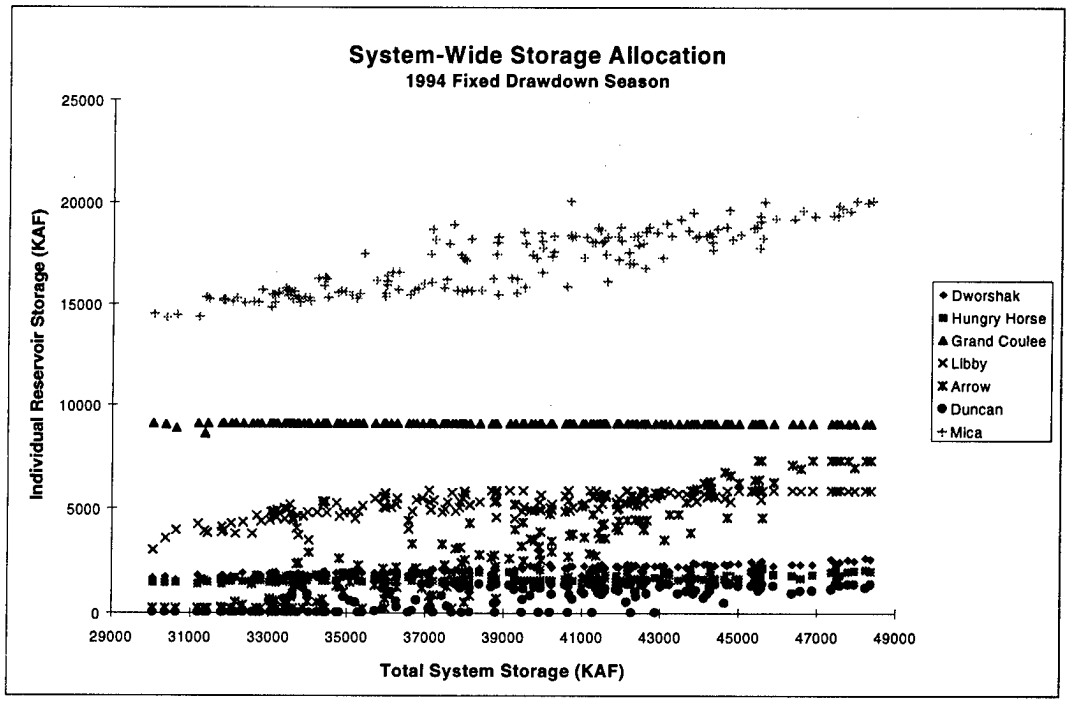


Figure 6.10 System-Wide Storage Allocation for Fixed Drawdown for 1994 Drawdown Study

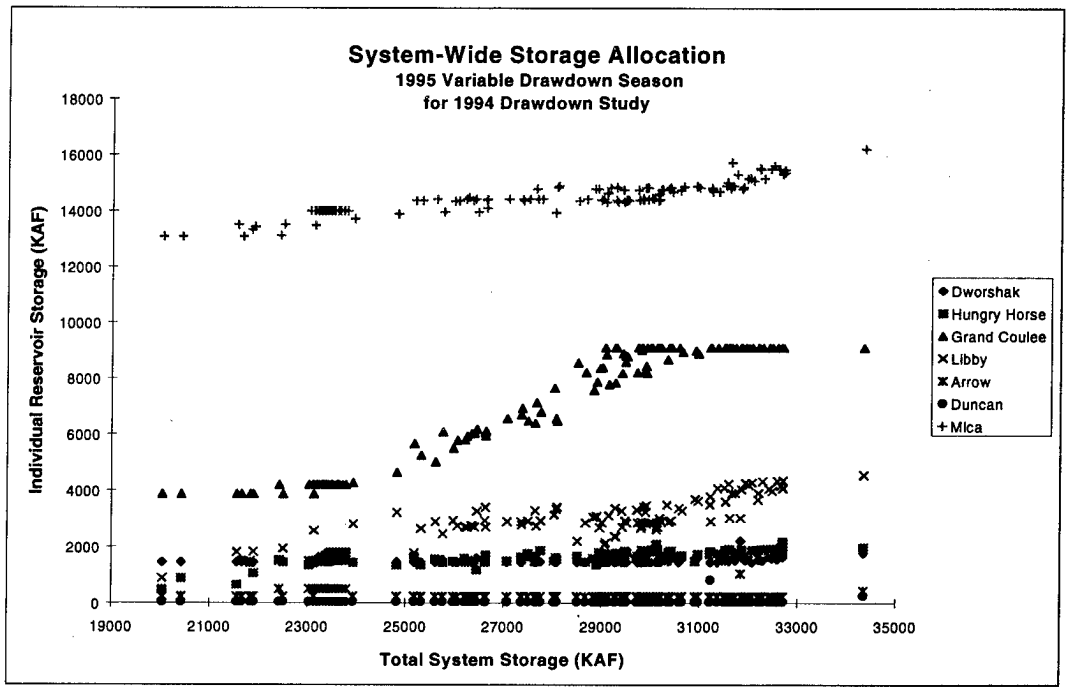


Figure 6.11 System-Wide Storage Allocation for 1995 Variable Drawdown for 1994 Drawdown Study

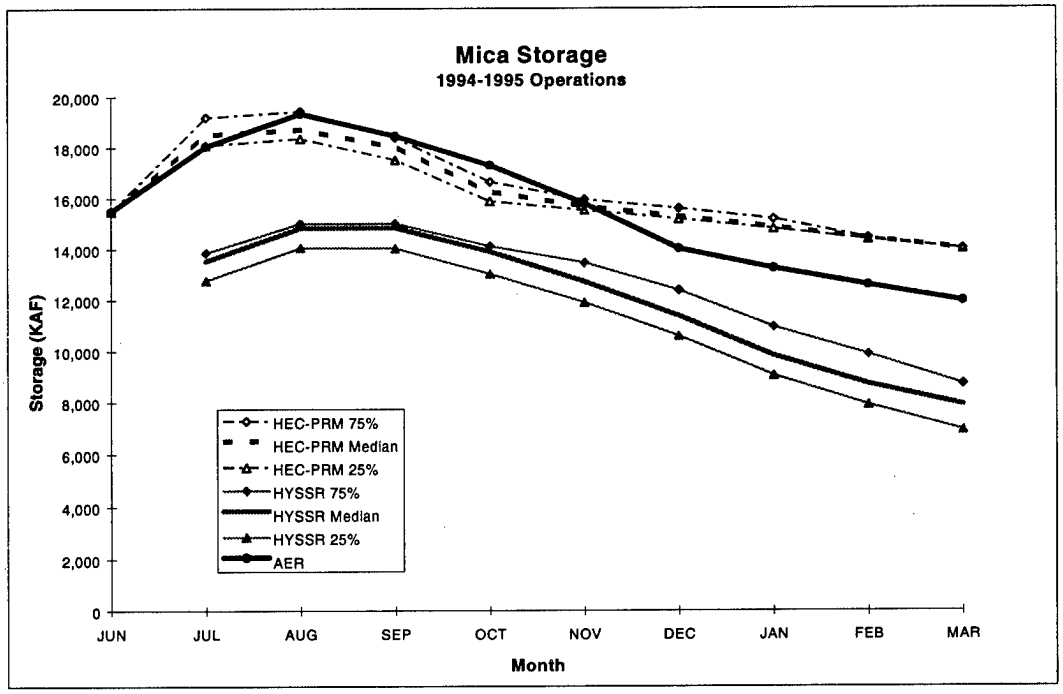


Figure 6.12 Comparison of Mica Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

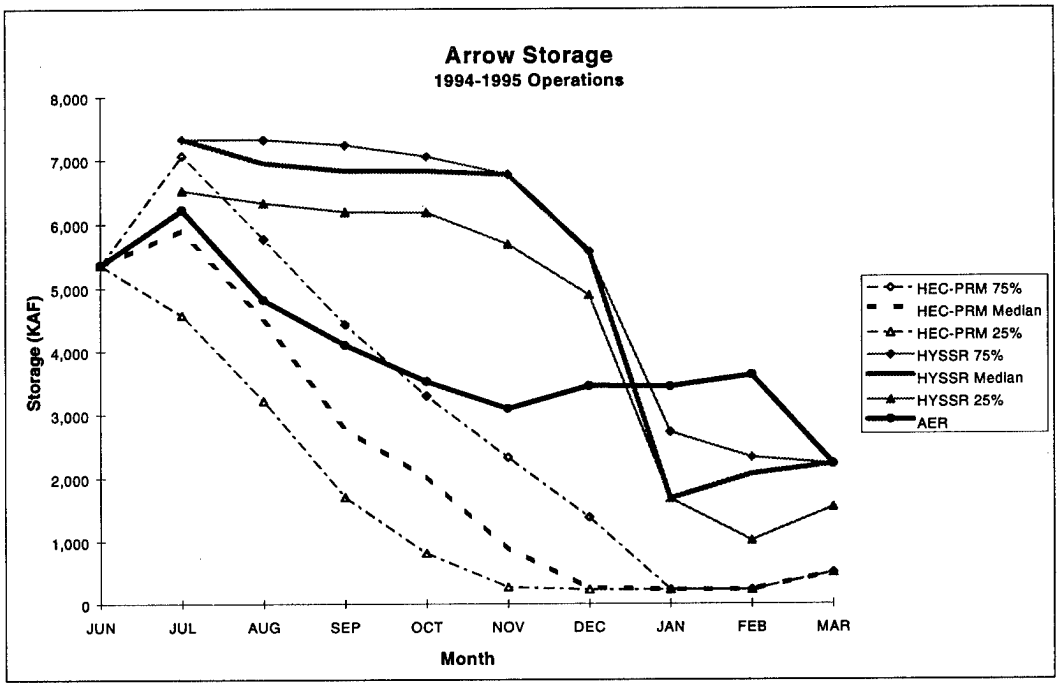


Figure 6.13 Comparison of Arrow Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

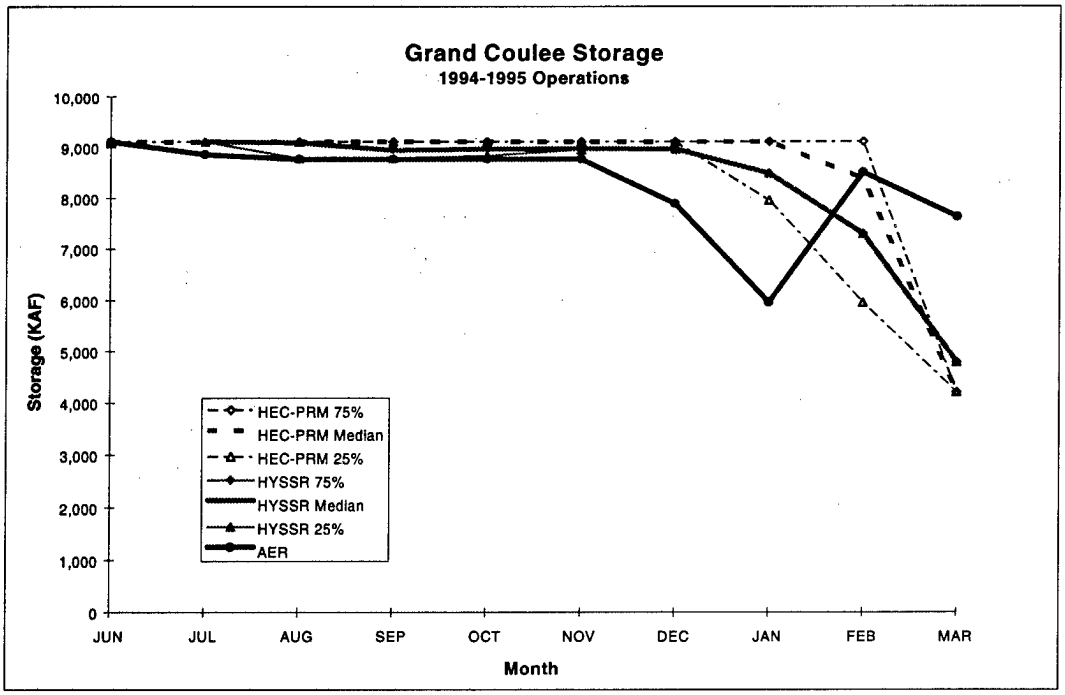


Figure 6.14 Comparison of Grand Coulee Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

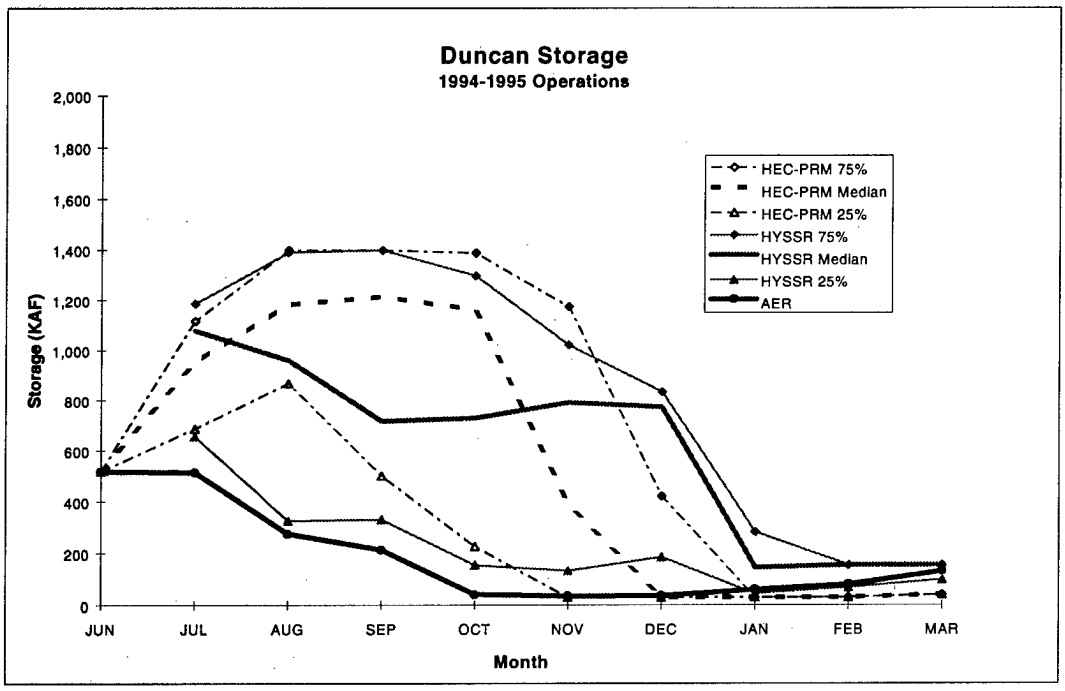


Figure 6.15 Comparison of Duncan Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

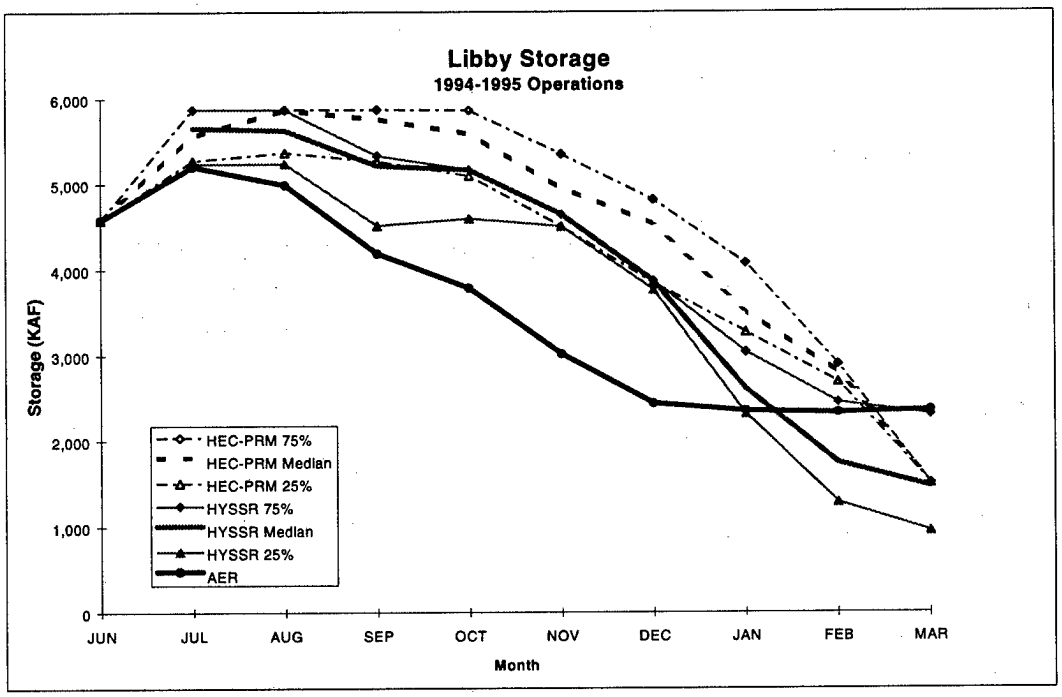


Figure 6.16 Comparison of Libby Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

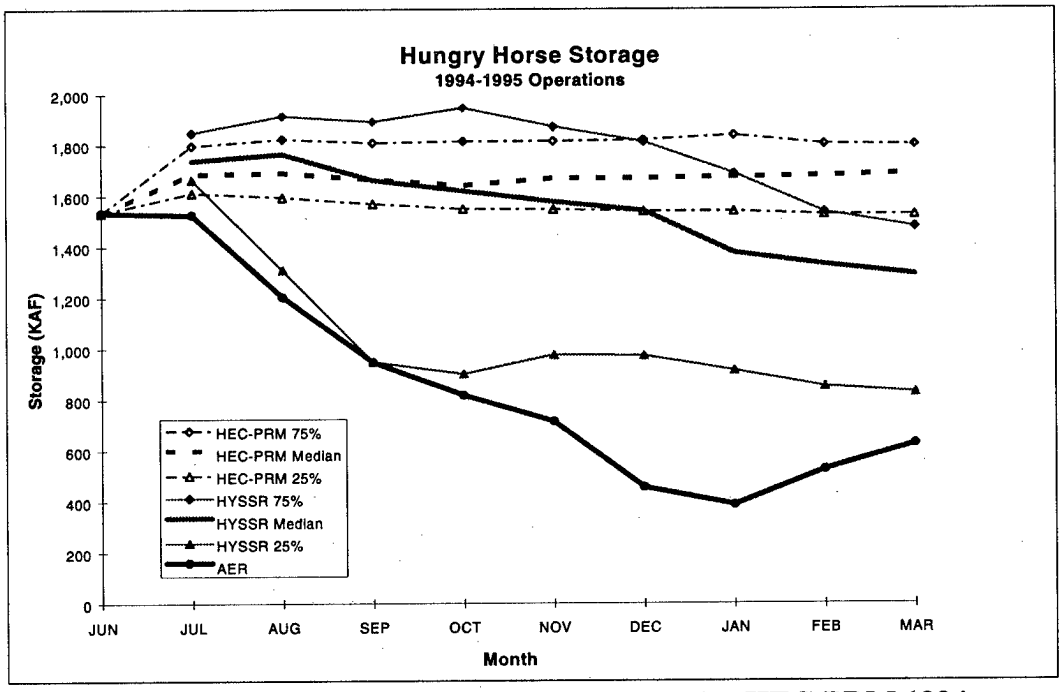


Figure 6.17 Comparison of Hungry Horse Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

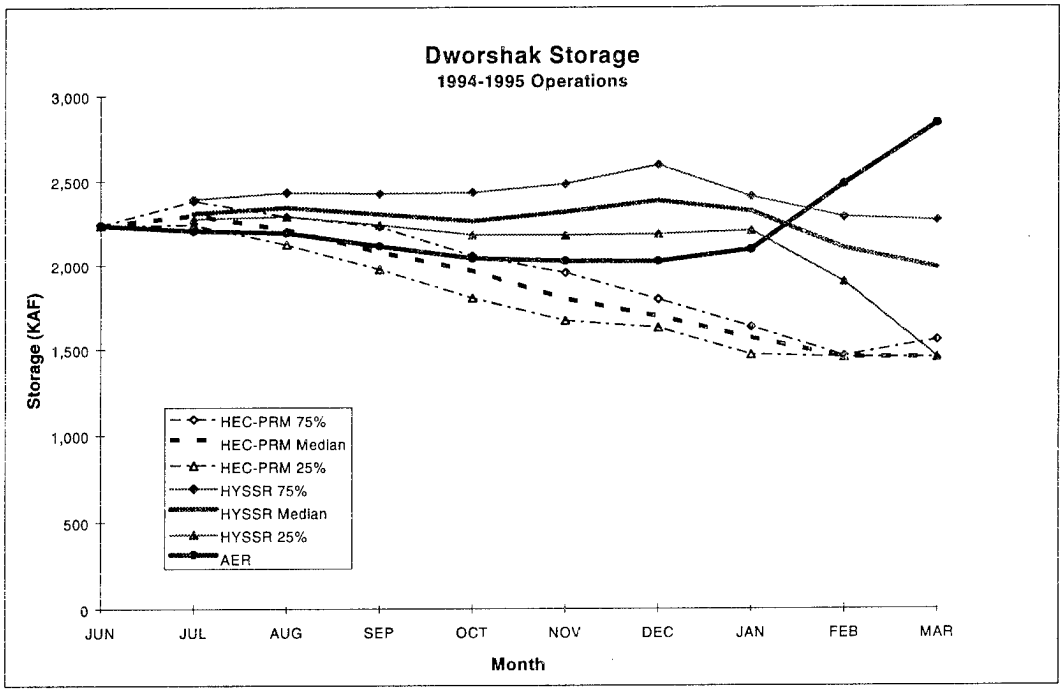


Figure 6.18 Comparison of Dworshak Storage for HEC-PRM 1994 Drawdown Study, 1994-1995 HYSSR and 1994-1995 AER Operations

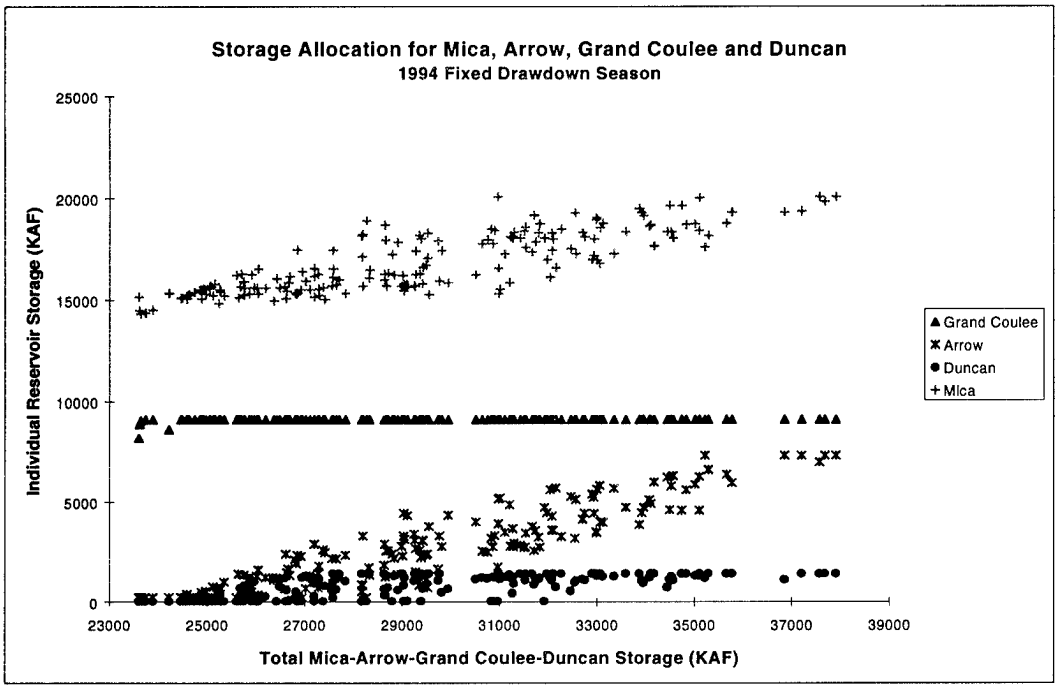


Figure 6.19 Storage Allocation for Mica, Arrow, Grand Coulee and Duncan for Fixed Drawdown for 1994 Drawdown Study

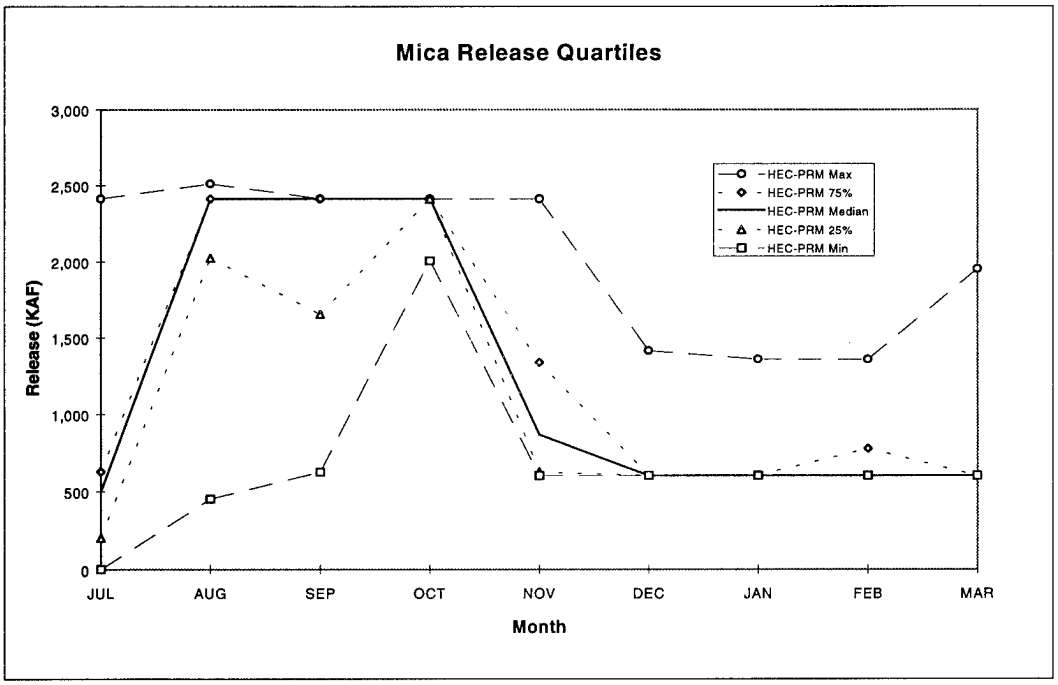


Figure 6.20 Mica Release Quartiles for HEC-PRM 1994 Drawdown Study

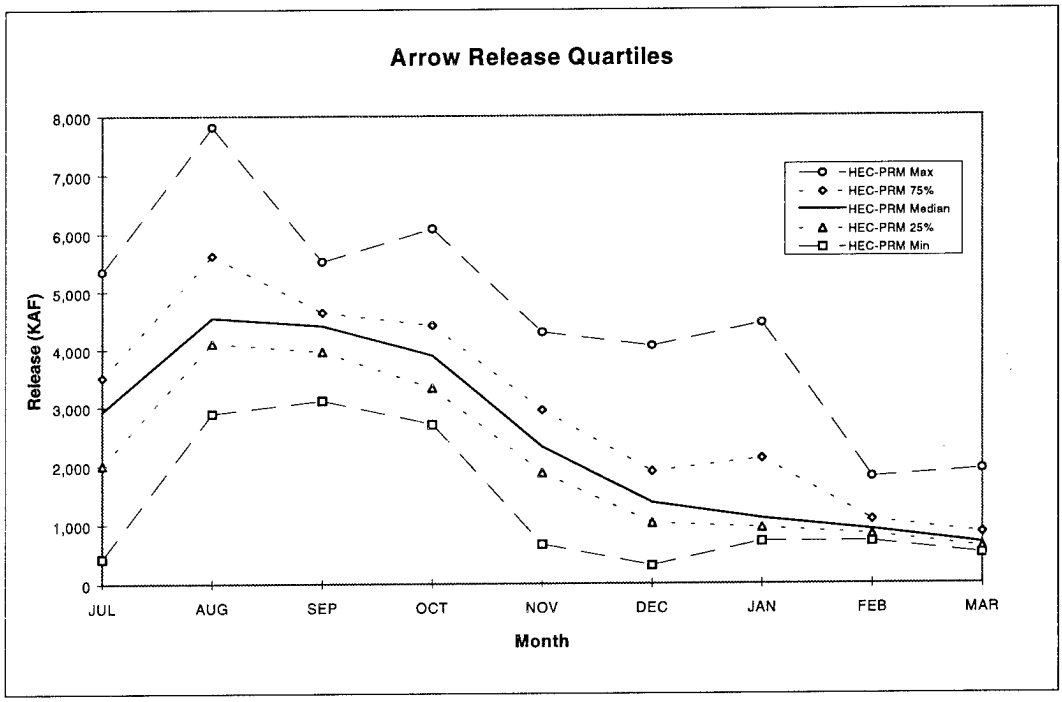


Figure 6.21 Arrow Release Quartiles for HEC-PRM 1994 Drawdown Study

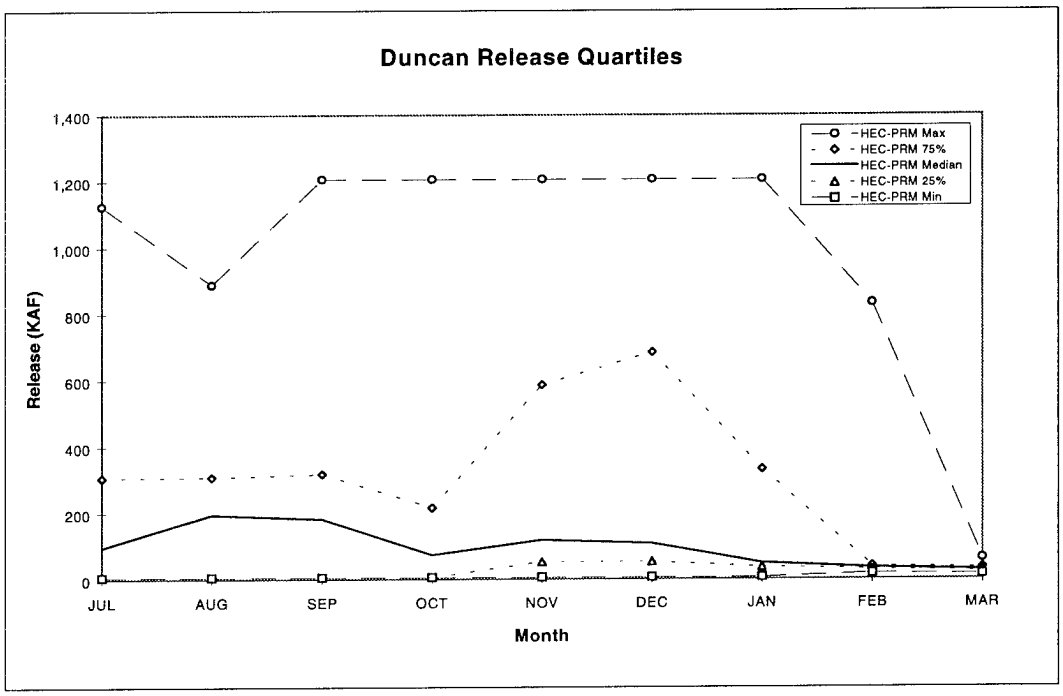


Figure 6.22 Duncan Release Quartiles for HEC-PRM 1994 Drawdown Study

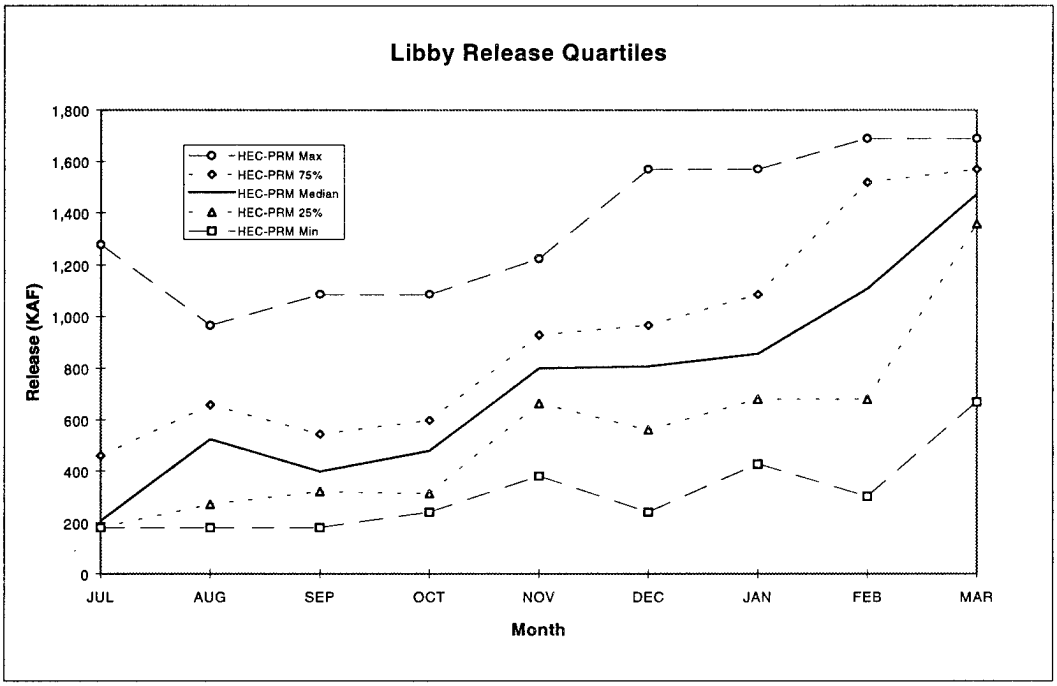


Figure 6.23 Libby Release Quartiles for HEC-PRM 1994 Drawdown Study

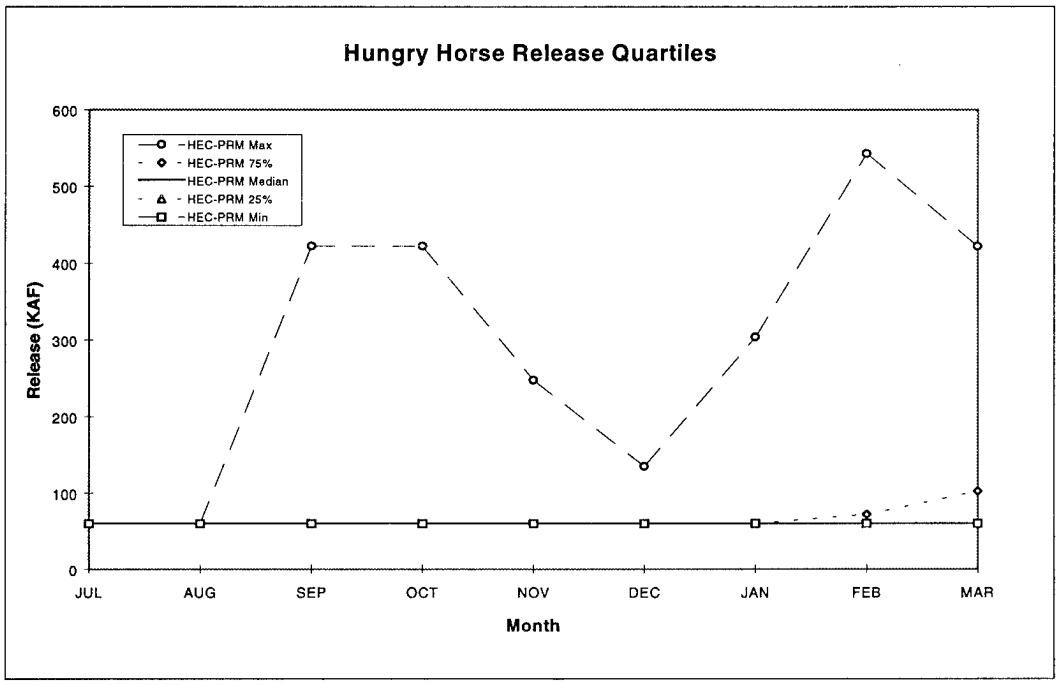


Figure 6.24 Hungry Horse Release Quartiles for HEC-PRM 1994 Drawdown Study

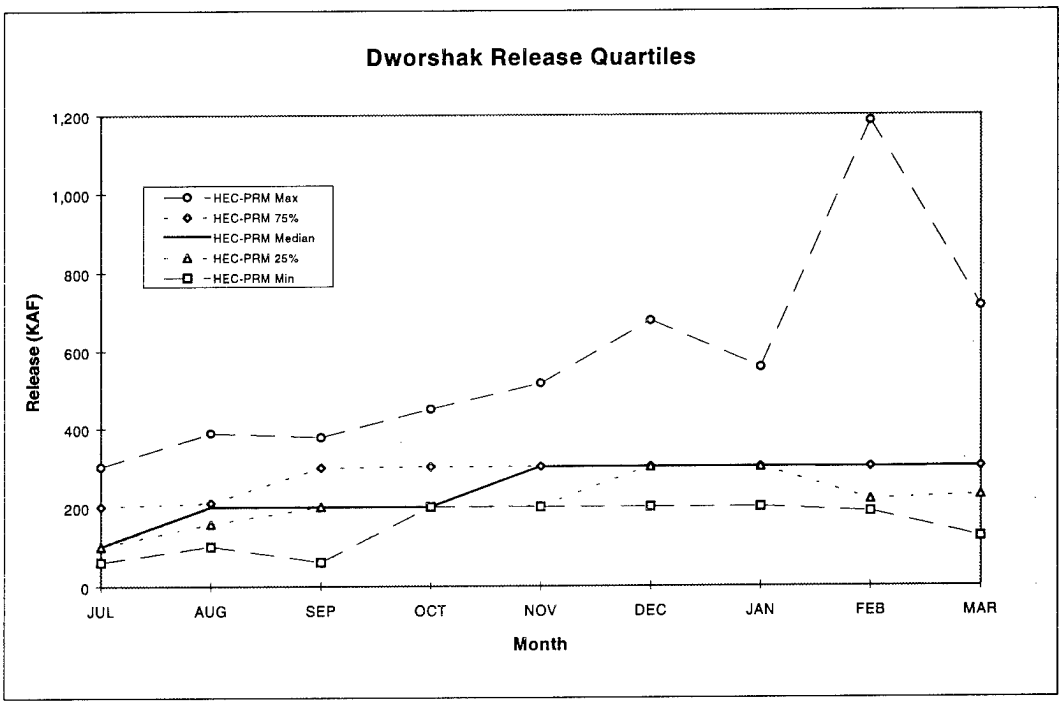


Figure 6.25 Dworshak Release Quartiles for HEC-PRM 1994 Drawdown Study

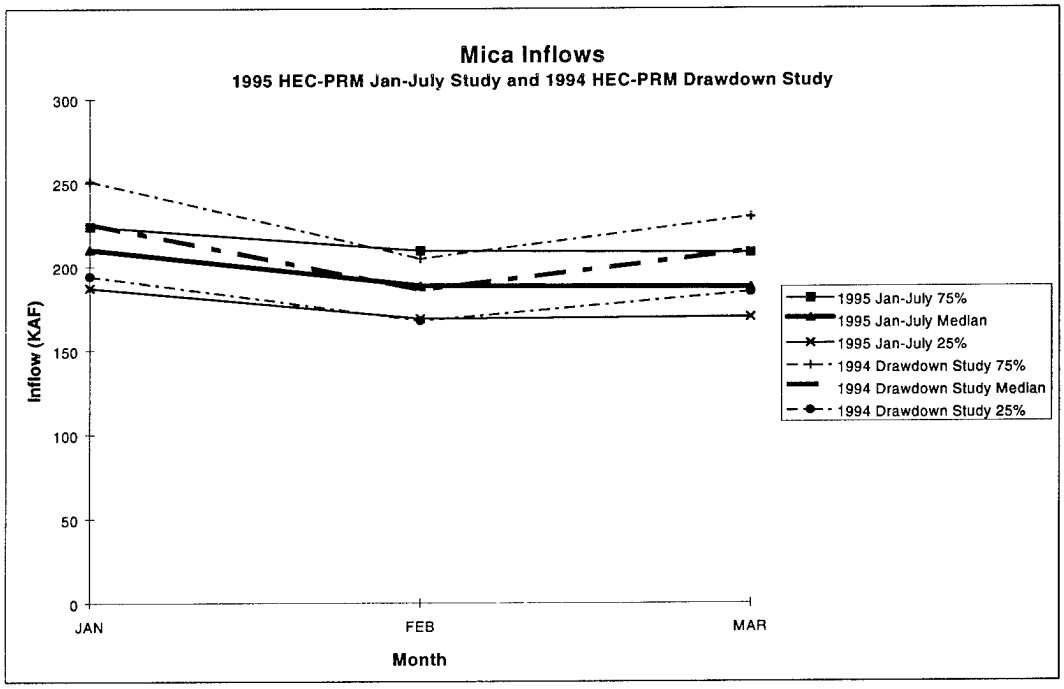


Figure 6.26 Comparison of Mica Inflows for 1995 Jan-July Study and 1994 Drawdown Study

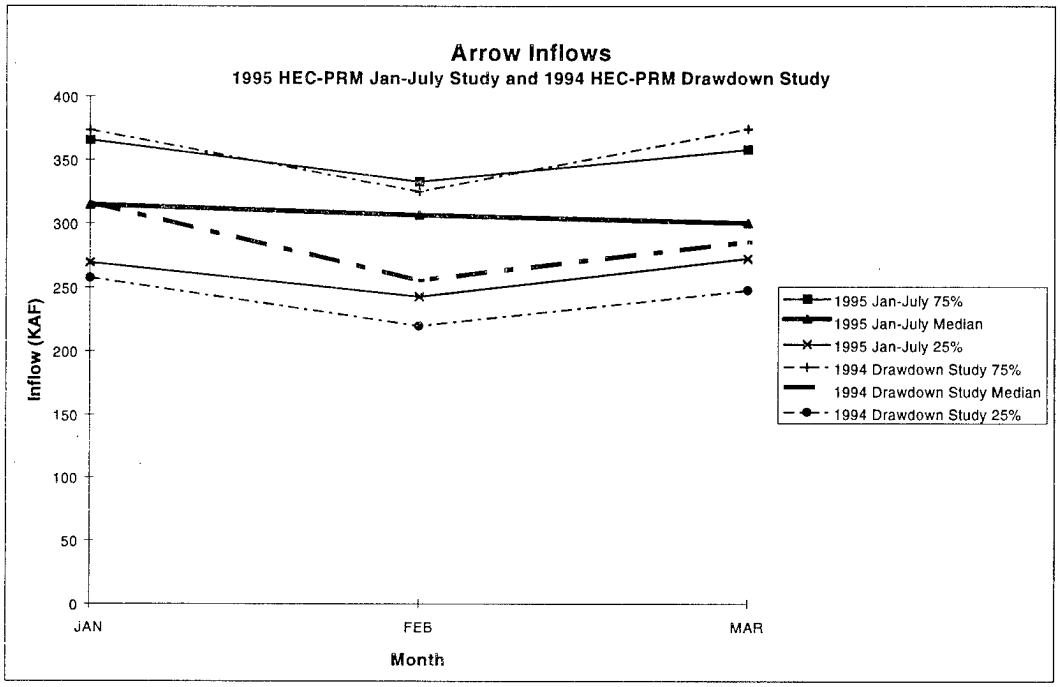


Figure 6.27 Comparison of Arrow Inflows for 1995 Jan-July Study and 1994 Drawdown Study

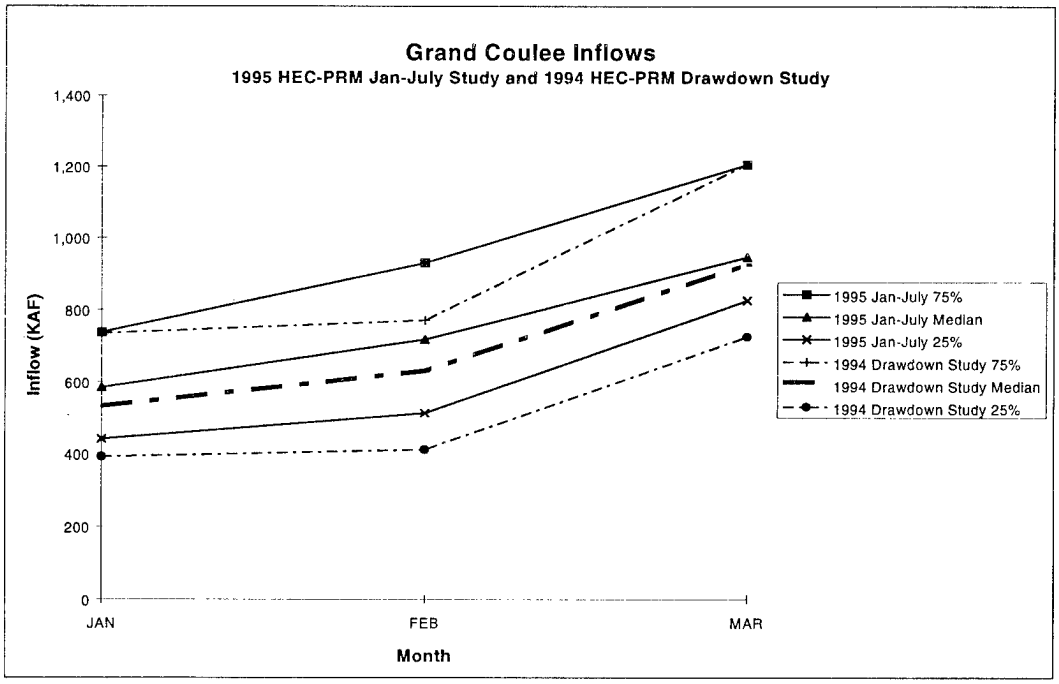


Figure 6.28 Comparison of Grand Coulee Inflows for 1995 Jan-July Study and 1994 Drawdown Study

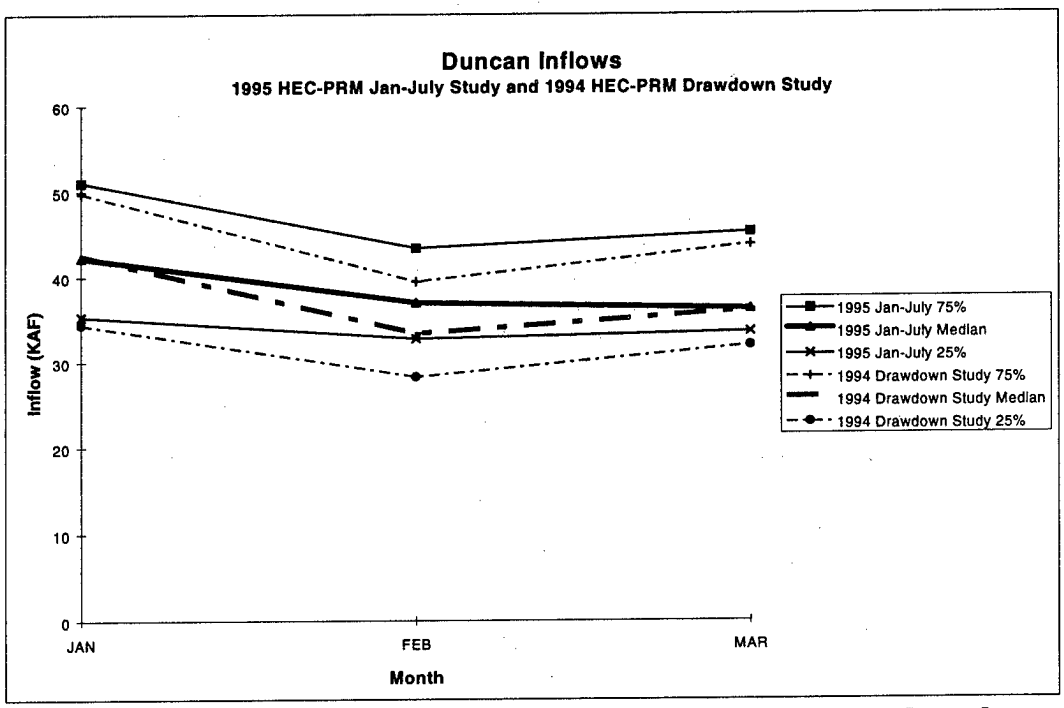


Figure 6.29 Comparison of Duncan Inflows for 1995 Jan-July Study and 1994 Drawdown Study

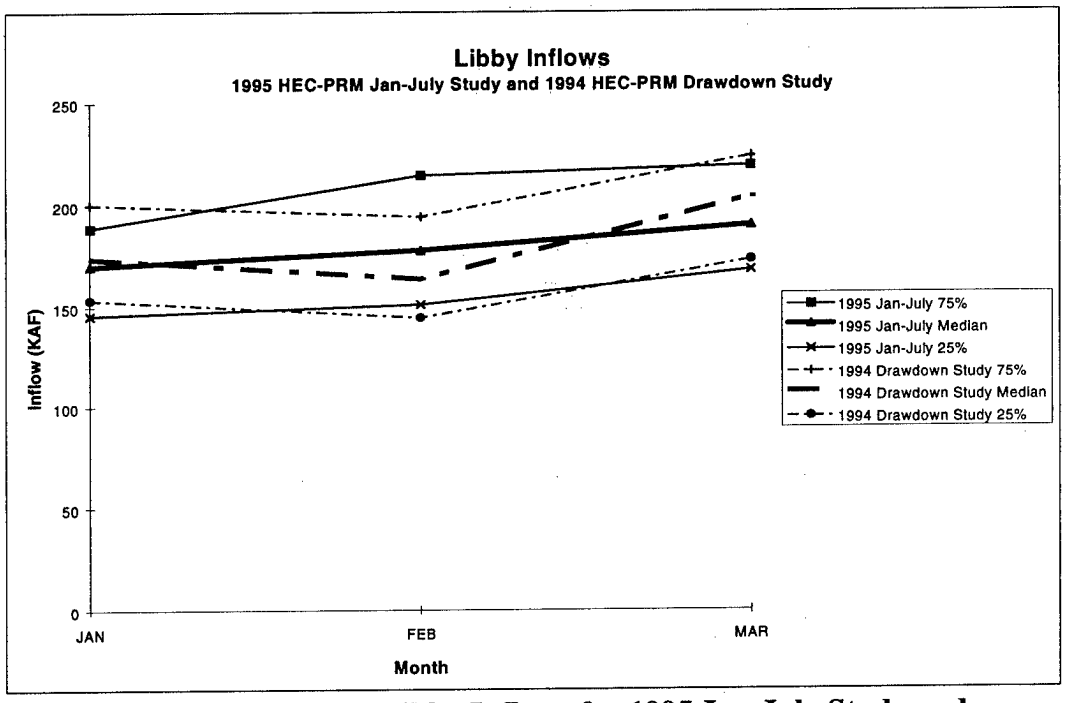


Figure 6.30 Comparison of Libby Inflows for 1995 Jan-July Study and 1994 Drawdown Study

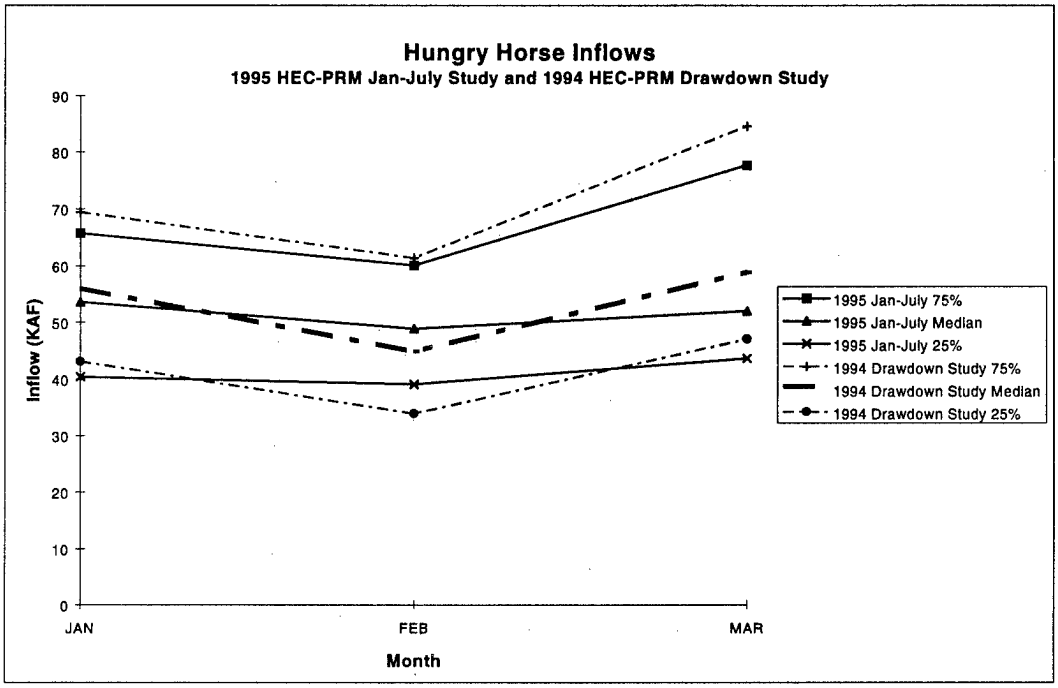


Figure 6.31 Comparison of Hungry Horse Inflows for 1995 Jan-July Study and 1994 Drawdown Study

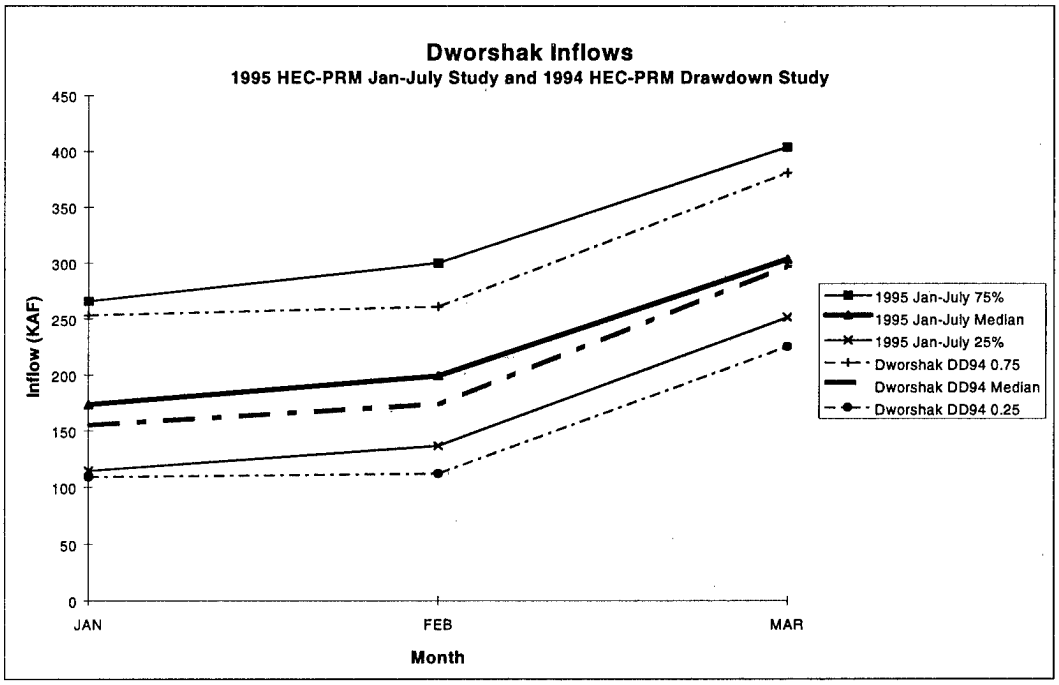


Figure 6.32 Comparison of Dworshak Inflows for 1995 Jan-July Study and 1994 Drawdown Study

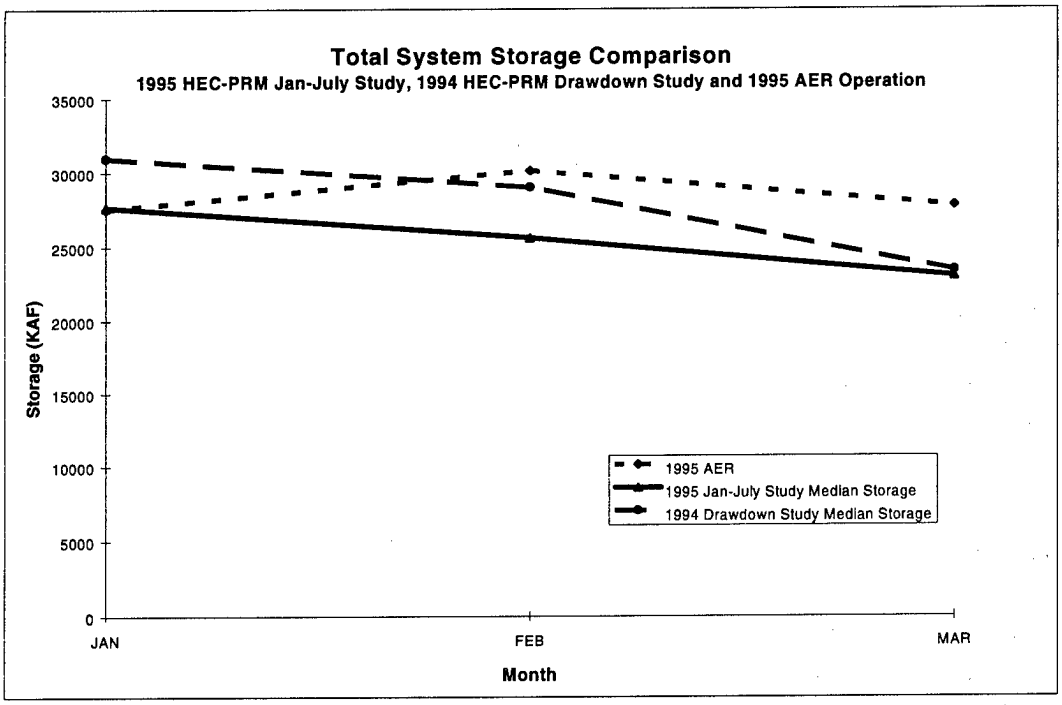


Figure 6.33 Comparison of Total System Storage for 1995 Jan-July Study, 1994 Drawdown Study and 1995 AER Operation

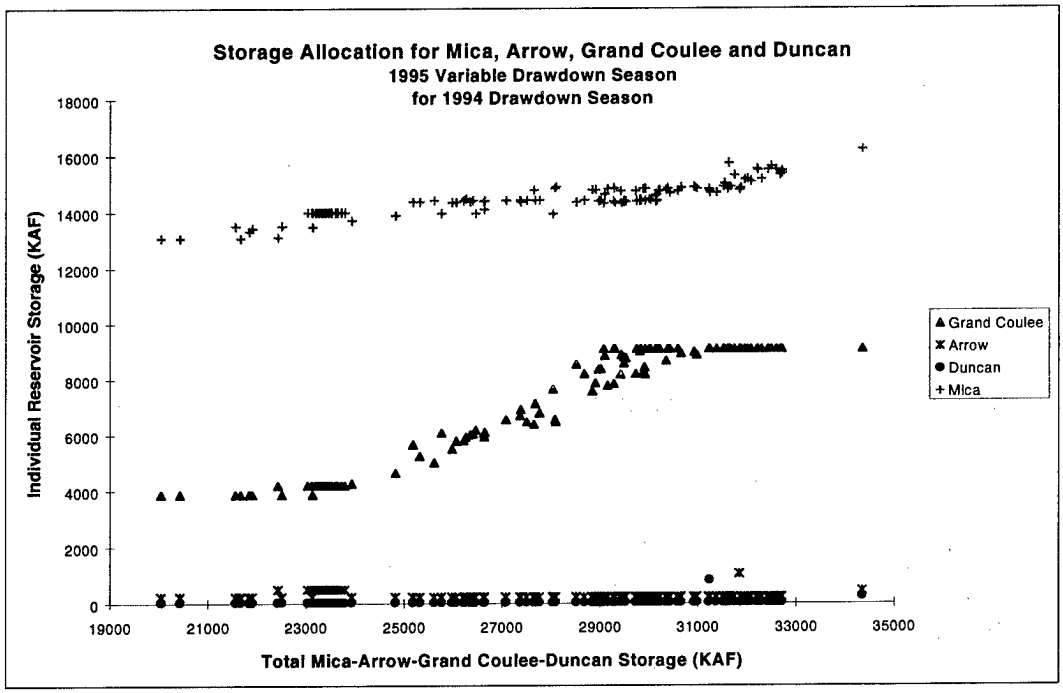


Figure 6.34 Storage Allocation for Mica, Arrow, Grand Coulee and Duncan for 1995 Variable Drawdown for 1994 Drawdown Study

Chapter 7

Conclusions

This chapter presents the conclusions of this report. The utility of HEC-PRM as a seasonal reservoir operation model is assessed. The feasibility of seasonal update runs is discussed. The HEC-PRM advice for each study is presented and compared with the other HEC-PRM studies and the AER operations.

7.1 HEC-PRM's Utility as a Seasonal Reservoir Operation Model

HEC-PRM has potential as a seasonal reservoir operation model using the position analysis approach. This judgment is based the following findings. HEC-PRM operates the Columbia River System similar to the Actual Energy Regulation (AER) operations, and offers consistent seasonal operation advice throughout the HEC-PRM studies. Typically, HEC-PRM and AER storage operations for a given season have similar trajectories. HEC-PRM storage magnitudes do differ from the AER storage values and between HEC-PRM studies, but updated HEC-PRM operations offer potentially useful advice that should be explored with simulation testing. For instance, HEC-PRM tends to store more water than the AER operation in Mica reservoir and less in Arrow reservoir than the AER storage.

HEC-PRM's ability to offer useful advice for reaching July refill target storage shows HEC-PRM's utility as a seasonal operation model. Constrained by the limited amount of water available in refill seasons, HEC-PRM suggests refilling the reservoirs with the highest energy values. HEC-PRM's storage allocation advice also is similar among the four studies. Lastly, HEC-PRM offers consistent specific quantitative advice throughout the HEC-PRM seasonal studies.

7.2 Feasibility of HEC-PRM Seasonal Update Runs

The use of HEC-PRM for seasonal update runs using forecasted inflows provides new seasonal operation advice based on more current conditions. A seasonal update run can provide updated reservoir operations from the recent reservoir storage levels and inflow forecasts. In chapter 4, the 1995 April - July season study, for instance, was an update run for the 1995 January - July period.

HEC-PRM offered modified operations for the April - July 1995 period when HEC-PRM was run with the April inflow forecasts and storage (Figure 4.40). The 1995 April - July study results are closer to the AER operation than the 1995 January - July study. The updated initial storage and forecasted inflows for the reservoirs in April resulted in a HEC-PRM seasonal

operation that models the AER operation more closely. Therefore, HEC-PRM's seasonal update advice for the April - July period matched the AER operation better than for the original run that begins on January 1st. The effort required to complete and interpret these runs is roughly equivalent to current HYSSR runs, although HEC-PRM should not be considered a substitute for HYSSR simulation.

7.3 HEC-PRM's Ability to Reach Reservoir Refill Targets

HEC-PRM offers realistic advice for reaching the July refill target storage. Throughout the three refill studies (1994 January - July study, 1995 January - July study and 1995 April - July study), HEC-PRM never refills every reservoir to its target storage for all inflow sequences. HEC-PRM advises refilling as many reservoirs as possible for all the inflow sequences, but the limited amount of water available throughout the system hinders HEC-PRM from operating all of the reservoirs at the target level all of the time.

Typically, HEC-PRM always refills those reservoirs with the largest inflows and highest energy storage values. For instance, Mica, Arrow, Grand Coulee and Libby reservoirs are always refilled to their July targets in the 1995 January - July season study (Figures 3.1 - 3.3 and 3.5). Note that the largest July inflows into the system in July in the 1995 January - July study are for Mica, Arrow, Grand Coulee and Libby reservoirs (Figure 3.8). In addition, HEC-PRM always refills Grand Coulee reservoir. When Grand Coulee inflows are not enough to meet the targeted level; water is used from Arrow reservoir to fill Grand Coulee in July (Figure 4.9). HEC-PRM always advises Grand Coulee reservoir refill probably because its hydropower production objectives are significant economically.

7.4 Utility of HEC-PRM's Seasonal Operation Advice

HEC-PRM advice both agrees with the AER operation and offers new seasonal operations in the four case studies. HEC-PRM's advice matches the AER operation often, which indicates that HEC-PRM is capable of suggesting reasonable seasonal reservoir operation advice. In addition, it is advantageous that HEC-PRM advice varies from the AER operation because HEC-PRM may be suggesting improved seasonal reservoir operations. Therefore, HEC-PRM advice should be explored further with simulation testing.

HEC-PRM advice appropriately reflects changes in inflow hydrology. For instance, HEC-PRM consistently stores less water in the variable drawdown season of the 1995 January - July study than in the 1994 January - July study. HEC-PRM operated the 1995 January - July study different than the 1994 January - July study because the model knows that more water is present in 1995 than 1994 to refill the system (Figures 3.11 and 5.17).

Typically, HEC-PRM's advice on storage trends and seasonal operation trajectories generally followed AER operations. Position analysis and quartile comparison plots show this well (Figures 3.17, 4.19, 5.26 and 6.12). However, HEC-PRM storage magnitude advice often

deviated from the AER operation. HEC-PRM encourages the storage of considerable amounts of water in the reservoirs.

On a system-wide basis, HEC-PRM advice varies, but typically AER operations agree with the median HEC-PRM system storage curve (3.11, 4.10, 5.17 and 6.8). HEC-PRM actually advises storing more water than the AER storage in some reservoirs and less in other ones, and, as a result, the total system operations are fairly similar.

HEC-PRM typically operates Mica with more water than AER operation in the variable drawdown season (Figures 3.17, 4.15 and 5.26). HEC-PRM draws Arrow reservoir down to its minimum allowable storage of 227KAF in the variable drawdown season, significantly lower than the AER operation (Figure 3.18, 5.27 and 6.13). Grand Coulee should be kept as high as possible, especially in the fixed drawdown season (Figure 6.14).

HEC-PRM tends to allocate system water similarly during the variable drawdown season in the seasonal studies. For instance, the 1994 and 1995 January - July studies draw down the system similarly from January to March (Figures 3.13 and 5.19). In addition, the 1994 Drawdown study and the 1995 January - July study have approximately the same order of drawdown for the system in the 1995 variable drawdown season (Figure 3.13 and 6.11).

HEC-PRM offers consistent specific quantitative advice throughout the four seasonal studies. According to the 1994 and 1995 January- July studies and the 1994 Drawdown study, the consistent advice for the variable drawdown season is that Mica should release 603KAF (minimum allowable release), Arrow should store 227KAF (minimum allowable storage), and Hungry Horse should release 60KAF (Tables 5.6 and 6.6). For the April - June period of the refill season, the 1995 January - July study and the 1995 April - July study both advise storing Grand Coulee at 9107 KAF (maximum allowable storage), releasing 6KAF (minimum allowable release) from Duncan, discharging 181KAF (minimum allowable release) from Libby and releasing 60KAF from Hungry Horse (Table 4.6).

Throughout the four seasonal studies, HEC-PRM clearly advises the use of Arrow reservoir for significant drawdown in the variable drawdown season (Figures 3.18, 5.27 and 6.13) . Arrow is a wise choice because there are no penalty functions constraining its operation. The HEC-PRM Arrow operation should be explored with simulation testing. Grand Coulee is used for large changes in storage probably because its great capacity allows for considerable discharges downstream.

7.5 Limitation of HEC-PRM

HEC-PRM has an omniscient perspective on inflows. The model always knows what inflows are going to arrive in the future. As a result, HEC-PRM can store water without the threat of flooding. This is an unrealistic perspective because reservoir operators never know exactly what inflows to expect. Though inflow forecasts, based on snowpack conditions and weather predictions, are useful to assist in reservoir operation, they will never compare to having complete knowledge of the future as HEC-PRM does. Therefore, there is the need to test and

refine operations suggested by HEC-PRM using simulation models.

7.6 Improvements for Future HEC-PRM Seasonal Operation Studies for the Columbia River System

A HEC-PRM seasonal operation study should be run based on observed operations. The four HEC-PRM seasonal studies in this report were run on the Actual Energy Regulation (AER) operations. The AER storage levels are designed to produce non-firm energy in wet years and to accommodate firm energy demands in dry years.

Fish requirements mandated from recent biological opinions should be included in the penalty functions. The lack of fish penalty functions throughout the system may be a reason that HEC-PRM tends to store lots of water, typically more water than the AER operations.

Duncan reservoir operation should be examined further. HEC-PRM's advice to draw down Duncan a considerable amount in July, in the 1994 and 1995 January - July studies and the 1995 April - July study, is unclear (Figures 3.20, 4.4 and 5.12).

Appendix A

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Appendix B

Description of HEC-PRM

The Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) is designed to optimize the allocation of available water in a reservoir system (USACE, 1991b). HEC-PRM optimizes operations by minimizing flow costs through a reservoir system network.

HEC-PRM is a network flow model by design. Therefore, the actual reservoir system under study is represented by a physical framework of nodes and links for HEC-PRM optimization purposes (Jensen and Barnes, 1980). The Columbia River system network is shown in Figure 1.2.

HEC-PRM is distinct as a prescriptive model. Prescriptive model results define solutions that are based on predetermined objectives. Penalty functions define these operational objectives. Then, the objective function of the network flow problem is developed by the sum of convex, piecewise-linear approximations of the penalty functions (USACE, 1991b). Operations may be controlled by constraints placed on the system operation also.

An extensive discussion on HEC-PRM is given in the Columbia River system Phase I report (USACE, 1991b). Additional information on HEC-PRM is available in the Missouri River System Phase I report also (USACE, 1991a).