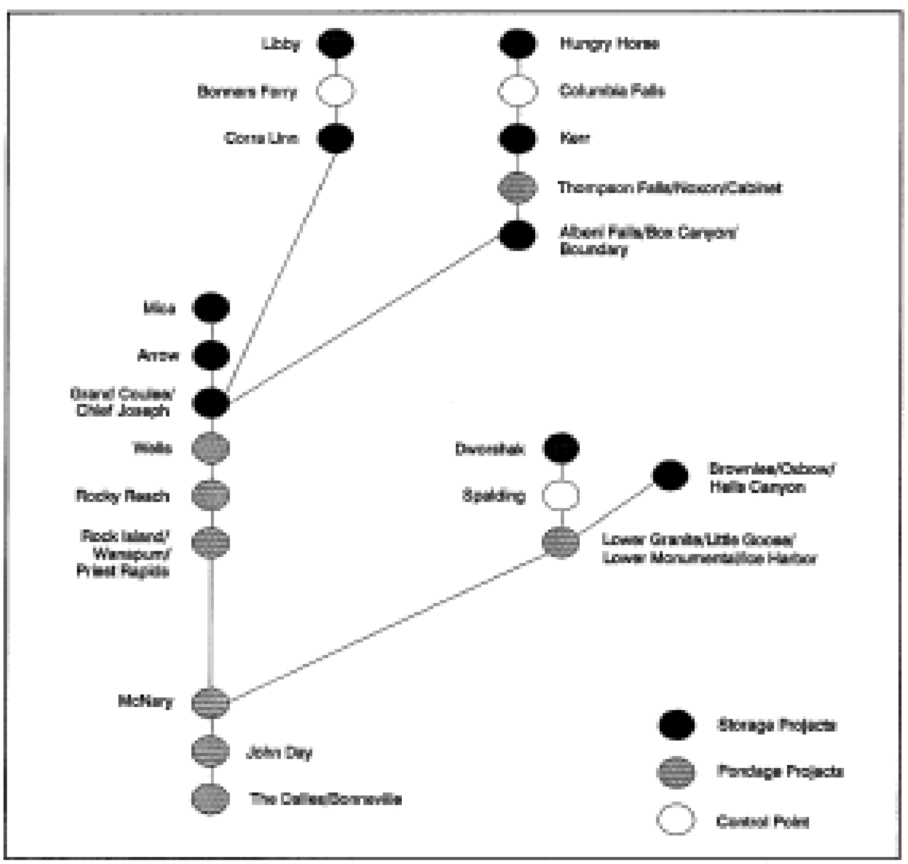
US Army Corps
of Engineers
Hydrologic Engineering Center

Columbia River System Analysis Model - Phase I

October 1991



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Report documenting the development of the HEC-Prescriptive Reservoir Model and its application of analyzing the operation of the Columbia River reservoir system. The model represents the system as a network and uses network-flow programming to allocate optimally the system water. Two applications are documented: (1) a validation test to determine the applicability of the model for the system, and (2) analysis of the critical period. The applications are performed using the best-currently-available estimates of flow data and penalty functions.

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PREFACE

The investigation reported herein is Phase I of a proposed two-phased study involving the application of the Hydrologic Engineering Center's Prescriptive Reservoir Model, designated HEC-PRM, to the Columbia River reservoir system. The model, applies network-flow programming, a special case of linear programming, to reservoir system operation analysis. Phase I, which began 1 January 1991, included preliminary analysis and testing and evaluation of the applicability of HEC-PRM to the Columbia River reservoir system. Phase II, planned for 12 additional months, will expand the model, and using enhanced flow and penalty function data, will apply the model to evaluate the optimal reservoir system operations for a set of alternatives.

The project is undertaken at the request of the North Pacific Division which funded the study. The project is a joint effort among the Hydrologic Engineering Center (HEC), responsible for the model development and application, and the Institute for Water Resources (IWR), responsible for economic aspects and development of penalty functions for the Columbia River system. The IWR report is published separately. Mike Burnham, Chief of Planning Analysis Division, served as project manager. Bob Carl, Planning Analysis Division, oversaw and contributed significantly to the technical aspects and review of the study. Richard Hayes, Training Division, assembled the model input data, participated in the analysis, and assembled the Phase I report material. Marilyn Hurst, Training Division, developed edited penalty functions for the model. Vern Bonner, Chief of Training Division, participated throughout and contributed with his expert reservoir experience to the project. Loshan Law, Planning Analysis Division, typed and assembled the report. David T. Ford, Engineering Consultant, provided expert advice and assistance in model formulation, development, and documentation. Darryl W. Davis, Director, provided general supervision and guidance throughout the project. HQUSACE point of contact for the work is Earl Eiker, Chief of Hydraulics and Hydrology Branch, Engineering Division, Civil Works Directorate.

COLUMBIA RIVER SYSTEM ANALYSIS

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COLUMBIA RIVER SYSTEM ANALYSIS

PHASE I

SUMMARY AND CONCLUSIONS

Operation of the Columbia River system reservoirs was analyzed with the Hydrologic Engineering Center's Prescriptive Reservoir Model, HEC-PRM. This model represents the system as a collection of nodes and links and uses network-flow programming to allocate optimally the system water to the links. This network approach was selected because it satisfies institutional, economic, environmental, and engineering criteria.

The network representation of the Columbia system includes major projects on the Columbia, Snake, Clearwater, and Pend Oreille Rivers. Monthly operation for hydropower, flood control, recreation, navigation, water supply, and fish and wildlife protection is modeled. Goals of and constraints on operation for these purposes are represented with penalty functions.

The purpose of the Phase I analysis was to explore application of HEC-PRM to the Columbia River system of reservoirs. Information necessary for the development of penalty functions for the Canadian treaty reservoirs, Mica and Arrow, was not available for Phase I analysis. Since the treaty projects are important components of the Columbia River system they have been included in the HEC-PRM network. The projects are operated within the current treaty storage limits. Phase II of the study will incorporate more detailed information on the treaty projects and the model will provide an additional tool to analyze uses of Columbia Basin resources.

Prior to application of HEC-PRM as a decision-support tool for the system operation review (SOR) study, HEC staff devised and executed a subjective model-validation test, using known system supplies and demands for September 1969 to July 1975. The HEC-PRM results were compared with results of the North Pacific Division's (NPD) HYSSR model. The operation prescribed by HEC-PRM matched well the operation found with HYSSR. Thus HEC-PRM was accepted for further analyses in the SOR study.

To demonstrate applicability of HEC-PRM, HEC staff analyzed system operation for the critical flow period from July 1928 to February 1932. The best-currently-available estimates of system penalty functions were used. These represent current goals of, and constraints on, operation.

Phase II of the Columbia River system study will (1) expand the system analyzed and make needed technical improvements to the HEC-PRM; (2) refine the penalty functions used; (3) analyze additional policy options; (4) refine the model's user interface; (5) upgrade HEC-PRM documentation; and (6) transfer the technology to the Columbia River SOR study team.

PROBLEM DESCRIPTION

The coordinated Columbia River system considered in this study includes major storage and pondage reservoirs on the Columbia, Snake, Clearwater, Kootonai, and Pend Oreille Rivers as shown in Figure 1. The dominant purposes for operation of these reservoirs are power generation, flood control, and protection of anadromous fish. The U.S. Army Corps of Engineers (USACE) and the Bureau of Reclamation (BuRec) operate the federal dams, and the Bonneville Power Administration (BPA) sells the power produced.

According to a public document titled *The Columbia River: A System Under Stress* (BPA, USACE, BuRec, 1990),

> *Growth in our region, along with changing priorities, are putting our river system increasingly under stress. There simply is not enough water flowing in the system to meet all the demands. Trade-offs must be considered...The agencies want a system operation review because, in recent years, demands by the various users of the river have increased dramatically, resulting in increasing conflicts among uses. Methods for resolving conflicts are not clearly defined.*

USACE-NPD (1990d) formally proposed this system operation review (SOR). According to the SOR plan of study and the accompanying management plan (USACE-NPD, 1990a, 1990b), the SOR will:

> *1. Identify and consider outstanding and unresolved issues regarding operation and use of the existing system of federal multiple-purpose water resource projects;*
>
> *2. Identify and evaluate alternative operations plans in response to public identification of water resource issues;*
>
> *3. Consider implementation of operational changes in response to issues within the existing authorities of the three responsible federal agencies;*
>
> *4. Consider operation plans and criteria which would improve balance among authorized uses;*
>
> *5. Evaluate and report on potential operational changes in response to issues which exceed existing authorities of the three agencies;*
>
> *6. Coordinate power generation operations of federal and non-federal projects to produce maximum power for the system as a whole in a manner consistent with non-power uses; and*
>
> *7. Prepare an environmental impact statement which will enable the three federal agencies to decide future actions on coordinated operation agreements.*

To provide technical information necessary to achieve the objectives of the SOR, a systematic analysis tool is required. This tool must evaluate system operation for all system purposes in terms of hydrologic, economic, and environmental efficiency.

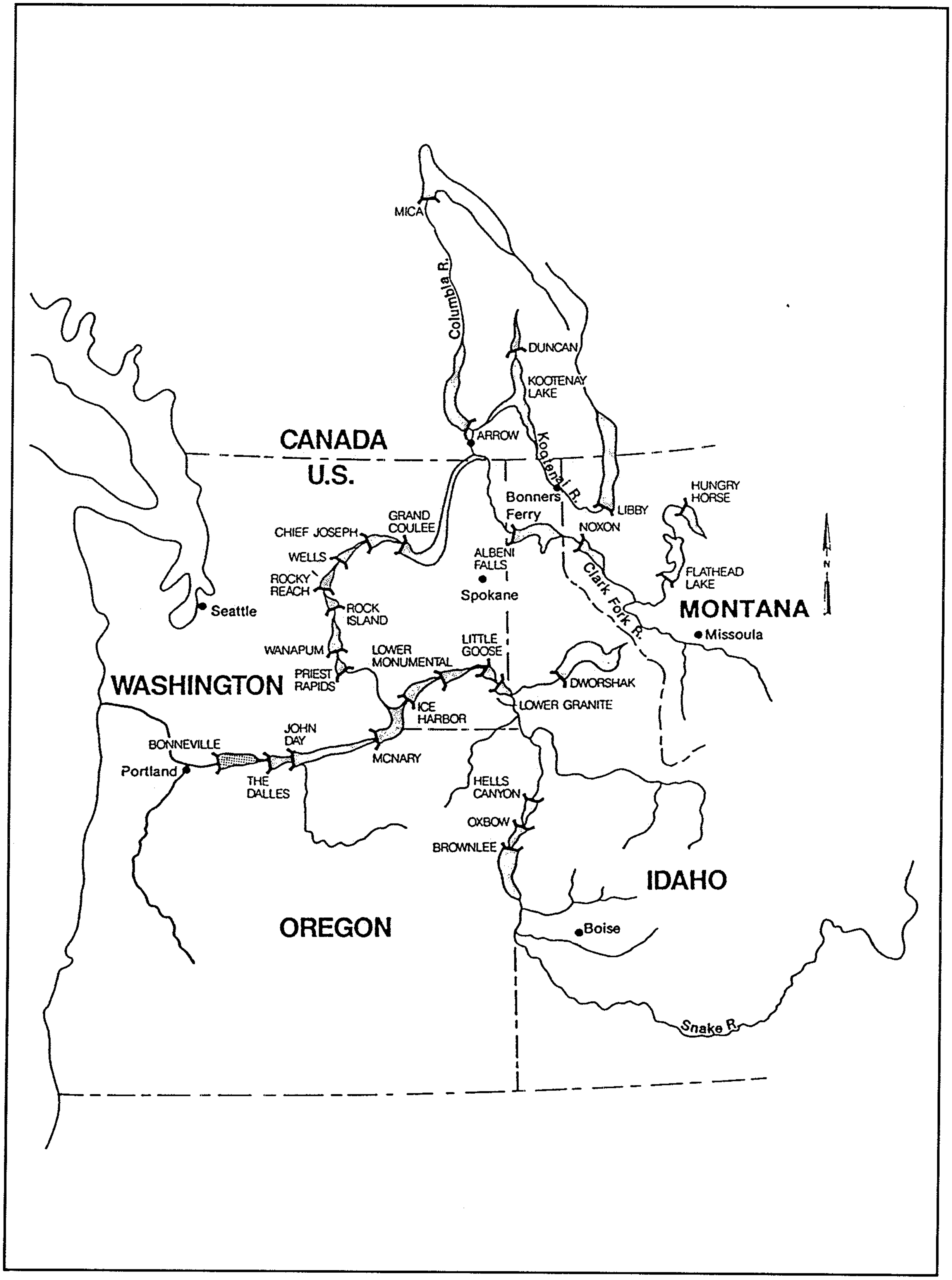


FIGURE 1 Columbia River System

PROPOSED SOLUTION

Alternatives Considered

Analysis techniques appropriate for the Columbia River SOR include (1) enumeration-with-simulation and (2) mathematical programming. Enumeration-with-simulation techniques seek the optimal operation policy by nominating iteratively trial policies and evaluating their efficiency. To evaluate a policy, the analyst simulates system operation. From the results of the simulation, performance criteria are evaluated. The optimal operation policy is the policy with best performance of all those evaluated. This procedure was proposed by NPD staff in the draft SOR plan of study (USACE-NPD, 1990a.) The efficiency of such a solution procedure depends on the ability of analysts to nominate "good" alternative policies for evaluation. In a complex system, this is a difficult task.

Mathematical-programming techniques seek the optimal operation policy via application of the calculus-based tools of operations research. These tools iteratively nominate an alternative policy and evaluate the feasibility and efficiency with an integrated simulation model. Calculus techniques lead from one alternative to another until all alternatives are explicitly evaluated or eliminated. Yeh (1985) provides an extensive review of mathematical reservoir management and operations models.

HEC's Prescriptive Reservoir Model, HEC-PRM

Based on literature review, experience with similar studies, and consultation with system-analysis experts, HEC staff proposed to apply a mathematical-programming model to identify optimal operation policies for the Columbia system. The HEC proposal is included as Appendix A of this report. The model, designated HEC-PRM, was developed initially for a similar study of operation of the Missouri River main-stem reservoirs (USACE-HEC, 1990c.) HEC staff reviewed HEC-PRM critically to evaluate its applicability to the Columbia River study and prepared a memorandum documenting their findings. That memorandum is included as Appendix B of this report.

HEC-PRM represents a multi-period reservoir-system operating problem as a minimum-cost network-flow problem. All water conveyance and storage facilities are represented as arcs in the network. Goals of and constraints on system operation are represented with functions that impose a penalty for storage or flow on the network arcs. The objective is to define the spatial and temporal allocation of water that minimizes the total penalty for the entire network. Additional details of HEC-PRM are presented in Appendix C of this report and in the program user's manual (USACE-HEC, 1991.)

Columbia River System Network

The network representation of the Columbia River system is shown by Figure 2. This network includes major projects on the Columbia, Snake, Clearwater, and Pend Oreille Rivers. For each period of analysis, the network includes 21 nodes and 20 channels. Reservoir inflows or incremental flows are introduced at each of the 21 nodes. Thirty storage or pondage projects are represented by 18 nodes; the three additional nodes represent system control points at which penalty functions are specified. Appendix D describes in detail the network established by HEC staff to represent the Columbia River system operation problem.

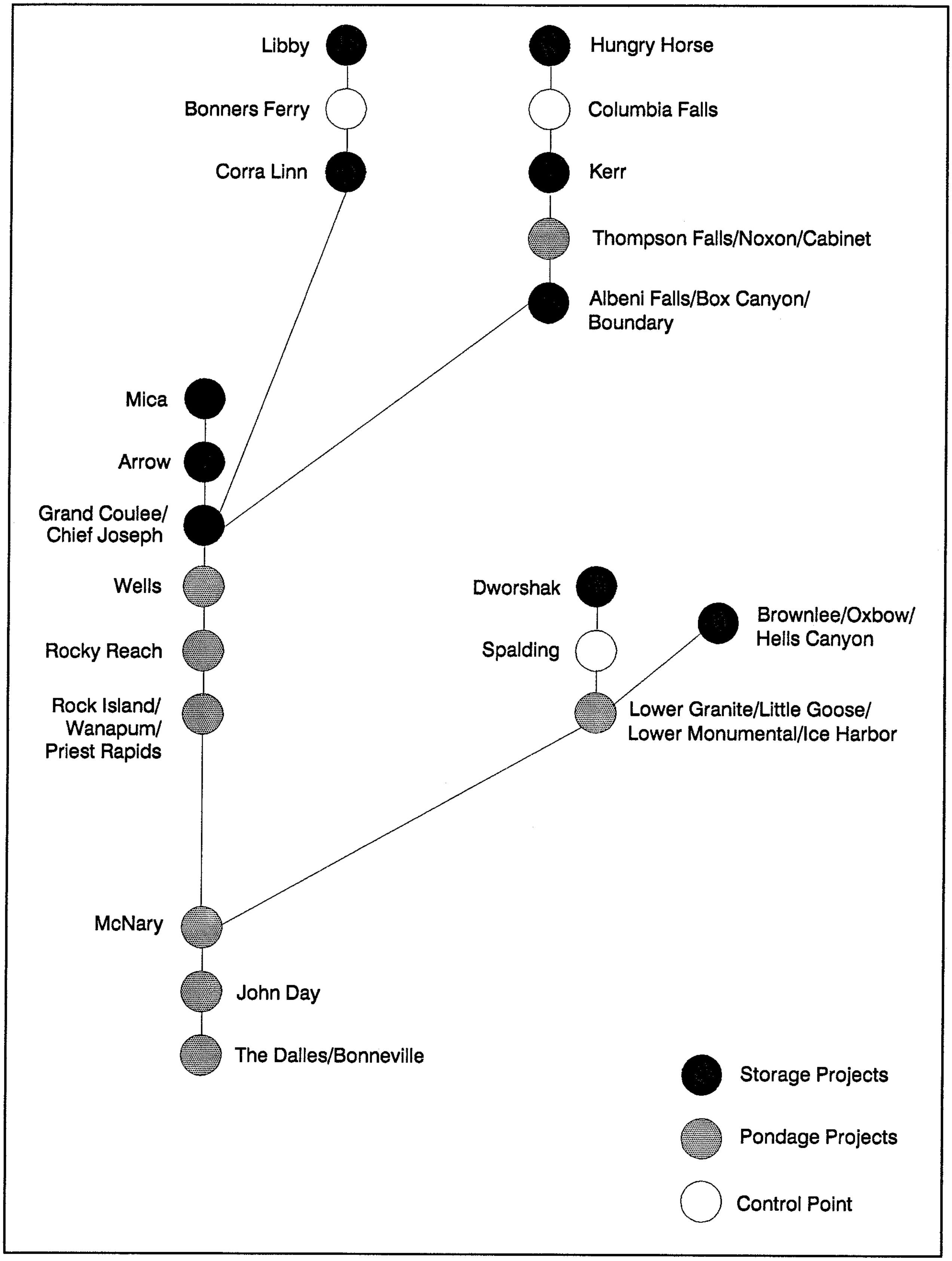


FIGURE 2 Single-period Link-node Representation of Columbia River System

Penalty Functions

Columbia River system penalty functions for authorized project purposes were developed by the Institute for Water Resources (IWR). The functions are of two types: cost-based or non-cost-based. The cost-based functions are developed by evaluating economic cost incurred or the value of opportunity foregone. The non-cost-based functions are developed to reflect environmental outputs and concerns, regional priorities on type and location of outputs, and risk management objectives. Details of these functions are presented in a separate report prepared by IWR (1991).

Penalty functions for each system control point were combined and edited to yield piecewise-linear convex functions required for HEC-PRM. These edited Phase I functions are included in Appendix E of this report.

PHASE I APPLICATIONS

Overview

For Phase I of this study, HEC staff made three applications of HEC-PRM. In the first, the model prescribed operation for a validation period, September 1969 to July 1975. This prescribed operation was compared with operation following current policy. In the second and third applications, HEC-PRM prescribed operation for the critical period, July 1928 to February 1932.

For these applications, computations were performed with an 80486 PC. The network-flow programming problem was solved with an algorithm from the Texas Department of Water Resources (1982.)

Validation

Motivation. Unlike a descriptive simulation model, a prescriptive model such as HEC-PRM cannot be validated directly by comparison with an observed data set. No such data set can exist because historical operation is never truly optimal for the objective function used in the model, and the objective function used in the model never reflects exactly all goals of, and constraints on, operation. Moreover, historical operation never represents a static condition, as demands continuously change, project goals evolve and new elements are added to the system.

HEC staff carefully reviewed model logic, input data, and solution algorithms. In addition, HEC staff conducted a subjective test to validate HEC-PRM by comparing the HEC-PRM prescribed operation to the operation with current rules. Such a test is based on an assumption that the system penalty functions reflect expectations of water users throughout the system. These expectations, in turn, are assumed to correlate with existing operation. Thus, the penalty functions, in some sense, represent current operation goals and constraints. If the HEC-PRM results were judged reasonable in this comparison, staff felt HEC-PRM would be accepted as a tool for subsequent analyses in the SOR.

Validation Procedure. September 1969 to July 1975 was selected for validation of HEC-PRM. This period was recommended by NPD staff as one which contains considerable variation in flows in a relatively brief period of time. Two very high-flow events and a very low-flow event occur in this time period.

For this validation, the following assumptions were made for application of HEC-PRM:

1. Reservoir evaporative losses are independent of system operation. Thus reservoir inflows are net flows. This simplifies somewhat the mathematical representation of the system operation problem.

2. Hydroelectric-energy penalty is a function of release only, rather than a function of head and release. This, too, simplifies the mathematical representation of the system operation problem.

3. As no penalty functions were provided for the Canadian reservoirs, Mica and Arrow, these reservoirs were assumed to follow current policy. They were represented in the validation operation by a specified release from Arrow reservoir. The Arrow releases for validation were determined by NPD staff using the HYSSR program. For the critical period analysis Mica and Arrow were operated without restriction within the current treaty storage limits.

Hydrologic data for the period were provided by NPD; these data include monthly reservoir inflows and local flows; and initial and final storage values for the system reservoirs. The provided inflow data included adjustments for evaporation and for 1980 level of depletions.

HEC staff compared HEC-PRM results with those of NPD's HYSSR reservoir simulation model. This comparison is intended only to identify obvious shortcomings of HEC-PRM, inexplicable results, or weaknesses that would render HEC-PRM unacceptable for further analyses. A perfect match of results was not expected. Indeed, the results should not be identical, as the models employ different simplifications of the real system and operate for different goals. HYSSR follows existing operation rules, and HEC-PRM operates to minimize total system penalty for the period. On the other hand, HEC-PRM should capture all critical aspects of the system. Furthermore, the penalty functions are related closely to historical operation following existing rules. Therefore, the operation prescribed by HEC-PRM should follow the same general trends as the HYSSR operation.

Results. The results from HEC-PRM and HYSSR compare surprisingly well. Figure 3 show the total system storage and the storage pattern computed with the two models for Libby and Corra Linn Reservoirs. Storages indicated by HEC-PRM are shown in green, and those indicated by HYSSR are shown in red in all figures. The pattern of emptying and filling is identical, and in most months, the magnitude is approximately the same. Figure 3 also shows flow at The Dalles, computed with the two models. Again, the pattern of high and low flows is approximately the same, although HEC-PRM tends to have higher highs and lower lows.

Computed reservoir storages for other major Columbia River system projects are shown on Figures 3 through 5. In general, the patterns of storage indicated by the two models match well. The exception is Corra Linn (Figure 3d). There HEC-PRM prescribes less storage. A maximum storage of 817 kaf was specified for HEC-PRM, but the HYSSR results show greater values, with a maximum of approximately 2200 kaf in 1974. This discrepancy occurs because the Corra Linn Dam impoundment and Kootenany Lake, a large natural lake over 20 miles upstream of the Corra Linn Dam, are represented in the model as a single storage node. This is appropriate most of the year when the two bodies have a common elevation and flows are moderate. During high lake stages flood releases from Corra Linn Dam are limited by a natural constriction in the Kootenany River between the dam and Kootenany Lake. Modifications to Corra Linn storage and penalty functions well be considered for Phase II.

Although the storage patterns at Hungry Horse match, HEC-PRM prescribes lower storage several months. Again, this may be due to slight discrepancies in either system data or penalty functions. Figure 5b shows the Hungry Horse releases proposed by the two models. The HEC-PRM releases are much greater for those months in which the storage prescribed is much less than that computed by HYSSR. The penalty function for flow between Hungry Horse and Columbia Falls encourages release of approximately 10,000 cfs (600 kaf), and no penalty is incurred for greater flows. Thus in 1973 and 1975, HEC-PRM prescribes flows that are much greater than those computed by HYSSR in order to minimize total system penalty for the entire validation period.

Conclusion. As a consequence of the validation test, HEC-PRM is accepted for subsequent analyses in the Columbia River system SOR. The validation test demonstrates that the model prescribes reasonable operation with the penalty functions provided. In some cases, the operation differs from that proposed by HYSSR when the current operation rules are followed, but the differences are due to discrepancies in data as indicated in the previous discussion on Corra Linn results.

Critical-period Analysis

Motivation. In addition to the "Validation" application, HEC staff conducted two subjective tests to observe the HEC-PRM prescribed solution for a critical time period of water shortage from July 1928 to February 1932. The goal was to demonstrate the applicability of HEC-PRM as a tool for the SOR. Again, for the Phase I study, evaporative losses were assumed to be independent of system operation, and hydroelectric-energy penalty was assumed to be a function of release only. In the absence of penalty functions for Mica and Arrow reservoirs, functions with zero unit penalty for storage in the normal conservation pool and extreme unit penalties for storage above or below that pool were used.

Two applications were completed: (1) analysis using the best-currently-available estimates of system penalty functions; and (2) analysis of the same critical period using the same penalty functions as in the first analysis except that hypothetical flow constraints for improving fish migration were used at Priest Rapids, The Dalles, and Lower Granite.

NPD is considering several water management actions which may assist the instream migration of juvenile and adult anadromous fish. The proposed actions are intended to improve flow conditions by increasing flow velocities during the April-September migration period. The actions include increasing releases from storage

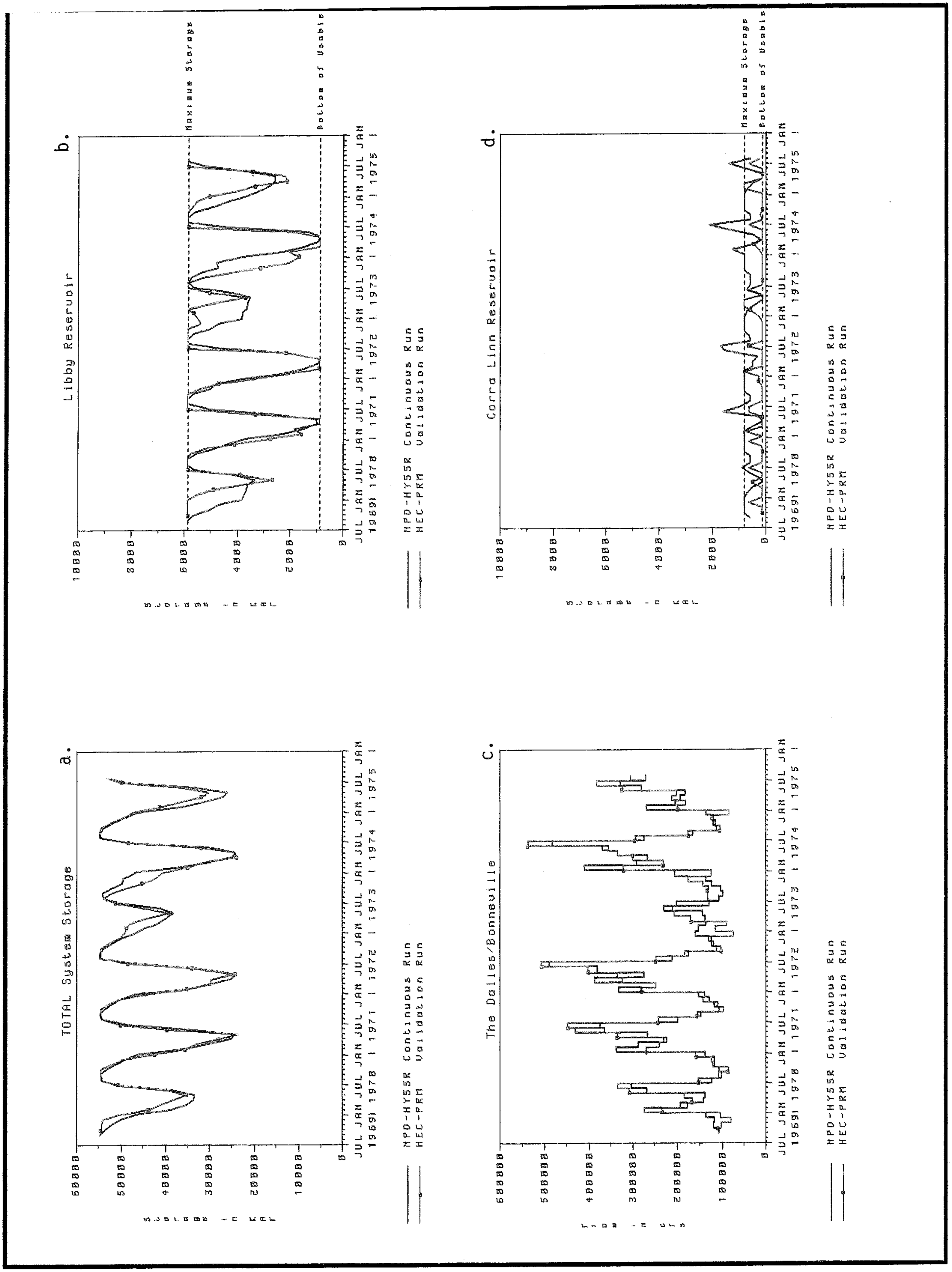


FIGURE 3 Validation Analysis Results: Storages for Total System, Libby, Flows at the Dalles, Corra Linn

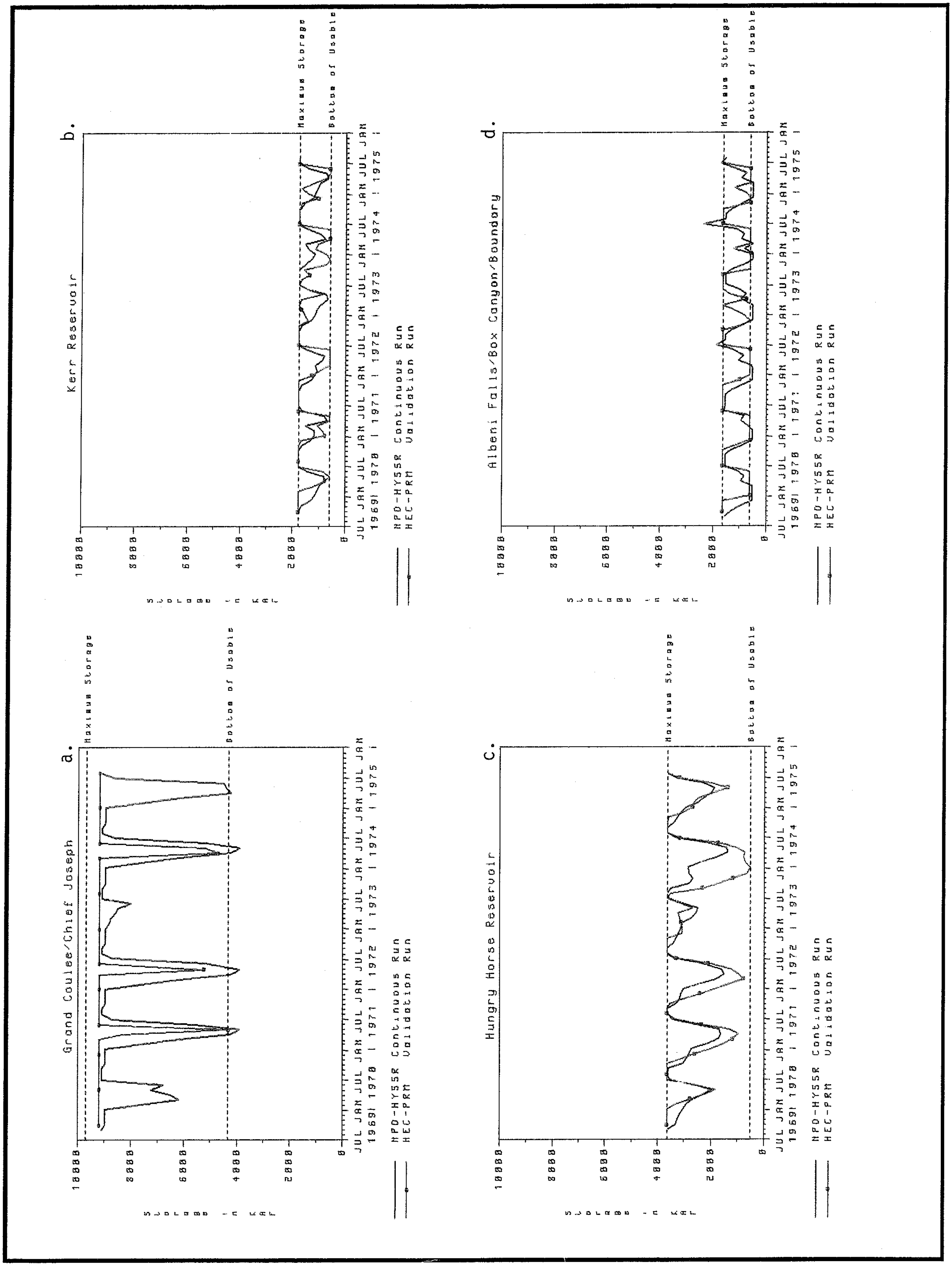


FIGURE 4 Validation Analysis Results: Storages for Grand Coulee, Kerr, Hungry Horse, Albeni Falls

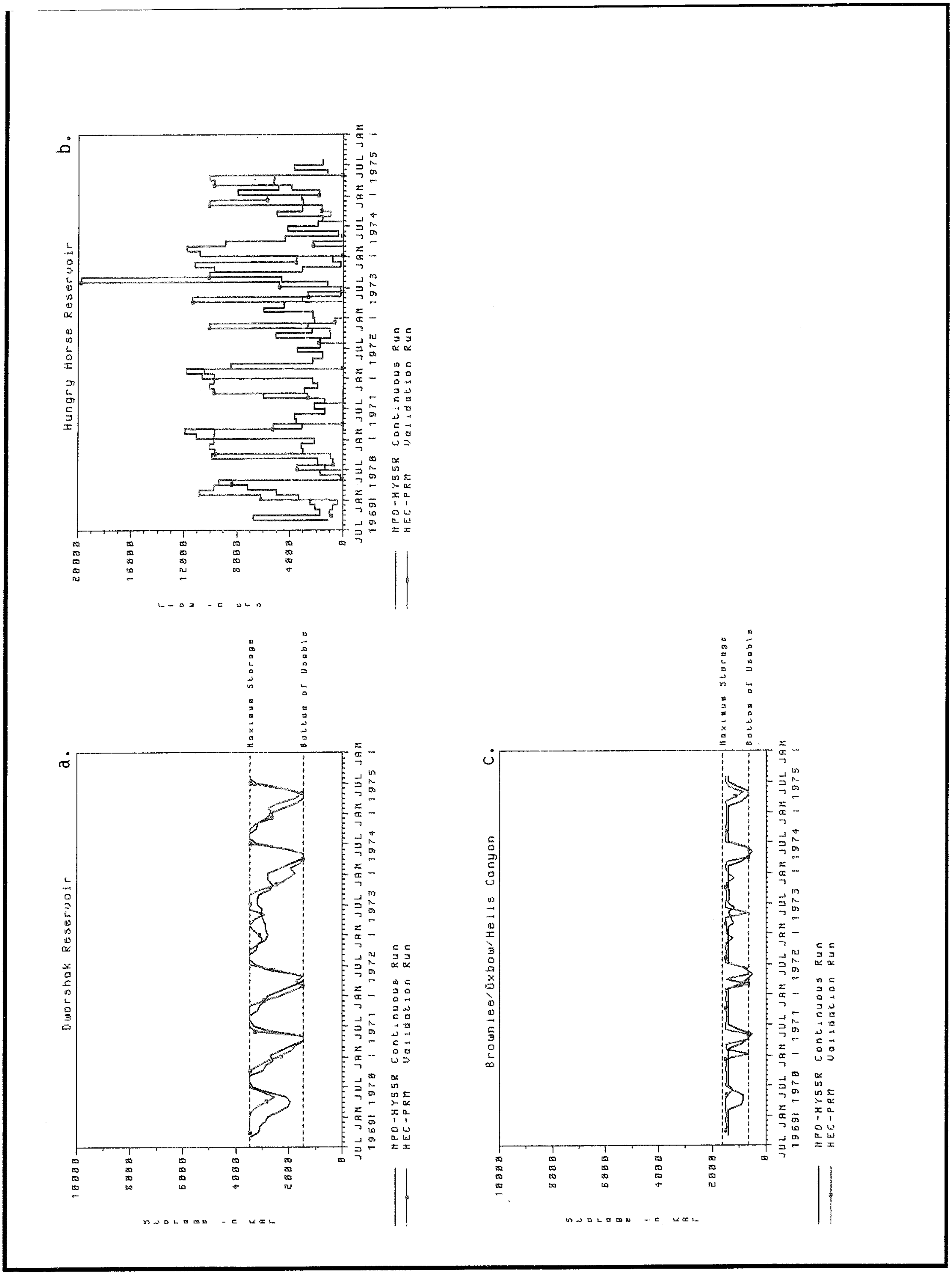


FIGURE 5 Validation Analysis Results: Storage for Dworshak, Flows at Hungry Horse, Brownlee

reservoirs such as Grand Coulee (flow augmentation) or drawing down pondage project pools such as Lower Granite (reservoir drawdown). HEC staff made a hypothetical HEC-PRM application to evaluate the flow augmentation water management action. Minimum levels of discharge (lower bounds or constraints) at specific locations were required on the Columbia River for the period April through July and on the Snake River for the month of May. The following constraints were used: 134,000 cfs (8,107 kaf/month) at Priest Rapids, 200,000 cfs (12,100 kaf/month) at The Dalles, and 100,000 cfs (6,050 kaf/month) at Lower Granite.

Results of Critical Period With Best-Currently-Available Penalty Functions

Figures 6 through 9 show storages and flows in red prescribed by HEC-PRM for the critical period. The storages seem to "switch" back and forth rather suddenly in some cases. This is due to the extreme-point (basic) solution procedure used to find the minimum penalty solution. The procedure can be illustrated with a simple one-month reservoir-operation problem. The reservoir capacity is 10 kaf, and the outlet capacity is 10 kaf/month. The initial storage is 3 kaf, and the net inflow is 7 kaf/month. The governing equation is the continuity equation:

$$S_f + R = S_i + I \qquad (1)$$

in which:

S_i = the initial storage;
I = inflow volume;
R = release volume; and
S_f = final storage.

Substituting known quantities on the right-hand side yields

$$S_f + R = 10 \qquad (1a)$$

Suppose that the unit penalty on storage is $1000/kaf, and the unit penalty on release is $1000/kaf. What is the minimum-cost operation? No unique optimal answer exists to that question. Any combination of release and final storage which totals 10 kaf is feasible (satisfies the continuity equation). Furthermore, any feasible combination will have exactly the same total penalty. A knowledgeable reservoir operator might select an operation with minimum variation from the previous month. However, the network solver will pick an extreme-point solution; a solution in which at least one of the decision variables is at its upper or lower bound. In the example, it will select either $R = 0$ kaf and $S_f = 10$ kaf or $R = 10$ kaf and $S_f = 0$ kaf.

Multiple reservoirs complicate this situation. With multiple reservoirs, the solver has many alternative extreme points to consider. Nevertheless, the solution always has some variables that are at their upper or lower bounds. Exactly which variables are at their bounds may switch from period to period. In fact, if two extreme points yield the same total system penalty, the solver is indifferent in selection of one or the other. That, in turn, accounts for switching in the solution. In practice, a knowledgeable reservoir operator would elect to avoid this switching. However, no such operation criterion is represented explicitly by the penalty functions, so HEC-PRM does not consider it in selecting releases.

The storage prescribed for Grand Coulee/Chief Joseph and shown on Figure 6 is surprising at first glance. HEC-PRM indicates maintaining constant storage at approximately 9190 kaf. Perusal of the penalty functions in Appendix E provides the reason. The penalty for storage at Grand Coulee/Chief Joseph is orders of magnitude greater than the penalty for storage at other reservoirs. However, if the storage at Grand Coulee/Chief Joseph reaches 9190 kaf, the penalty drops to zero. Thus HEC-PRM, in considering optimal spatial and temporal allocation of available storage, maintains Grand Coulee/Chief Joseph storage at 9190 kaf, thus eliminating any penalty.

As shown in Figure 4a, the operation pattern at Grand Coulee/Chief Joseph was not maintained successfully in the validation test because of large flood flows in three months. The downstream penalties at The Dalles cause HEC-PRM to prescribe a reduction in storage to store flood waters. This illustrates that penalty functions for flow at system control points do, in fact, have some impact on system operation during the critical period. Most notably, the penalty function at The Dalles tends to keep the flow above a minimum there. This, in turn, affects the operation of all upstream reservoirs to some extent.

Results of Critical Period With Fish Migration Enhancement Penalty Functions

The third application of HEC-PRM analyzed the critical period with additional constraints. Figures 6 through 9 show storages and flows in green prescribed for the critical period for this application. The additional constraints were added to reflect proposed changes in water management which may improve instream migration of juvenile and adult anadromous fish. Several interesting observations can be made.

The constraint on the Snake River at Lower Granite forces Brownlee to draft down to the bottom of usable storage and Dworshak to draft down significantly during May 1930 and May 1931. It is more straightforward to evaluate operations when a constraint is supplied for one month (May in this case). From initial review of Table 1 storage - unit penalty relationships, it would seem that Dworshak should draft first followed by Brownlee because of Dworshak's higher unit cost (storing water in Brownlee reduces the total cost more than storing in Dworshak):

TABLE 1
Brownlee and Dworshak Storage - Unit Penalty Relationships

Brownlee		Dworshak	
Storage (kaf)	Unit Penalty	Storage (kaf)	Unit Penalty
0 - 1464	-5.922	0 - 2869	-2.954
1464 - 1500	0	2869 - 3195	-2.890
		3195 - 3468	-2.136

However, further evaluation of the release - unit penalty relationships shown on Table 2 shows that Brownlee releases reduce the total cost more than Dworshak releases and the flow penalty function at Spalding always has a positive unit cost (the most beneficial flow at Spalding is zero discharge):

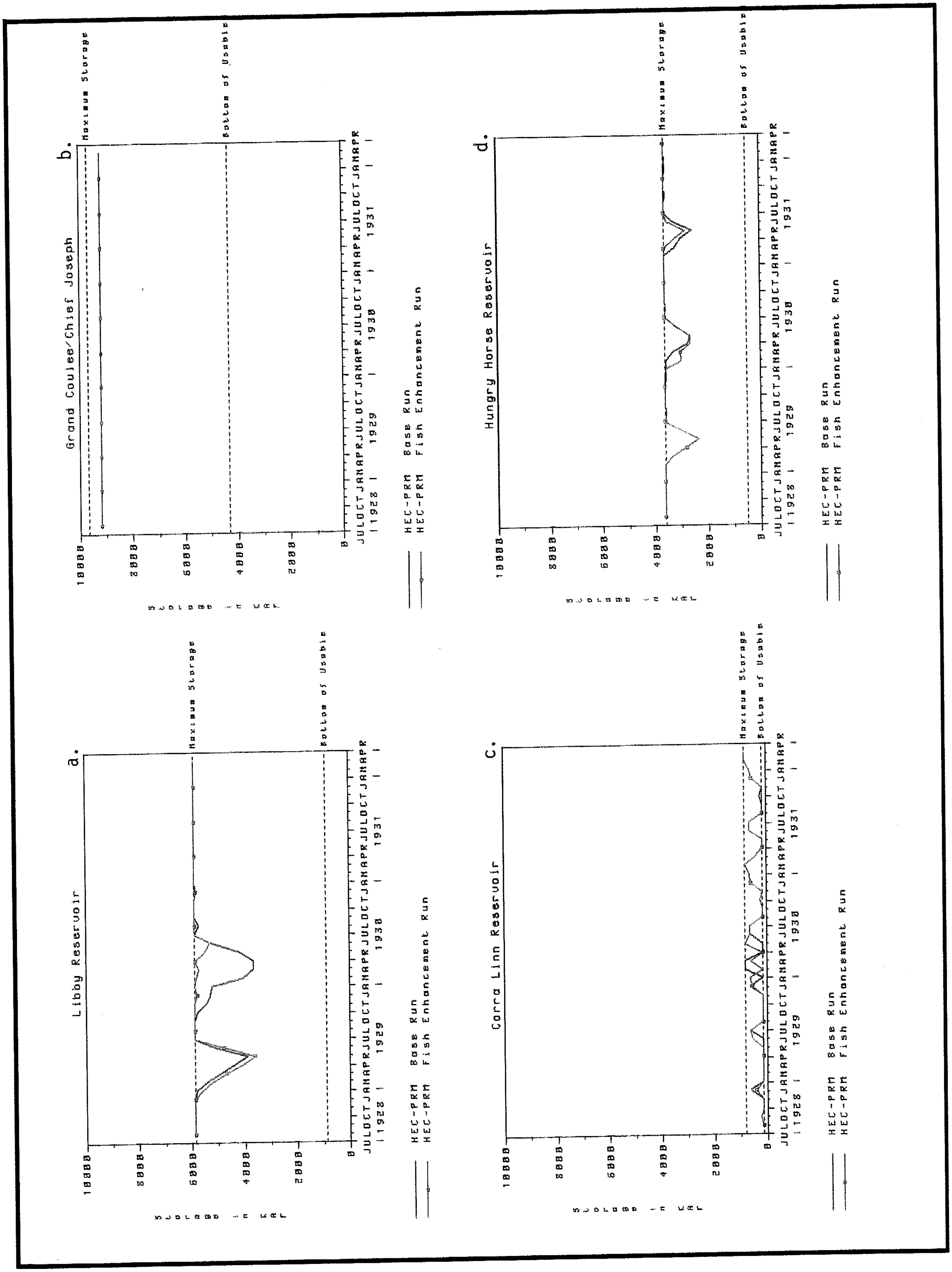


FIGURE 6 Critical Period Reservoir Storages: Libby, Grand Coulee, Corra Linn, Hungry Horse

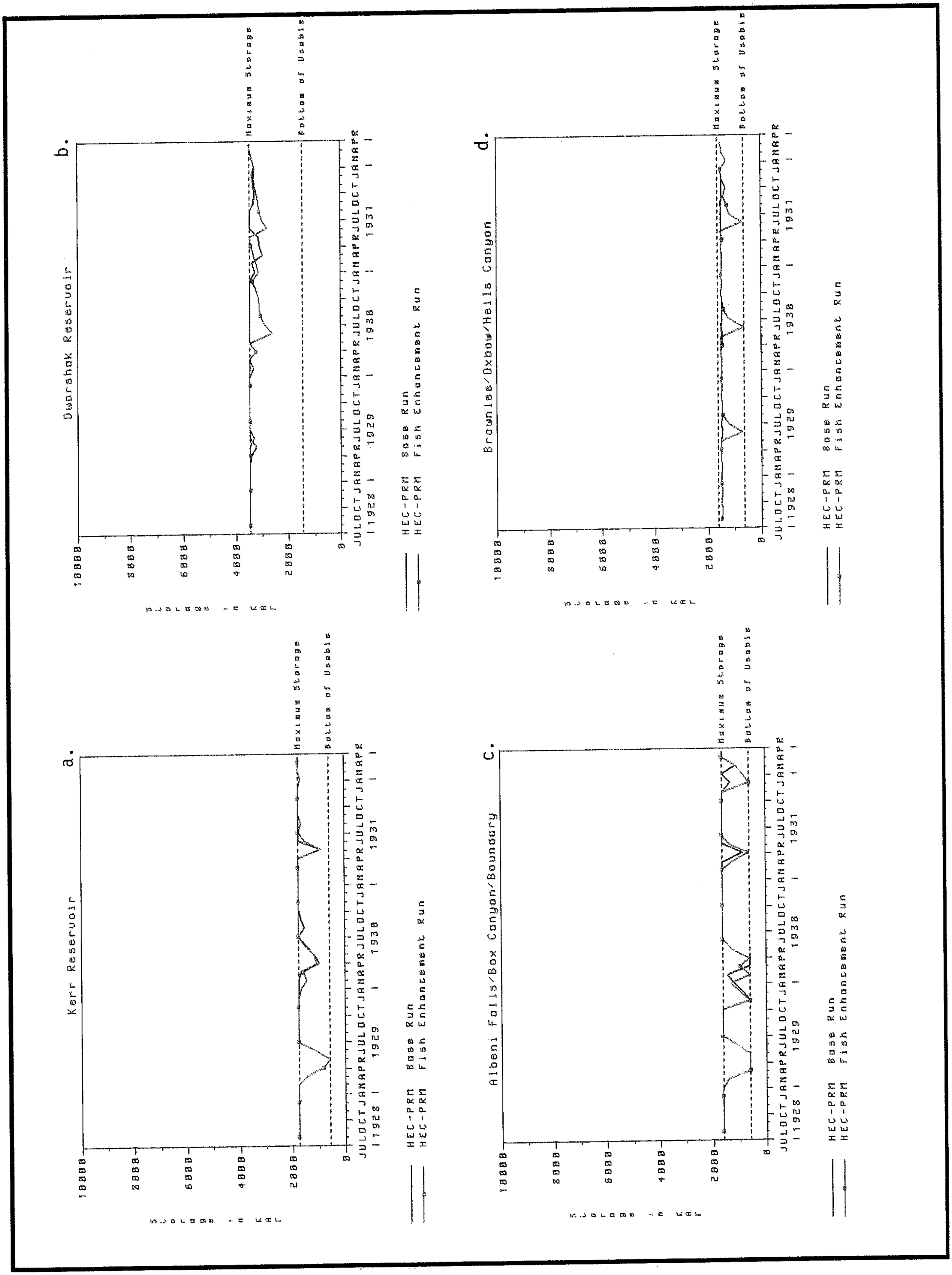
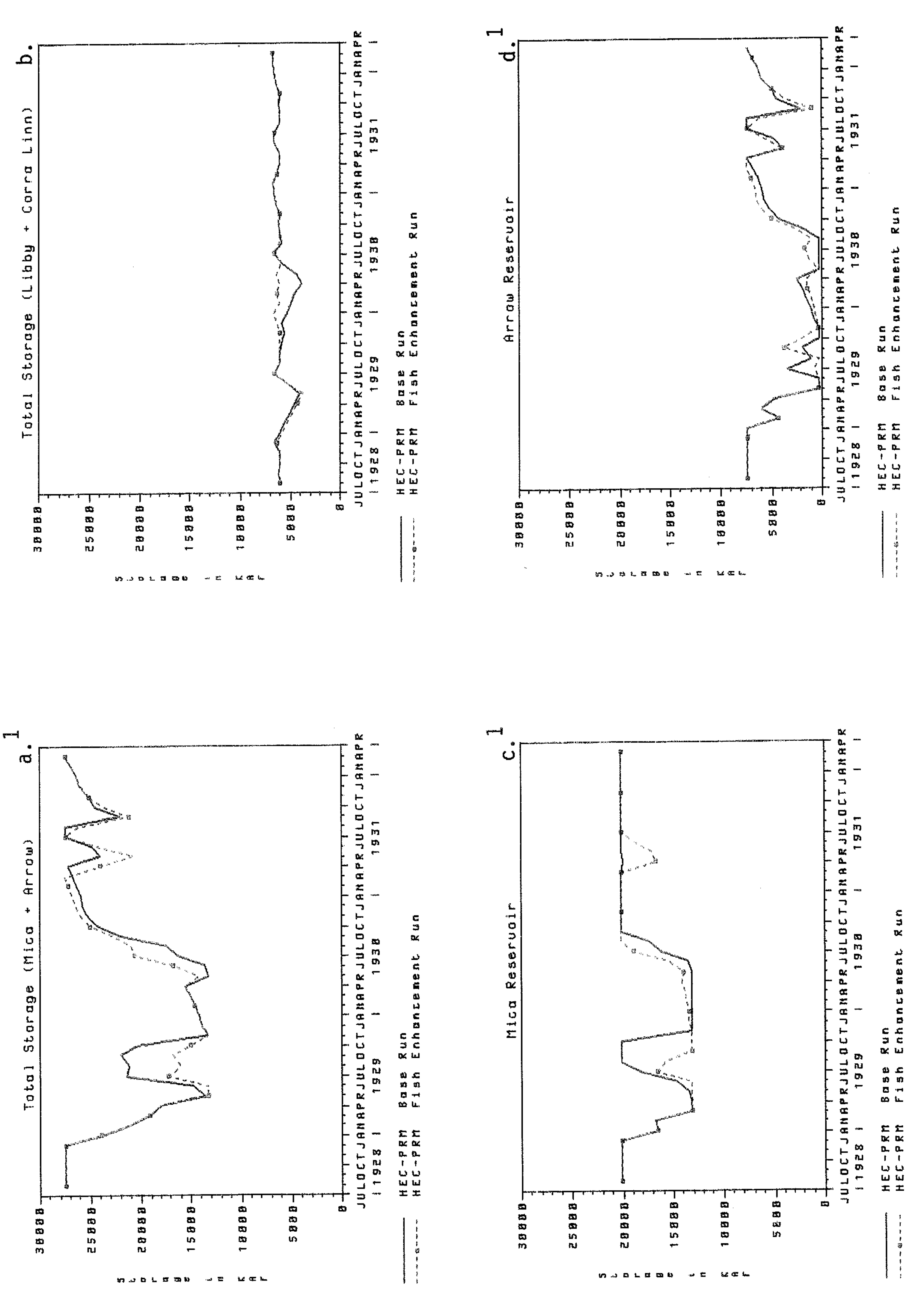


FIGURE 7 Critical Period Reservoir Storages: Kerr, Dworshak, Albeni Falls, Brownlee



1 No penalty functions were utilized in the analysis of Mica and Arrow Reservoirs. For critical period analysis, they were operated without restriction within the current treaty storage limits.

FIGURE 8 Critical Period Reservoir Storages: Mica+Arrow, Libby+Corra Linn, Mica, Arrow

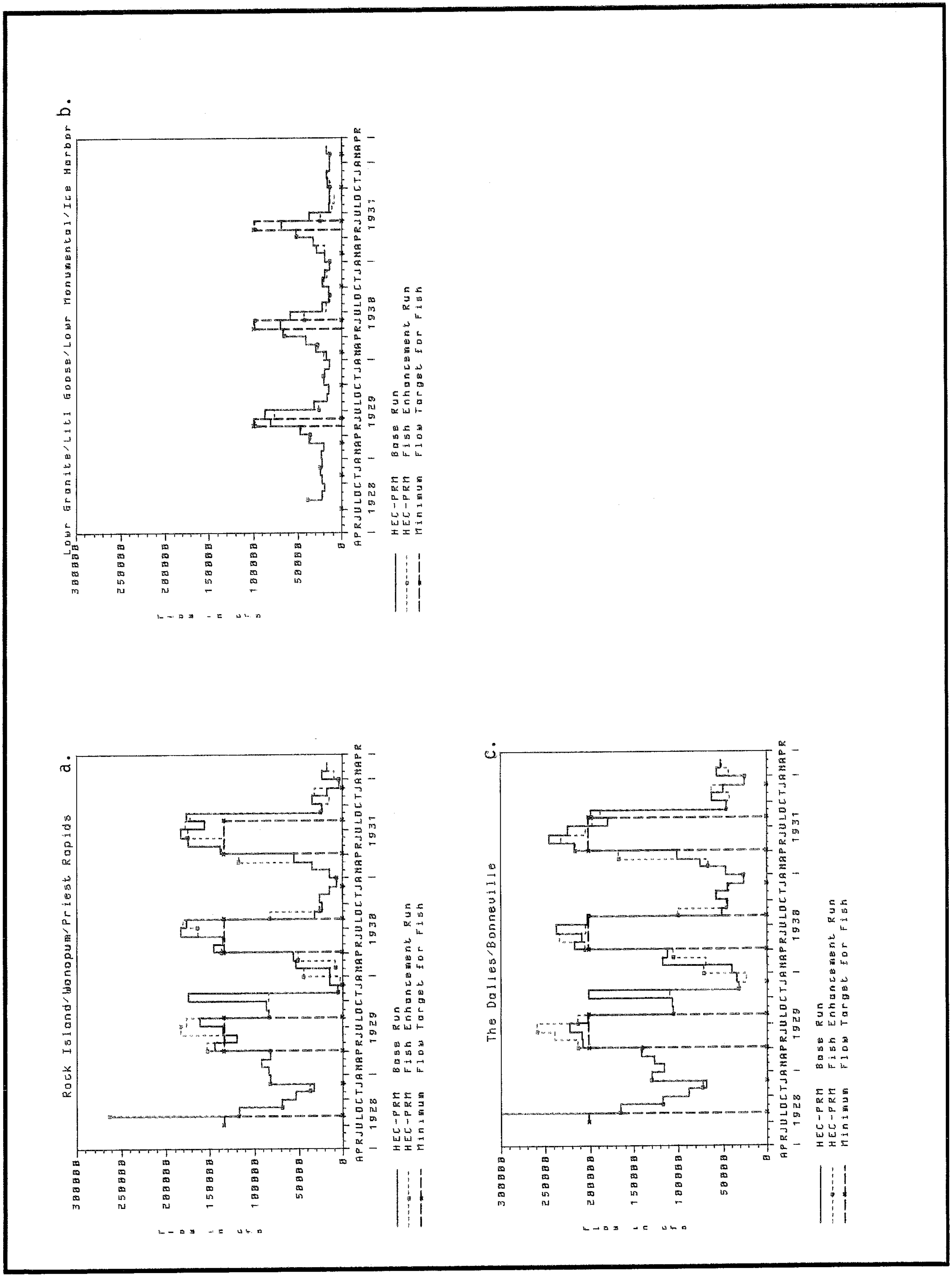


FIGURE 9 Critical Period Flows: Rock Island, Lower Granite, The Dalles

TABLE 2
Brownlee, Dworshak, and Spalding Release - Unit Penalty Relationships

Brownlee		Dworshak		Spalding	
Release (kaf/mo.)	Unit Penalty	Release (kaf/mo.)	Unit Penalty	Release (kaf/mo.)	Unit Penalty
0 - 302	-15.331	0 - 500	-9.934	0 - 5490	.28051
302 - 2108	-5.365	500 - 650	-6.627	5490 - 5500	65730.0
2108 - 5720	0	650 - 2300	0		

The target flow at Lower Granite is 100,000 cfs (6,050 kaf/month). The uncontrolled local flow is 49,157 cfs (2,974 kaf/month). Therefore, the needed release from reservoirs is 50,843 cfs (3,076 kaf/month). Since both reservoirs are at maximum pool, we know that they both must pass at least inflow. Brownlee has an inflow of 12,610 cfs (763 kaf/month) and Dworshak has an inflow of 10,050 cfs (608 kaf/month) for a total inflow of 22,660 cfs (1,371 kaf/month). Brownlee and Dworshak must be drafted down 1,705 kaf (Lower Granite target minus local inflow minus reservoir inflow or 6,050-2,974-1,371=1,705 kaf). To determine the most optimal release, the solver must consider the cost of drawing down reservoirs against the cost of releasing water.

At Brownlee, after passing inflow (763 kaf/month), the next increment of release from 763 to 799 kaf/month has a unit cost of -5.365 and storage draft unit cost of 0 for a net unit cost of -5.365. At Dworshak, after passing inflow (608 kaf/month), the next increment of release from 608 to 650 kaf/month has a unit cost of -6.627, a storage draft unit cost of +2.136, and a Spalding channel flow unit cost of +.281 for a net unit cost of -4.210. Based on this first increment of storage drawdown, Brownlee would supply the first 36 kaf/month of flow. The unit cost of drawing Brownlee down further is -5.365 (release), and +5.922 (storage drawdown) for a net unit cost of +.557. Thus, the next increment of release would come from Dworshak (unit cost -4.210) rather than Brownlee (unit cost +.557). This process could continue until the lower bound (constraint) at Lower Granite was reached. Simple logic shows that additional flow requirements would be met by Brownlee because releases which draft storage from Dworshak in excess of 650 kaf result in a net unit cost of +3.235 which is greater than Brownlee (unit cost of +.557). Thus, Brownlee is drafted to the top of inactive storage and Dworshak supplies the balance of the required flow for May. Although not trivial, the analyst can verify by hand calculations that HEC-PRM is determining the most optimal solution for this time period assuming that it need not operate to meet constraints or costs on the mainstem Columbia or for future time periods.

The other interesting observation is the operations on the Columbia River. The penalty functions for Mica and Arrow are hypothetical since neither storage nor release penalty functions were available for these reservoirs. A unit cost of 0.0 (zero) was assigned for storage between top of inactive and maximum allowable storage. This allows HEC-PRM to vary storage at these two projects with no consequences to the total cost of the objective function. It is much harder to evaluate the solution for the Columbia River because of the large number of projects having both storage and release penalty functions, the many pondage projects having release penalty functions, and several months (April through July) at two locations having the constraints for fish. It is obvious from Figure 8 that the additional flows for fish migration require the drafting of Mica and Arrow lower than in the base run. It is also obvious that a feasible and optimal solution requires the use of storage from Libby, Corra Linn, Hungry Horse, Kerr, and Albeni Falls reservoirs. It is not obvious why Libby is drawn down lower in the base run than it is in the Fish Enhancement Run. It is logical that it is drawn down during the October through June period when there is a lower storage unit cost than in the July through September period. HEC-PRM determines that this drawdown is an optimal solution that is feasible within the constraints applied.

PHASE II ACTIVITIES

In Phase I of this study, HEC staff proposed to assess the applicability of HEC-PRM and apply it on a trial basis. This has been done, and the results are reported herein.

If the results of the Phase I trial application are acceptable, HEC staff will: (1) expand the system analyzed and make needed technical improvements to the HEC-PRM to better model operation of the Columbia system; (2) refine the penalty functions used; (3) analyze additional policy options; (4) refine the model's user interface; (5) upgrade HEC-PRM documentation; and (6) transfer the technology to the Columbia River SOR study team. These tasks are described in detail in the HEC proposal, which is included as Appendix A of this report.

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APPENDIX A

PROPOSAL FOR
APPLICATION OF SYSTEM ANALYSIS
TO COLUMBIA RIVER SYSTEM OPERATION REVIEW STUDY

By

Hydrologic Engineering Center

August 29, 1990

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PROPOSAL FOR
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APPENDIX A

PROPOSAL FOR
APPLICATION OF SYSTEM ANALYSIS
TO COLUMBIA RIVER SYSTEM OPERATION REVIEW STUDY

by
Hydrologic Engineering Center
August 29, 1990

SUMMARY

This proposal presents a plan to apply system analysis methods for the Columbia River System Operation Review (SOR) study. We propose to:

a. Prepare a document assessing the applicability of network-flow programming system analysis method for the study,

b. On a trial basis, formulate and apply a network-flow model to the Columbia River System,

c. Develop and document preliminary project output value functions (penalty functions) for use with the model, and

d. Present the results in a Phase I summary report.

Following review and analysis of the trial model formulation and application, approval for Phase II would:

e. Expand the conceptual and geographic scope of the network-flow model to the full Columbia River system and issues,

f. Refine the value (penalty) functions,

g. Perform several system analyses for selected policy options and prepare summary report,

h. Refine input, output reporting, and user interface for the Columbia system model,

i. Upgrade documentation, and

j. Conduct workshop for Columbia River SOR study team staff on model application.

Phase I will be completed 6 months after initiation at a cost of $77,000. Phase II will be completed 12 months following Phase I and is estimated to cost $110,000 for a total cost of $187,000. The Phase II cost is preliminary and will be finalized following Phase I. Table A-1 lists the tasks and estimated staff time to accomplish. Figure A-1 presents the proposed project schedule. The proposed start of Phase I is January 1991.

The model proposed for application to the Columbia River SOR study is under development for application to the Missouri River Main Stem Master Water Control Manual Update study. Development was initiated in July 1990 with completion scheduled for January 1992. The model development proposed herein is deliberately scheduled to begin upon completion of Phase I of the Missouri River system model development. The Phase I Columbia River study will be underway concurrently with Phase II Missouri River system efforts. The Missouri River system developmental effort is expected to provide useful insight into development/application considerations to the Columbia River system. The Missouri River system has several very large storage projects with capacity of about 4 times the mean annual flow. Recent droughts have heightened competition for water for recreation, navigation, and instream fish & wildlife use. The Columbia River system has many storage reservoirs, several large ones but the total storage capacity is about one-fourth of the mean annual flow. Issues are similar to the Missouri River with hydropower regulation verses instream fisheries as perhaps greater concern.

The proposal presented herein is considered preliminary and will be refined in November - December 1990 to reflect progress and lessons learned in the Missouri River system analysis model project.

BACKGROUND

The Columbia River System Operation Review (SOR) study is described in the Draft Plan of Study dated 5 June 1990, SOR Management Plan dated 6 June 1990, and a flyer (undated) entitled "The Columbia River: A System Under Stress". The existing Columbia River Master Water Control Manual (labeled re-draft) provides detailed information about the system. These documents describe the objectives of the study, identify the significant issues, describe the complex institutional structure involved, and briefly outline the study strategy.

The Columbia River system encompasses a large diverse geographic region and a variety of climate regimes. A number of large main-stem projects within Canada and the US provide significant regulatory storage. A large number of storage projects are located on the major and minor tributary streams. The main-stem projects are owned and operated by the federal government (Corps of Engineers and Bureau of Reclamation), Canada, and public and private utilities. Purposes served by the projects include hydroelectric power, flood control, irrigation, navigation, municipal and industrial water supply, fish and wildlife, and recreation. Project operations are coordinated on a regional basis with power operations coordinated by the Bonneville Power Administration. A system of marketing contracts, international treaties, coordination agreements, and other institutional arrangements result in an extremely complex operating environment for system projects. Operating plans for the main-stem reservoir projects are under investigation for improvement in the SOR study.

The study strategy presented in the Draft Plan of Study is that of identifying alternative operating plans, evaluating the impacts of alternative plans, and based on these impacts and views of others, selecting a plan. The early studies will emphasize, respectively, the several purposes served by system projects. The findings of these studies will provide the basis for formulating and evaluating balanced, integrated plans that would be subject to further study. System analysis methodology poses the problem in a different context: given the system characteristics, system operation purposes, and impact relationships, develop the operating scheme that best accomplishes the system goals. The system hydrologic simulation, impact evaluation, and subsequent storage utilization and releases are formulated such that the computation results are the desired system operation.

System analysis methods develop information in a prescriptive rather than a descriptive manner. The viability of the analysis is contingent on the ability to represent the essence of system performance and impacts such that the system operation is formulated in a tractable structure that can be solved. Our proposal is to develop a tool that can provide information and insight into operation options and trade-offs that are not easily surfaced in the methodology currently being used. Implementing the system analysis model will not resolve the real conflicts that exist - there is not enough water during drought years. It will assist in devising means for sharing negative impacts and developing long term strategies that are equitable among basin water resource system beneficiaries.

PROPOSAL

Our proposal is based on performing the model development and application in two phases. The first phase will test the applicability of the approach. If the first phase is applicable, the detailed analysis, user interfaces, output reports, and documentation will be developed in Phase II. The tasks comprising the proposed work are described in following paragraphs.

<u>Phase I Activities</u>

a. **Network-Flow Model Applicability Assessment.** A number of successful system analysis applications to reservoir system operation problems are reported in the literature. Texts, (see for example Loucks, et. al. 1981) and journal articles (Yeh, 1985) present a wide range of methods and applications examples of system analysis technology. Proposed applications to water resources system operations are many and are reported on a continuing basis in the literature. Few have achieved the status of practical applications.

    Based on literature review, experience with similar studies, and consultation with system analysis experts, we propose to develop and apply a network-flow programming model to the Columbia River SOR study. This task will develop a document describing the important determinants in applying network-flow programming to the Columbia River system. The document will be written with Columbia River SOR study participants and managers as the target audience.

b. **Formulate and Apply Preliminary Model.** Examples of successful applications to problems similar to that of the Columbia River system are described in (Sigvaldason, April 1976) and (Chung et al, March 1989). HEC Successfully developed a model for planning dredged-material disposal based on network-flow programming (Corps of Engineers, US Army 1984). A network-flow programming model is presently under development as part of the Missouri River Main stem system operation studies. Documents from that study will become available early in this proposed project. A description of the network-flow model proposed herein is included as an appendix.

The test application will construct a preliminary network-flow model and use a commercially available network solver for the solution. It will likely prove desirable to construct the network for a limited portion of the complete period-of-record and selected physical components. The solution for network flows will be interpreted and recast into tabulations and displays for report presentation.

c. **Develop Preliminary Penalty Functions.** The functions needed for the network-flow model are relationships between flow in the arcs (releases/stream flow, reservoir storage) and a penalty associated with not meeting the most desirable flow targets. The network is solved by routing flow through the arcs of the system to achieve an overall minimum penalty. The penalties are aggregated by stream reach. The logic is applied for river flow for recreation, power generation, fish and wildlife, and navigation, and for reservoir storage for recreation and fisheries purposes. To reflect operations desirable for environmental purposes such as enhancing the habitat of an endangered species, a penalty function can be devised and adjusted to cause operation of the system to occur in the desired manner.

The project purposes described in the Draft Plan of Study are hydropower, flood control, water supply, recreation, irrigation, fish and wildlife, and navigation. For the trial application, we propose to develop preliminary penalty functions for all these purposes for the Columbia River system for which data are readily available. Figure A-2 presents stylized penalty functions for flood control, water supply, navigation, hydropower, and reservoir recreation as examples.

d. **Phase I Summary Report.** The results of Phase I tasks a. - c. will be presented in a brief summary report. A technical appendix will describe the model development and application.

The main report will describe the trial application and the model applicability to the issues assessed for the full Columbia River system. The scopes of the tasks for the accomplishment of Phase II will be refined from those presented in this proposal. The report will be written for the target audience of the Columbia River SOR study participants, and local agency managers and officials.

Phase II

The Phase II tasks described below are contingent upon acceptance of the results of the Phase I effort. To a substantial degree, the efforts needed to successfully accomplish the tasks are dependent on findings of the Phase I studies. The assumption here is that the test application proves successful and that the test adequately demonstrates the usefulness of the model in the Columbia River SOR study.

e. **Expand Model to Full System and Issues.** This task will expand the Columbia River network-flow model to include additional upstream and tributary reservoirs, intervening and downstream reaches, and system operation purposes as needed. The full-flow record will be analyzed. Methods to account for future diversions and techniques to permit analysis of selected time windows of the historic record will be developed. The construction of the model and data preparation will be documented in a technical report.

f. **Refine Penalty Functions.** The penalty functions used in the Phase I application are based on available data. In Phase II the functions will be expanded to include all project purposes, stream reaches, and reservoirs. They will be refined to improve their reliability. If needed, additional research will be conducted to develop more reliable penalty functions. It will be undertaken separate from the model development project addressed by this proposal. The full scope of this task is highly dependent on the credibility of the functions adopted for the test application and the performance of the model regarding sensitivity of modelled system operations to changes in penalty functions.

g. **Perform Selected System Analysis.** In the interest of providing efficient analysis for the on-going Columbia River SOR study, several key system analysis will be performed by HEC. System operation policy sets representing differing views will likely have surfaced by the time the full model capabilities are operational. Several complete analyses will be planned. One will be chosen to emphasize and illustrate operation for fish and wildlife goals such as sustaining anadromous fisheries. The results will be summarized for use in the Columbia River SOR study.

h. **Improve Generalized Network-flow Model Construction Capability and User Interface.** Construction of the network-flow model for the Columbia River SOR to this point of the study will be adapted from the Missouri River system model and crafted to the system, data, and issues initially defined. The automated network construction algorithm developed for the Missouri River system will be modified to the needs of the Columbia River system. This will provide the capability for the user to describe the problem and data in understandable terms without knowledge of the technical details of the network-flow model.

i. **Improved User Documentation.** A draft user's manual is planned as a product for the Missouri River system model project. The manual will be expanded and improved to serve the needs of the Columbia River SOR study. The manual will describe the capabilities and limitations of the model, summarize the technical methodology, provide an input description, output explanation, and include a test example application. The manual will be prepared in the style of existing HEC computer program user's manuals.

j. **Workshop.** A two to three day workshop on model application will be formulated and presented to Columbia River SOR study team staff and other interested local staff in NPD. The workshop will include presentations and discussions on data development, data entry, program applications, and output analysis. The model will be used in workshop sessions.

RESPONSIBILITIES, COORDINATION, AND MANAGEMENT

The system analysis model development and application project will be performed by the Hydrologic Engineering Center for the North Pacific Division, Corps of Engineers. HEC will rely on the Institute for Water Resources (IWR) and Columbia River SOR staff for the development of the penalty functions. IWR, and Columbia River SOR staff will assist in the network construction and act as advisors on other aspects of the project. Oversight will be provided by HQUSACE engineering and planning divisions. The project will be coordinated on a continuing basis with check point meetings as shown on the schedule in Figure A-1. Attendance by all project participants will be encouraged. Substantial assistance will be required from the North Pacific Division, and other Columbia River SOR study participants in several areas.

NORTH PACIFIC DIVISION RESPONSIBILITIES

NPD will:

* Provide detailed definition of the requirements of the system analysis application to the Columbia River SOR study,

* Furnish Columbia River system hydrologic data of monthly flows,

* Provide physical data on the reservoirs diversions, target flow requirements, etc. for the Columbia River system and tributaries. Specific needs will be agreed upon in consultation with NPD staff,

* Provide assistance in the development of the cost data needed to construct the penalty functions, and

* Provide consultation and guidance on a continuing basis during the performance of the project.

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TABLE A-1
TASK SUMMARY
*****Phase I*****

Task	Staff-days
a. Network-flow model applicability assessment	
b. Formulate/apply preliminary model - define preliminary system requirements - formulate network model - compile hydrologic, system data - generate network - apply test, interpret results	
c. Develop preliminary penalty functions - specify functions, define data needs - compile data, formulate functions - test functions - document development, application	
d. Prepare Phase I summary report, Phase II work plan	
SUBTOTAL PHASE I	116
*****Phase II*****	
e. Expand model to full Columbia River SOR system, issues - complete system requirements specification - expand network model - arcs, nodes, penalties - complete data compilation, data entry - test expanded model - prepare technical report	
f. Refine and finalize penalty functions - complete function specification - update and incorporate additional data - prepare technical, applications documentation	
g. Perform selected system analysis (assume 4)	
h. Improve network generator and user interface - adapt Missouri River system network generator - re-design user interface, reports - improve user interface	
i. Improved user documentation	
j. Workshop	
SUBTOTAL PHASE II	174
GRAND TOTAL	290

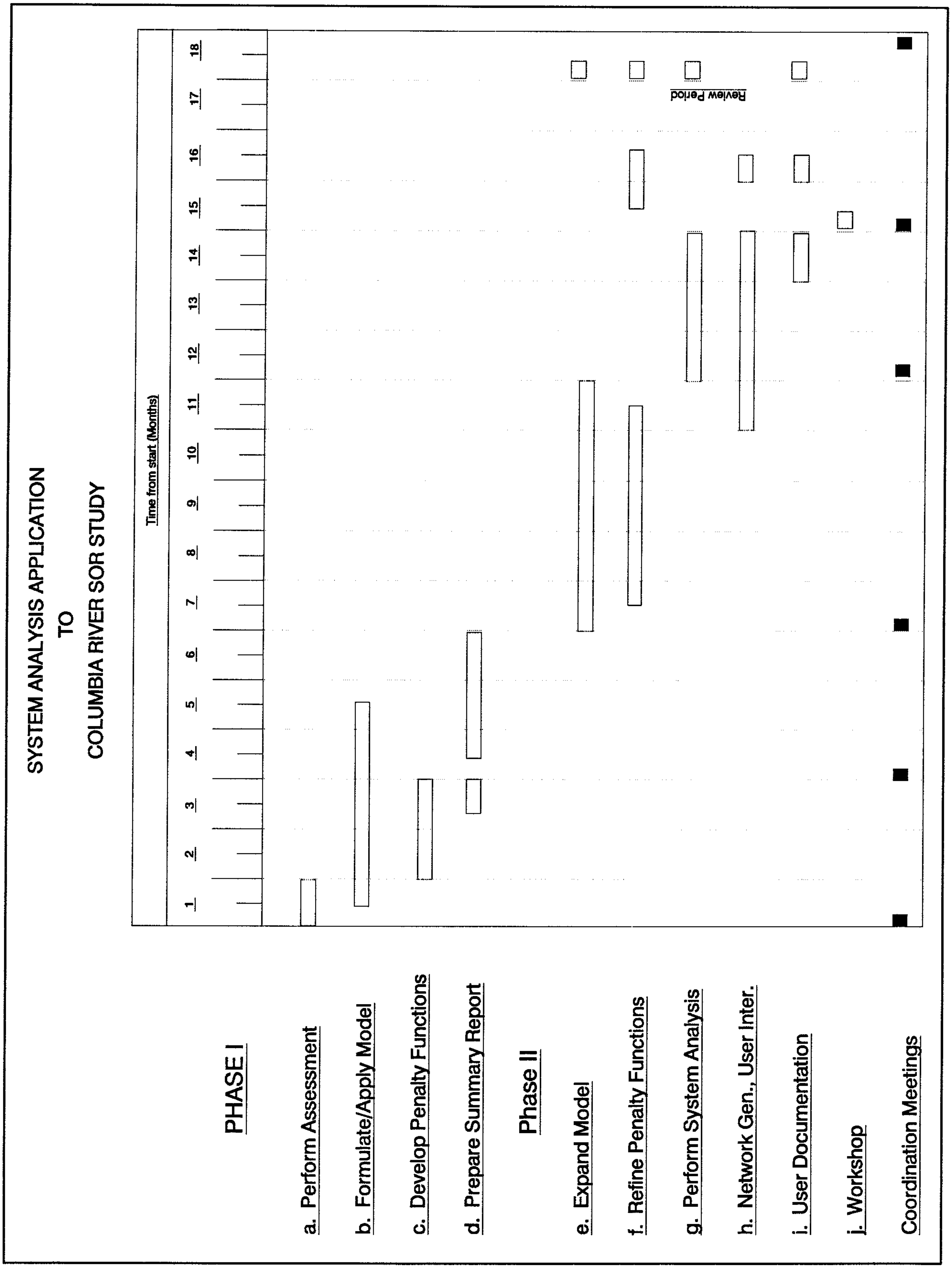

FIGURE A-1 Study Schedule

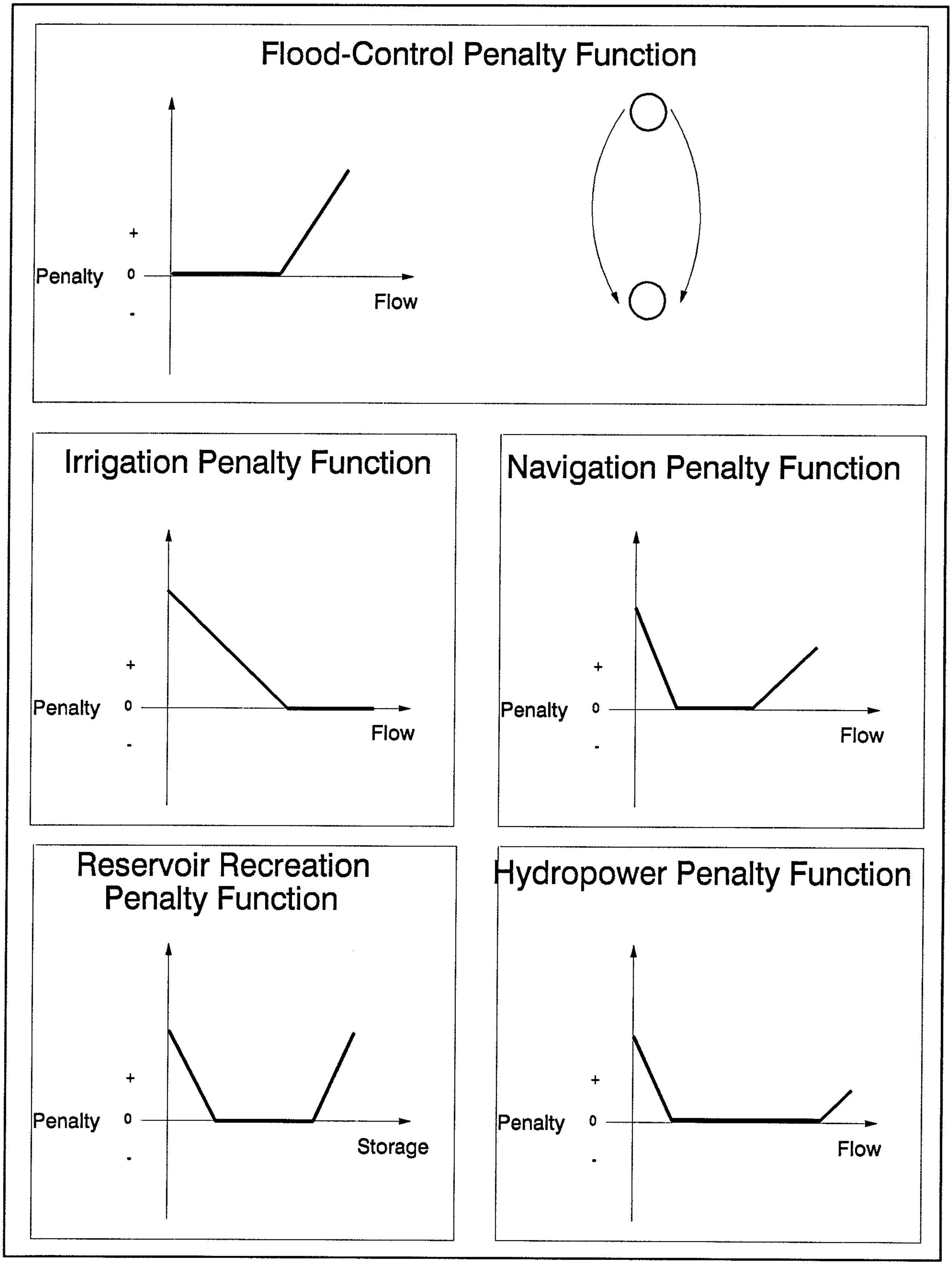

FIGURE A-2 Example Penalty Functions

EXHIBIT A-1

PROPOSED NETWORK-FLOW MODEL FOR COLUMBIA RIVER SOR STUDY

A network-flow model represents the pertinent characteristics of a reservoir system, the objectives of operation, and limitations on actions with a set of simultaneous linear equations. The variables in the equations represent decisions that must be made by system operators. For example, the reservoir releases and storages are represented by variables in the equations. The equations that describe relationships of these variables are of three types: (1) An objective function equation; (2) continuity equations; and (3) upper and lower bounds on the variables. For convenience, the set of equations and the decision variables can be represented by a graph of nodes connected by directed arcs. Nodes represent river or channel junctions, gage sites, monitoring sites, reservoirs, or water-demand sites. Flow is conserved at these nodes: The total volume of water in the arcs originating at any node must equal the total volume in arcs terminating at that node. Arcs represent river reaches or diversion channels. Water moves from node to node through the arcs. A penalty (cost) is incurred for each unit of water that moves through an arc. Each arc is capacitated. That is, each has a minimum and a maximum flow that it must carry.

The proposed network-flow model of the Columbia River system is a layered model, with each layer representing one time period (one month in the model proposed). To develop this model, the network representation is developed first for a single month. Figure A-3 illustrates a simplified version of this network. Node 3 is a reservoir. Node 4 is a downstream demand point. The arc from node 3 to node 4 represents the total reservoir outflow. Node 1 is a hypothetical node that provides all water for the system. The arc from node 1 to node 3 represents the reservoir inflow. The arc from node 1 to node 4 represents the local runoff downstream of the reservoir. Node 2 is the hypothetical sink for all water from the system. The arc from node 4 to node 2 carries water from the reservoir/demand point network to this sink.

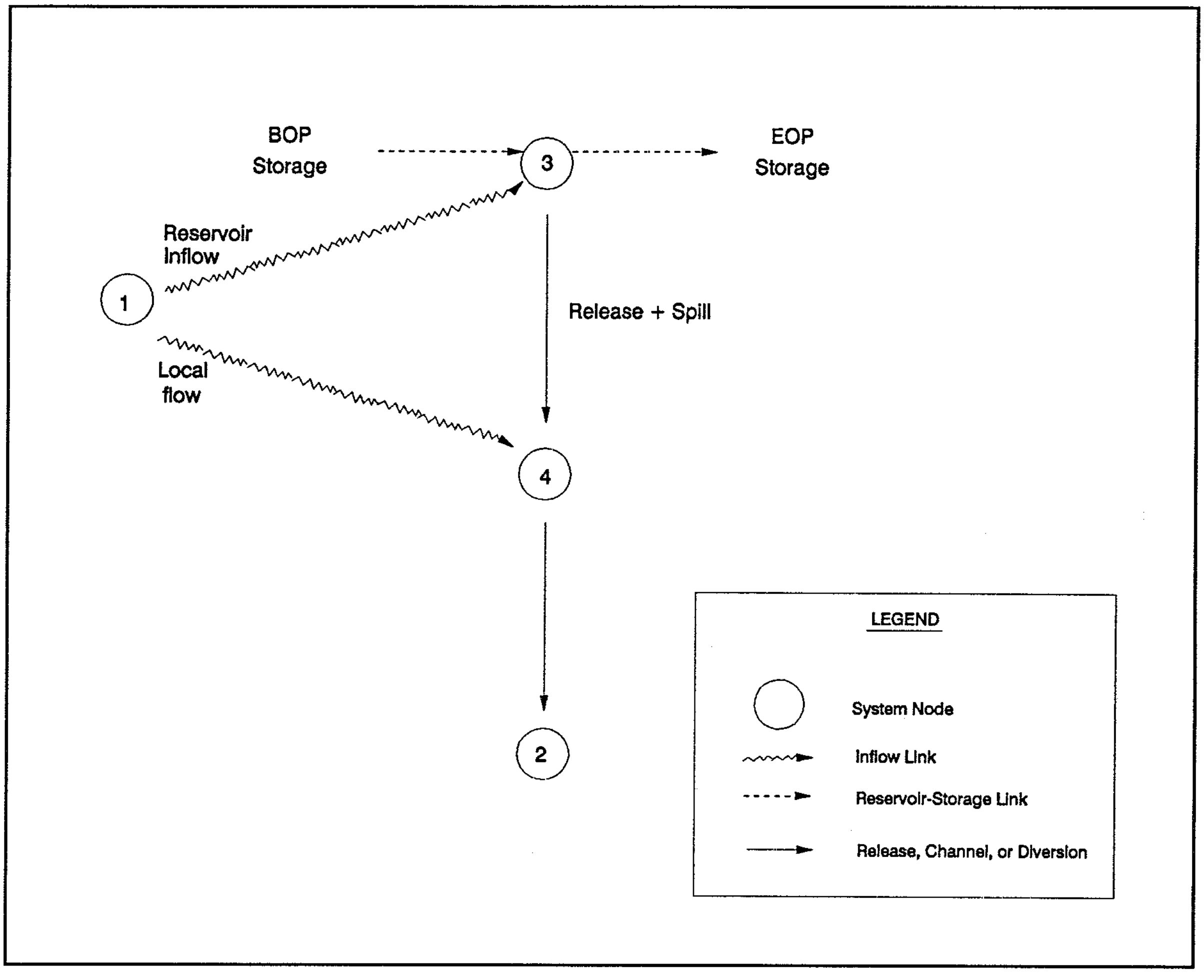

FIGURE A-3 Simplified Single-period Network

For each time period to be analyzed, the arc-node representation of the reservoir system is duplicated. Figure A-4 illustrates this. A single source node (node 1) and a single sink node (node 2) are included. The duplicate networks are connected by arcs that represent reservoir storage. For example, in Figure A-4, the arc connecting node 3 in period 1 to node 3 in period 2 represents the storage. The flow in this arc is the end-of-period 1 (beginning-of-period 2) storage. Likewise, the flow in the arc connecting node 3 in period 2 to node 3 in period 3 represents the end-of-period 2 storage. The single source node (node 1) and single sink node (node 2) are excluded from the figure for clarity.

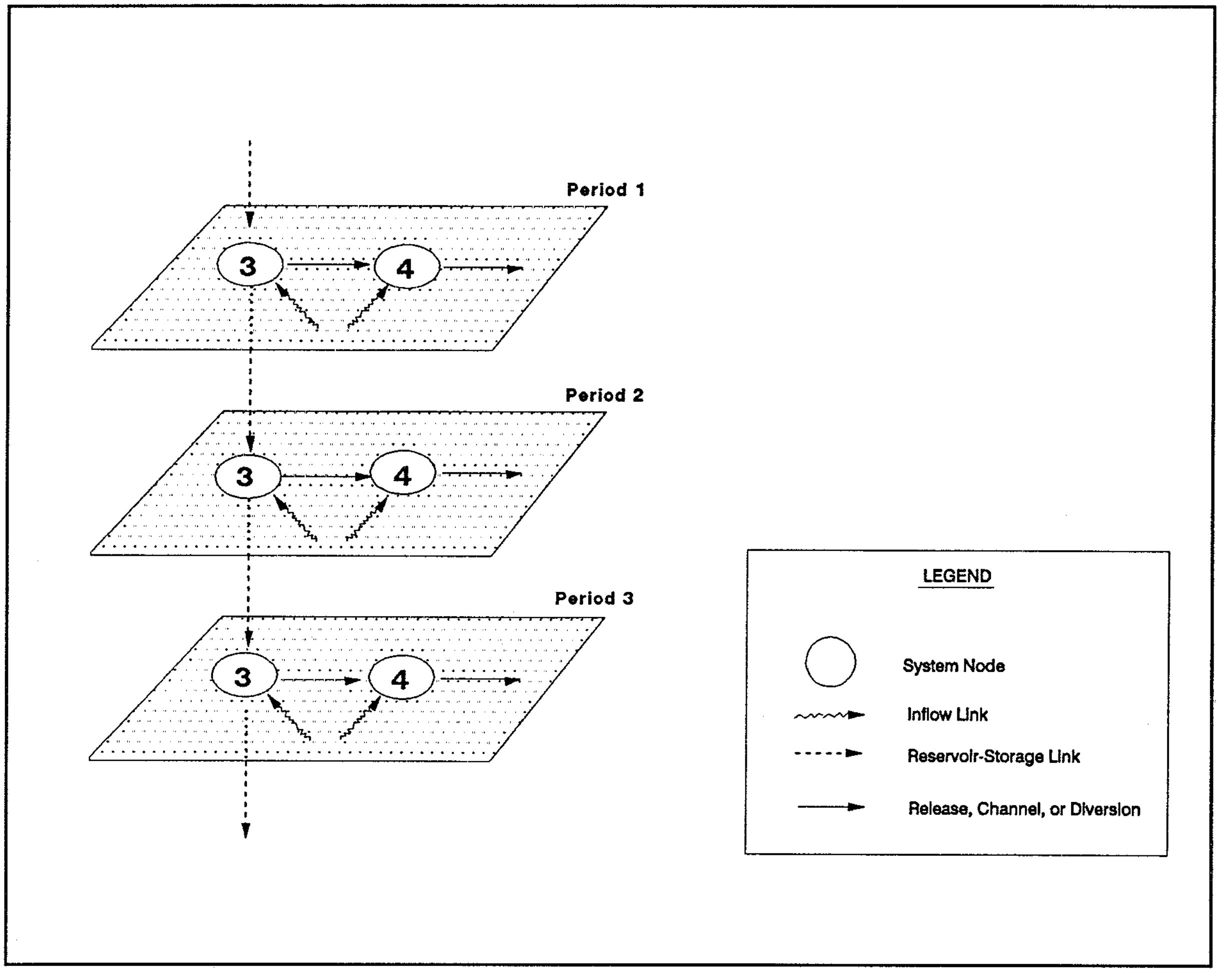

FIGURE A-4 Multiple-period Network

The optimal allocation of water in the layered network is determined with a network solver. The solver finds the flow in each network arc that yields the total minimum-penalty circulation for the entire network, subject to the continuity and capacity constraints. These flows may be translated into reservoir releases, hydropower generation, storage rates, diversions, and channel flows.

APPENDIX B

ASSESSMENT OF APPLICABILITY OF HEC-PRM TO COLUMBIA RIVER SYSTEM

APPENDIX B

ASSESSMENT OF APPLICABILITY OF HEC-PRM TO COLUMBIA RIVER SYSTEM

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APPENDIX B

ASSESSMENT OF APPLICABILITY OF HEC-PRM TO COLUMBIA RIVER SYSTEM

SUMMARY

The Hydrologic Engineering Center Prescriptive Reservoir Model, HEC-PRM, is appropriate for analysis of the Columbia River system. HEC-PRM satisfies institutional, economic, environmental, and engineering requirements for a model of that system. Further, given the complexity of the system, the network-flow programming approach used in HEC-PRM may be the *only* practical prescriptive tool for long-term analysis of monthly operation of that system.

DESCRIPTION OF HEC-PRM

HEC provided a detailed description of HEC-PRM in documents prepared for Phase I of the Missouri River main-stem operation study. The description is summarized here for completeness.

HEC-PRM is a prescriptive model for analysis of monthly reservoir system operation. It represents the reservoir-system operating problem as a minimum-cost dynamic network flow problem. Network arcs and nodes represent the components of the physical system. HEC-PRM represents the dynamic nature of the operation problem by creating a network for each month and interconnecting these networks. The interconnecting arcs represent storage in system reservoirs.

HEC-PRM represents goals of and constraints on system operation with penalties (costs) assigned for flow on the arcs. A network solver finds the allocation of flow to the arcs to minimizes the total penalty for the dynamic network. The allocation maintains continuity throughout the network and is subject to limits on flow on the individual arcs.

HEC-PRM post-processes the results of the solver and stores the results with the HEC data storage system (HEC-DSS). Thus the user may plot conveniently reservoir releases, storage volumes, channel flows, and other pertinent variables, or create reports of these variables.

To the extent possible, HEC-PRM is a general purpose program. It includes the following model-building components:

a. Inflow link;
b. Initial-storage link;
c. Diversion link;
d. Final-storage link;
e. Channel-flow link;
f. Simple reservoir-release link;
g. Hydropower reservoir-release link;

h. Reservoir-storage link; and
i. Node.

An analyst can specify the characteristics of and the configuration of these components to represent any system.

INSTITUTIONAL ISSUES

a. Will HEC-PRM solve the Columbia River reservoir system operation problem? No, but HEC-PRM will provide information that will *help* solve the system-operation problem. For example, HEC-PRM will demonstrate clearly the economic cost of allowing storage at Lower Granite to fluctuate. This cost information will promote rational policy debate.

b. Can HEC-PRM be implemented in time to provide information for decision making in the Columbia River basin SOR? Assuming penalty functions can be developed by NPD and IWR staff in time, HEC-PRM can be implemented in time. The HEC-PRM software took its "maiden voyage" in Phase I of a 1990 study for MRD. Based on the results of that application, HEC staff are eliminating bugs in and improving the software.

c. Will decision makers accept the results of HEC-PRM? HEC cannot guarantee that decision makers will accept the results, but HEC-PRM has characteristics that increase the likelihood of acceptance. The network approach is intuitive, and the solution procedure is relatively straightforward. HEC-PRM will include, in some fashion, all purposes and priorities, thus permitting comparison of alternatives with a common metric. Finally, HEC-PRM is flexible, so it is available for answering, in a timely fashion, any "what-if" questions that may be raised by decision makers.

d. Can the mathematical model results be translated into terms that decision makers understand? Yes, the results can directly be translated to hydrologic terms. Use of the HEC-DSS expedites this. For example, HEC-DSS permits display of commonly-used flow time traces at system control points. Likewise, with HEC-DSS utility programs, the program user generate desired reports and perform additional analyses of results.

e. Can HEC-PRM represent all system operation purposes fairly? Yes, HEC-PRM can represent all operation purposes if system performance for those purposes can be expressed as a function of flow, storage, or both. How fairly the purposes are represented depends on the fairness of the penalty functions.

f. Can HEC-PRM evaluate alternative priorities proposed for system operation? Yes, alternative priorities can be evaluated by altering the penalty functions, modifying the system configuration, or imposing "hard" constraints on flow or storage.

g. Can the network model be modified or expanded easily as more information becomes available, as understanding of the system operation improves, or as the users become more sophisticated? The network structure of the model and the general-purpose software developed by HEC staff make modification easy. Modification of the system configuration or operating goals and constraints requires only identification of new nodes or links and specification of the penalty functions.

h. Can HEC-PRM be used on the computer hardware available to users? HEC staff developed HEC-PRM for use on a state-of-the-art PC (80386 with 80387 or 80486 processor, with extended memory). For Phase I of this study, HEC staff will execute the model on PCs in Davis. At the conclusion of Phase II, HEC will provide the software to NPD staff and insure proper installation on available hardware.

ECONOMIC ISSUES

a. Can HEC-PRM evaluate accurately the economic impact of operation decisions? HEC-PRM will evaluate the economic impact of operation decisions to the extent that the penalties assigned to flow in the network arcs are related to economic costs. Otherwise, the evaluation is in terms of relative satisfaction of demands for water.

b. Can the penalty functions required for HEC-PRM be obtained with reasonable effort? The data required for economic analysis with HEC-PRM are the same data that would be required for economic analysis with any model of the reservoir system. Costs and benefits must be related to hydrologic parameters. Further, non-economic penalties must also be related to hydrologic parameters and expressed in commensurate terms. This task is difficult, but MRD and IWR staff successfully developed functions for the Missouri system.

ENVIRONMENTAL/CULTURAL/SOCIAL ISSUES

a. Can HEC-PRM treat operation for anadromous fish protection? The penalty functions required for HEC-PRM need not be direct economic costs. Instead, they may be any commensurate units of relative dissatisfaction related to hydrologic phenomena. The penalty magnitude is assigned by the analyst. Consequently, the analyst can assign a penalty as large as required to achieve desired flows or storages for fish. The model will demonstrate the trade-offs with other purposes as these penalties are adjusted.

Further, the flow in network arcs can be constrained absolutely if required for fish protection. In that case, the network solver will find the optimal allocation of flow, given the absolute constraints (if a solution is possible).

b. Can the model represent cultural or social requirements on operation (such as those at Libby reservoir)? The network model can represent these requirements if they can be expressed in terms of monthly flow or storage. As described above, the requirements can be expressed in terms of penalties or as absolute limitations.

ENGINEERING ISSUES

a. Does HEC-PRM use readily-available engineering data? HEC-PRM requires reservoir characteristics, channel and outlet capacities, diversion requirements, reservoir inflows, and local flows. These same data are required for HYSSR, the existing NPD reservoir system simulation model, so they should be readily available.

c. Can alternative future inflow or demand sequences be studied conveniently? Inflows are defined with input time series, and demands are defined with input penalty functions. Both are retrieved from HEC-DSS. Alternative sequences can be studied simply by changing the appropriate HEC-DSS files.

d. Can HEC-PRM account for risk? The network model does not account for risk explicitly. However, it is possible to account for risk implicitly by analyzing the frequency of various network-model results. For example, the network model may be applied to determine the optimal allocation of water for the 50-year historical record, given a set of penalty functions. As a consequence of this application, the monthly-average channel discharge time series is computed. The channel discharge-frequency curve can be computed with this time series. The frequency curve will account for risk of failing to meet discharge demands. Similar frequency analyses can be made for reservoir release, power generation, diversion flow, or other pertinent variables. To increase the reliability of the statistical analyses, alternative inflow and demand sequences can be developed with a stochastic-hydrology model and analyzed with the network model.

f. Is HEC-PRM dependable? Yes, HEC-PRM is dependable because it is uses dependable technology, implemented in supportable software. Representation of water-management problems as network-flow problems is well-known. Texas and California water agencies use this approach, as do various engineering consultancies and public utilities. HEC staff have experience with network models for analysis of dredged-material disposal and operation of the Missouri River system. Network solvers have been the subject of research and development since the 1960's. The solution technology is understood well and is reliable.

The implementation of the network model relies heavily on the HEC-DSS and HEC software library routines. HEC staff have tested this software extensively and are expert users.

g. Is the network-solver fast enough? Network solution algorithms are amongst the fastest mathematical-programming algorithms. In the Missouri River system study, HEC employed a generalized network solver to account for reservoir evaporation as a function of surface area. Researchers report that these solvers execute in one-tenth to one-hundredth the time required with a fast linear programming solver. For the Columbia system, NPD staff have accounted for evaporation through adjustments to the inflow data. Consequently, a pure network solver may be used. Researchers report such solvers require one-half to one-quarter the time required by the generalized network solver.

APPENDIX C

REQUIREMENTS FOR PRESCRIPTIVE MODEL OF RESERVOIR SYSTEM OPERATION

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APPENDIX C

REQUIREMENTS FOR PRESCRIPTIVE MODEL OF RESERVOIR SYSTEM OPERATION

SUMMARY OF REQUIREMENTS

The reservoir system operation problem will be addressed as a problem of optimal long-term allocation of available water. A prescriptive model will be developed to solve this problem. The model will identify the allocation that minimizes poor performance for all defined system purposes. Performance will be measured with analyst-provided penalty functions of flow or storage or both.

To determine the optimal water allocation, the physical system will be represented as a network, and the operating problem will be formulated as a minimum-cost network flow problem. The objective function of this network problem is the sum of convex, piecewise-linear approximations of the penalty functions. An off-the-shelf solver will be used to define the optimal allocation of water within the system. The results of the solver will be processed to report and display reservoir releases, storage volumes, channel flows, and other pertinent variables.

To the extent possible, the software to implement the model will be general purpose. Accordingly, the software will include the following model-building components:

1. Inflow link;
2. Initial-storage link;
3. Diversion link;
4. Final-storage link;
5. Channel-flow link;
6. Simple reservoir-release link;
7. Hydropower reservoir-release link;
8. Reservoir-storage link; and
9. Node.

An analyst can specify the characteristics of and the configuration of these components to represent any system.

PROBLEM STATEMENT

The problem addressed by the proposed system model is identification of the optimal long-term operation plan for the reservoirs of that system. This plan will identify the priorities to be assigned to conflicting objectives of operation. For example, the plan will identify whether water should be released from a system reservoir if a demand exists for downstream flow for wildlife protection and a conflicting demand exists for continued storage of the water for reservoir recreation.

The model will quantify system performance for various purposes in multi-objective terms. The economic cost of operation will be considered. Also, the social and environmental cost will be considered. These costs will be expressed in commensurate terms to permit display of trade-offs in operation for various purposes.

Constraints on the physical system will be included. For example, the outlet capacity of the reservoirs will be modeled explicitly. However, inviolable constraints on system operation will used frugally. This will avoid the problem described by Hitch and McKean (1960) when they wrote "...casually selected or arbitrary constraints can easily increase system cost or degrade system performance manyfold, and lead to solutions that would be unacceptable to the person who set the constraints in the first place." Instead, operation limitations will be imposed through value functions. This will permit clear evaluation of the impacts of limitations. For example, instead of specifying maximum flow requirements for flood control, the system model will represent this requirement through high costs of failure to meet the requirement.

PROPOSED SOLUTION

The proposed solution considers the reservoir operation planning problem as a problem of optimal allocation of available water. The proposed solution to this water allocation problem is as follows:

(1) Represent the physical system as a network;

(2) Formulate the allocation problem as a minimum-cost network flow problem;

(3) Develop an objective function that represents desirable operation;

(4) Solve the network problem with an off-the-shelf solver; and

(5) Process the network results to define, in convenient terms, system operation.

Represent System as a Network

For solution of the water allocation problem, the reservoir system will be represented as a network. A network is a set of arcs that are connected at nodes. The arcs represent any facilities for transfer of water between two points in space or time. For example, a natural channel transfers water between two points in space and is represented by an arc. A reservoir transfers water between two points in time; this transfer is represented by an arc.

Network arcs intersect at nodes. The nodes may represent actual river or channel junctions, gage sites, monitoring sites, reservoirs, or water-demand sites. Flow is conserved at each node: the total volume of water in arcs originating at any node equals the total volume in arcs terminating at that node.

Figure C-1 illustrates a simple network representation. Node 3 represents a reservoir. Node 4 represents a downstream demand point. Two additional nodes with associated arcs are included to account completely for all water entering and leaving the system. Node 1 is the source node, a hypothetical node that provides all water for the system. Node 2 is the sink node, a hypothetical node to which all water from the system returns. The arc from node 1 to node 3 represents the reservoir inflow. The arcs shown as dotted lines represent the beginning-of-period (BOP) and end-of-period (EOP) storage in the reservoir. The BOP storage volume flows into the network from the source node. The EOP volume flows from the network back to the sink node. The arc from node 3 to node 4 represents the total reservoir outflow. The arc from node 1 to node 4 represents the local runoff downstream of the reservoir. The arc from node 4 to node 2 carries water from the reservoir/demand point network to the sink.

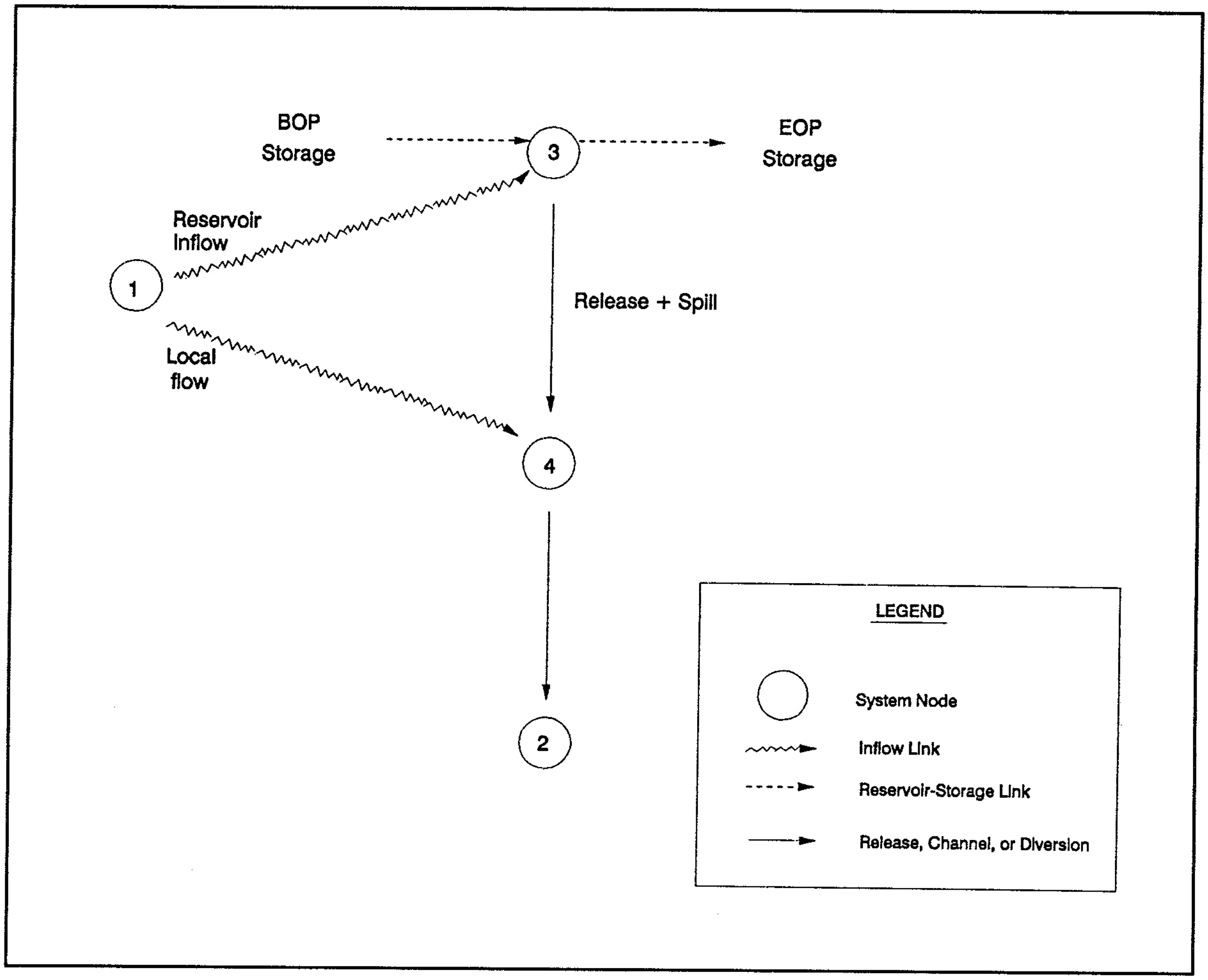

FIGURE C-1 Simplified Single-period Network

To analyze multiple-period system operation, a layered network will be developed. Each layer represents one month. To develop such a layered network, the single-period network representation is duplicated for each time period to be analyzed. Figure C-2 illustrates this. A single source node and a single sink node are included. For clarity, these have been omitted from the figure. The duplicate networks are connected by arcs that represent reservoir storage. For example, in Figure C-2, the arc connecting node 3 in period 1 to node 3 in period 2 represents the storage. The flow along this arc is the end-of-period 1 storage. This is equivalent to the beginning-of-period 2 storage. Likewise, the flow along the arc connecting node 3 in period 2 to node 3 in period 3 represents the end-of-period 2 storage. This also is the beginning-of-period 3 storage.

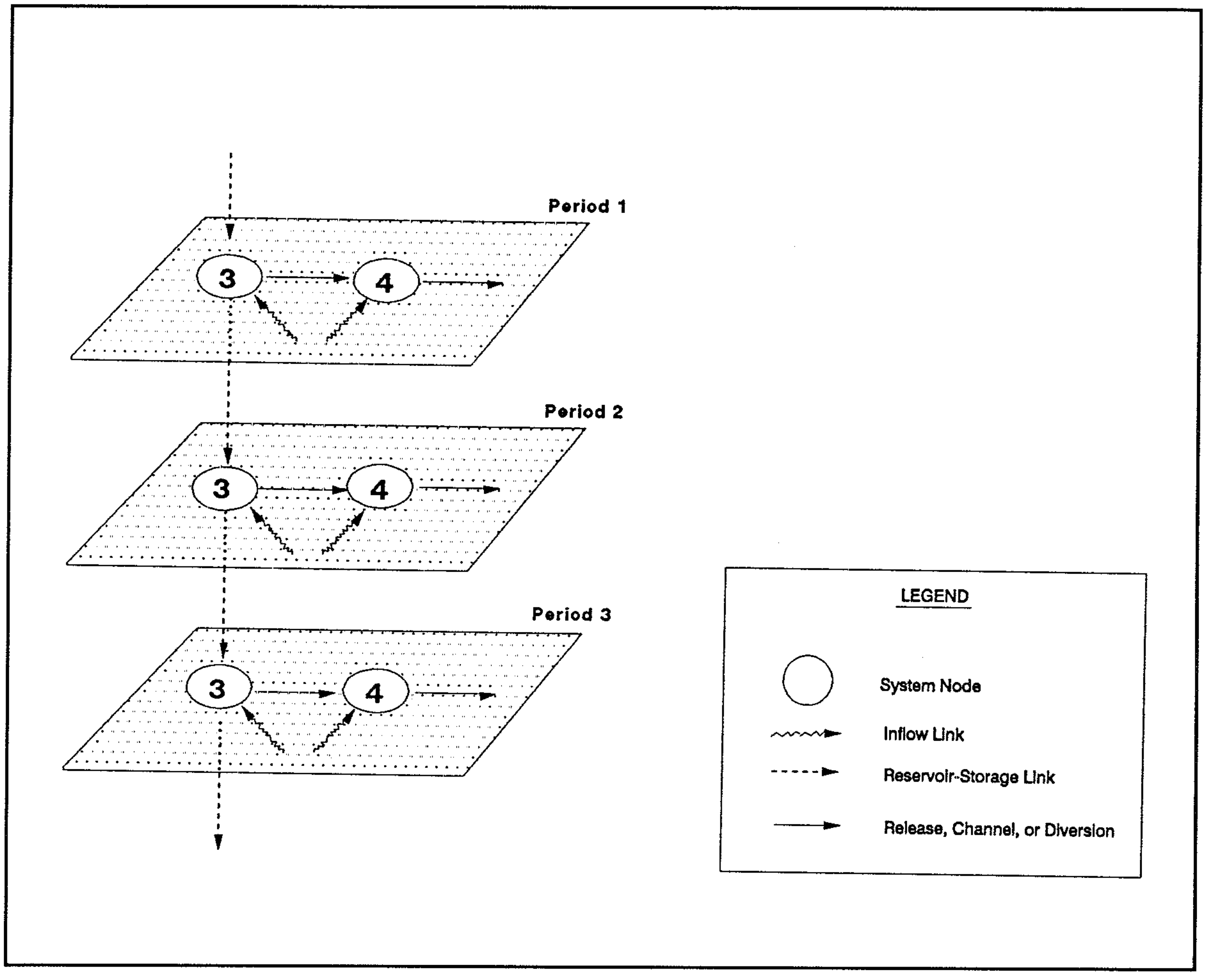

FIGURE C-2 Multiple-period Network

Formulate the Allocation Problem as a Minimum-cost Network-flow Problem

The goals of and constraints on water allocation within the reservoir system can be represented in terms of flows along the arcs of the network. If a unit cost is assigned for flow along each arc, the objective function for the network is the total cost for flow in all arcs. The ideal operation will be that which minimizes this objective function while satisfying any upper and lower bounds on the flow along each arc. The solution also must maintain continuity at all nodes.

Minimum-cost Objective Function. A network solver finds the optimal flows for the entire network simultaneously, based on the unit cost associated with flow along each arc. The functions that specify these costs are defined by the analyst.

The simplest cost function is a linear function, such that shown in Figure C-3. This function represents the cost for flow along one arc of a network. The cost increases steadily as the flow increases in the arc. The unit cost is the slope of the function. Here, it is positive, but it may be negative. The total cost for flow along the arc represented is the product of flow and the unit cost.

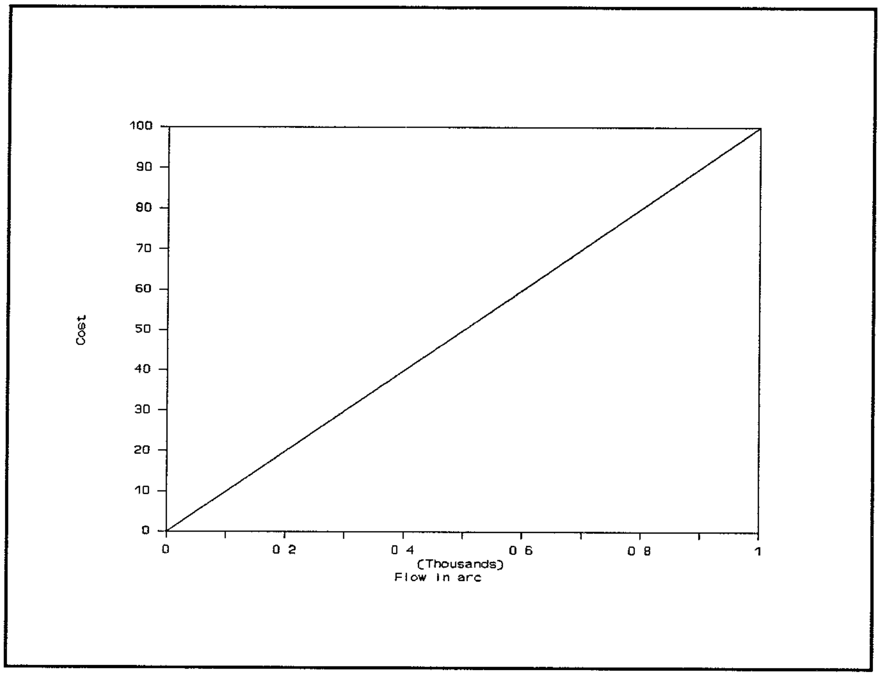

FIGURE C-3 Simple Linear Cost Function

The simplest linear function may be too simple to represent adequately many of the goals of reservoir operation. Instead, nonlinear functions, such as those shown in Figures C-4(a-c), may required.

Piecewise-linear Approximation. If the cost functions are convex, as are those in Figures C-4(a-c), they can approximated in a piecewise linear fashion for the proposed network model. Figure C-5 illustrates piecewise approximation of a complex cost function. Linear segments are selected to represent the pertinent characteristics of the function. The analyst controls the accuracy of the approximation. More linear segments yield a more accurate representation. However, the time required for solution of the resulting network-flow programming problem depends on the number of arcs included in the network. Thus, as the approximation improves, the time for solution increases. Jensen and Barnes discuss this approximation in detail (1980, pgs. 355-357).

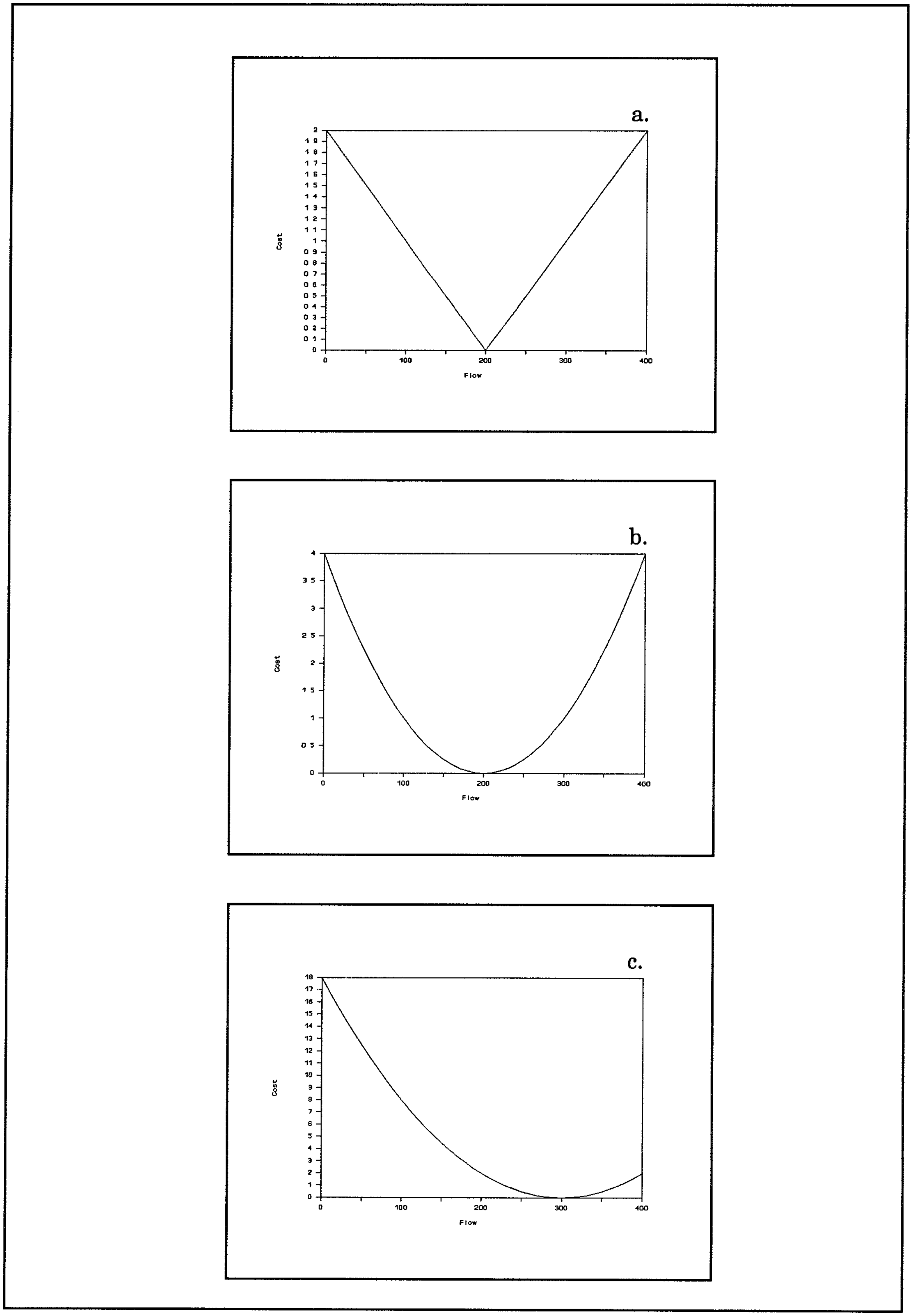

FIGURE C-4 Nonlinear Penalty Functions

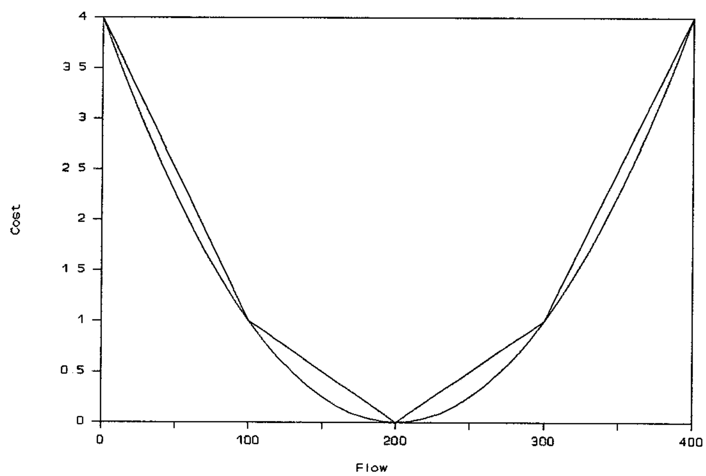

FIGURE C-5 Piecewise Linear Approximation of Nonlinear Penalty Function

With a piecewise linear approximation, the physical link for which the function applies is represented in the network by a set of parallel arcs. One arc is included for each linear segment of the piecewise approximation. For example, suppose the cost function in Figure C-5 represents the cost of release from the reservoir represented by node 3 in Figure C-1. In the proposed network model, four parallel arcs will connect node 3 to node 4. Characteristics of the arcs are shown on Table C-1.

TABLE C-1
Example Network Model Arc Characteristics

Arc Number (1)	Lower Bound (2)	Upper Bound (3)	Unit Cost (4)
1	0	100	(1-4)/100=-0.03
2	0	200-100=100	(0-1)/100=-0.01
3	0	300-200=100	(1-0)/100= 0.01
4	0	400-300=100	(4-1)/100= 0.03

Arc 1 has the least marginal cost. Therefore, as flow is increased from node 3 to node 4, flow will pass first through arc 1. When the capacity of this arc is reached, flow begins to pass through arc 2. Arc 3 will have non-zero flow if and only if arc 2 is at its upper bound. Finally, arc 4 will have non-zero flow only when arcs 1, 2, and 3 are flowing full. Because the objective is to minimize cost, if two or more arcs are parallel, the one with the lowest unit cost is used first.

Develop Objective Function Representing Desirable Operation

Penalty Functions. All goals of system operation cannot be represented adequately with economic costs. Some of the goals are socially, environmentally, or politically motivated. Consequently, the objective function for the proposed model is formed from penalty functions, rather than cost functions. These penalty functions are in commensurate units, but those units are not necessarily dollars. The penalty functions represent instead the relative economic, social, environmental, and political penalties associated with failure to meet operation goals. For example, even if failure to meet an environmental operation goal has no measurable economic cost, the penalty may be great.

Flow Penalty Functions. All operation goals related to reservoir-release, channel-flow, or diversion flow are expressed with flow penalty functions. These functions may represent operation goals for navigation, water supply, flood control, or environmental protection.

Figure C-6 is an example of a flow penalty function. This function represents the relative penalty for diverting flow when the minimum desired diversion is 100 cfs. Less diversion is undesirable. More diversion is acceptable, but that water does not reduce further the penalty.

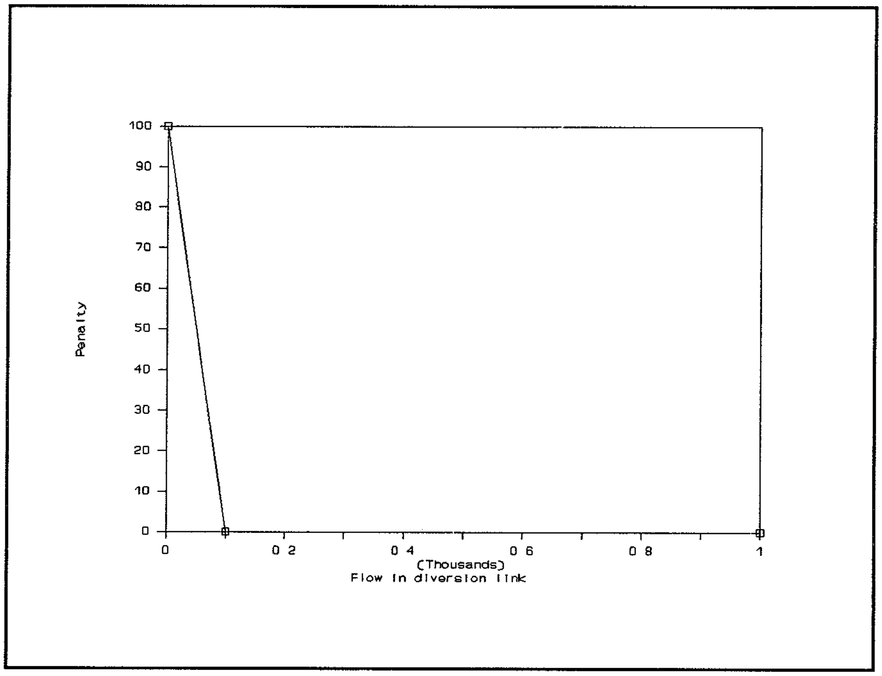

FIGURE C-6 Typical Flow Penalty Function

The penalty function of Figure C-6 is represented in the network by two parallel arcs. The characteristics of these arcs are shown on Table C-2.

TABLE C-2
Penalty Function Arc Parameters

Arc Number (1)	Lower Bound (2)	Upper Bound (3)	Unit Cost (4)
1	0	100	(0-100)/100=-1.00
2	0	1000-100=900	0.00

The first arc represents flow up to the desired rate. As the flow increases from 0 cfs to 100 cfs, the total penalty decreases. At 100 cfs, the unit penalty is 0.00. As the flow increases beyond 100 cfs, the unit penalty remains 0.00.

Similar penalty functions can be developed for reservoir release and channel flow.

Storage Penalty Functions. All reservoir operation goals uniquely related to storage are expressed through penalty functions for arcs that represent reservoir-storage. These functions may represent operation goals for reservoir recreation, water supply, or flood control.

Figure C-7 is an example of a reservoir storage penalty function. For this example, the top of the permanent pool is 200 kaf, the top of the conservation pool is 800 kaf, and the top of the flood-control pool is 1000 kaf. The function represents penalty for storage when the reservoir operation goal is to keep the inactive and conservation pools full and the flood control pool empty.

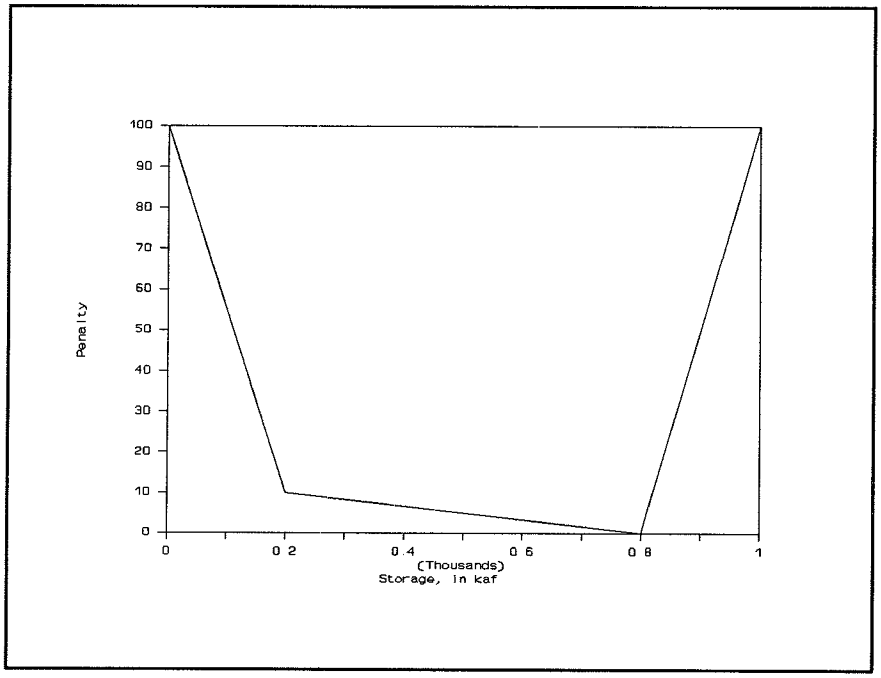

FIGURE C-7 Typical Storage Penalty Function

The function of Figure C-7 is represented in the network by three parallel arcs. The flow along one arc represents storage in the permanent pool. Increasing the flow along this arc reduces the penalty rapidly. Flow along the second arc represents storage in the conservation pool. Increasing flow along this arc also decreases the penalty, but not as rapidly as does flow along the inactive-pool arc. The third arc represents storage in the flood-control pool. Increasing flow along the flood-control pool arc increases the penalty. The solver will allocate flow to the arcs to minimize the total system penalty: first to the inactive-pool arc, then to the conservation-pool arc, and finally to the flood-control pool arc.

Storage and Flow Penalty Functions. Certain system operation goals depend on both storage and flow. The most significant is hydroelectric energy generated at a reservoir. This is a function of the product of release and head on the turbine. Head is the difference in reservoir-surface elevation and downstream water-surface elevation. Reservoir-surface elevation is a function of reservoir storage, and downstream water-surface elevation is a function of release. Thus, the energy generated is a complex function of storage and flow.

Figure C-8 illustrates a typical hydropower energy penalty function. Here, penalty is measured in terms of reduction in value of the energy produced, when compared to the firm energy target. Additional energy generated has a value, but that value is less that firm energy. Thus the slope is less.

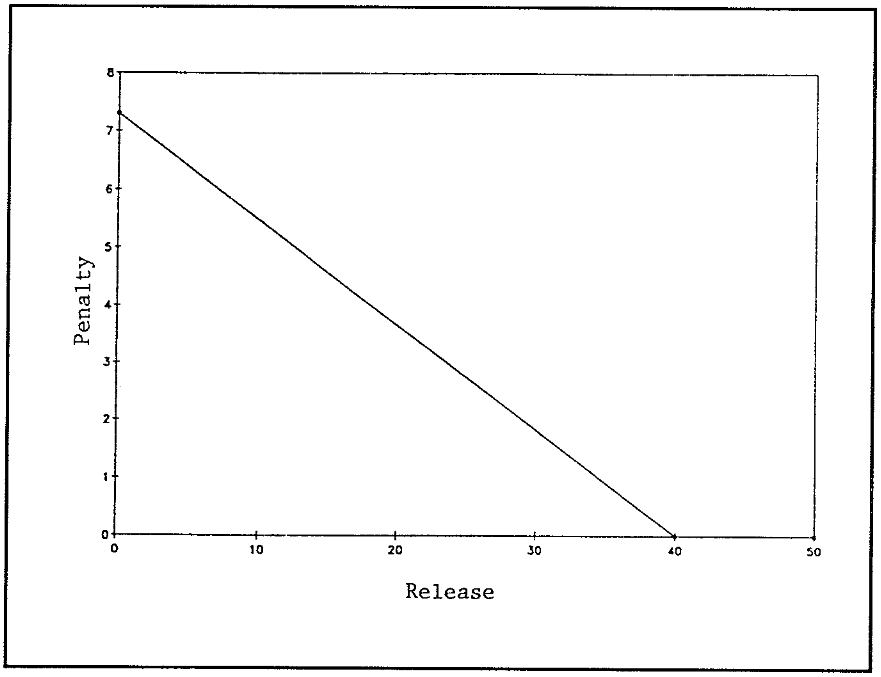

FIGURE C-8 Typical Hydropower Energy Penalty Function

Solve the Network Problem with an Off-the-shelf Solver

Mathematical Statement of Problem. The optimization problem represented by the network with costs associated with flow can be written as follows (Jensen and Barnes, 1980):

$$\text{Minimize: } \sum_{k}^{m} h_k f_k \tag{1}$$

subject to

$$\sum_{k \in M_O} f_k - \sum_{k \in M_T} a_k f_k = 0 \quad \text{(for all nodes)} \tag{2}$$

$$l_k \leq f_k \leq u_k \quad \text{(for all arcs)} \tag{3}$$

in which:

- m = total number of network arcs;
- h_k = unit cost for flow along arc k;
- f_k = flow along arc k;
- M_O = the set of all arcs originating at a node;
- M_T = the set of all arcs terminating at a node;
- a_k = multiplier for arc k;
- l_k = lower bound on flow along arc k; and
- u_k = upper bound on flow along arc k.

Equations 1, 2, and 3 represent a special class of linear-programming (LP) problem: the *generalized minimum-cost network-flow problem*. Solution of the problem will yield an optimal allocation of flow within the system.

Network Solvers. Jensen and Barnes (1980) describe a variety of solutions to the generalized minimum-cost and other network-flow programming problems. One solution is the flow-augmentation algorithm developed by Jensen and Bhaumik (1974). This algorithm determines the minimum-penalty flow in a generalized network by iteratively performing two computations. In the first computation, at the first iteration, the algorithm solves a shortest-path problem. That is, it determines a set of arcs that provide the minimum-penalty path from the source node to the sink node. In each successive iteration, the shortest-path computation deletes an arc with flow at upper bound from the path. It then adds the most promising available arc to create a new path. The second computation determines the maximum flow that can be directed from source to sink through the current shortest path. It increases flows in the arcs to achieve the maximum possible flow at the sink. If this flow equals an analyst-specified flow requirement at the sink, the algorithm terminates. Otherwise, the algorithm continues with the first computation. FORTRAN routines implementing this algorithm were published by Jensen and Bhaumik and used by Martin (1982). These routines are available at HEC.

Post-process Network Results

The optimal allocation of water in the layered network is determined with a network solver. The solver finds the flow along each network arc that yields the total minimum-penalty circulation for the entire network, subject to the continuity and capacity constraints. These flows must be translated into reservoir releases, hydropower generation, storage volumes, diversion rates, and channel flows to be useful to the reservoir system operators.

For convenience, the results after translation will be stored with the HEC data storage system (HECDSS). Then the results can be displayed or processed further as needed to provide information required for decision making.

MODEL-BUILDING SOFTWARE

To the extent possible, the software to implement the network model will be general-purpose software. With this software, an analyst will be able to define the layout of any existing or proposed reservoir system. Further, the analyst will be able to describe the physical features of the system reservoirs and channels and the goals of and constraints on their operation. The operation goals will be defined by penalty functions associated with flow, storage, or both.

To permit representation of any reservoir system as a network, the software will include the following model-building components:

1. Inflow link;
2. Initial-storage link;
3. Diversion link;
4. Final-storage link;
5. Channel-flow link;
6. Simple reservoir-release link;
7. Hydropower reservoir-release link;
8. Reservoir-storage link; and
9. Node.

By selecting the appropriate links and the manner in which they are interconnected, the analyst can describe any system. By describing the characteristics of the links and the penalties associated with flow along the links, the analyst can define operating constraints and goals.

Inflow Link

An inflow link brings flow into the reservoir-system network. It originates at the source node and terminates at any other system node. In Figure C-1, the link from node 1 to node 3 is an inflow link. It originates at the source node, node 1, and carries flow into the system at node 3.

The flow along the arc representing the inflow link is an input to the model. This known inflow may be an observed inflow from the historical record, or it may be an inflow from a sequence generated with a statistical model. To insure that the link carries the specified flow, the arc upper and lower bounds are equal, and the unit penalty is zero.

Initial-storage Link

An initial-storage link is a special case of an inflow link. It originates at the source node and terminates at a node that represents a reservoir in the first period of analysis only. It introduces to the network the volume of water initially stored in the reservoir. In Figure C-2, the storage link terminating at node 3 in period 1 is an initial-storage link; it represents the beginning-of-period 1 storage.

As an initial-storage link carries a specified flow, no decision is represented by this link. To insure that the link carries the specified flow, the arc upper and lower bounds are equal, and the unit penalty is zero.

Diversion Link

A diversion link carries flow out of the system. It originates at any system node and terminates at the sink node. In Figure C-1, the arc from node 4 to node 2 is a diversion link. It originates in the system at the downstream control point, node 4. It carries flow out of the system to the sink, node 2.

The flow along a diversion link is a decision variable, selected to minimize total system penalty. The diversion penalty function is specified by the analyst as a convex piecewise approximation of the true penalty associated with deviating from the diversion desired. This function may vary by month. The software will define appropriate arc bounds and unit costs to represent the function.

The analyst may specify also inviolable minimum and/or maximum flow for a diversion link. If the analyst specifies both minimum and maximum, and if these values are the same, the diversion link will be represented in the network by a single arc. The upper and lower bounds of the arc are equal. In that case, the only feasible solution is one in which flow equals the specified value, regardless of cost. Any penalty function defined by the analyst for the link is ignored in that case, as it has no impact on the solution.

If the analyst specifies only a lower bound or only an upper bound, the software will impose the bound on the appropriate network arcs. If the penalty function is a simple function, like that of Figure C-3, the bound is applied to the single arc representing that function. For example, if the analyst specified a lower bound of 25 cfs and an upper bound of 800 cfs, the network arc will have $l_k = 25$ and $u_k = 800$ (see Equation 3).

For more complex penalty functions, the software must include an algorithm to determine the proper network arcs on which to impose the bound. For example, the penalty function of Figure C-6 is represented by two parallel arcs, with bounds and cost. If the analyst specifies an inviolable lower bound of 25 cfs and an upper bound of 800 cfs, the network arcs must be adjusted to have parameters shown on Table C-3.

TABLE C-3
Diversion Link Arc Characteristics

Arc Number (1)	Lower Bound (2)	Upper Bound (3)	Unit Cost (4)
1	25	100	-1.00
2	0	800-100=700	0.00

For the first arc, the lower bound increases from 0 to 25. The upper bound remains 100. The unit cost does not change. For the second arc, the lower bound remains 0, and the upper bound now is 800 - 100 = 700. The unit cost does not change.

Final-storage Link

A final-storage link is a special case of a diversion link. It carries flow out of the system, but only from a reservoir in the last period of analysis. The final storage link thus originates at any system reservoir and terminates at the sink node. In Figure C-2, the storage link originating at node 3 in period 3 is a final-storage link. The final-storage link is included in the system model to permit assignment of a future value for water in system reservoirs. Otherwise, the network solver will be indifferent regarding final storage. The solver may chose any storage state, including empty or full, without regard for future use.

Just as with the diversion link, the flow along a final-storage link is a decision variable, selected to minimize total system penalty. The penalty function is specified by the analyst as a convex piecewise approximation of the true penalty associated with deviating from the an ideal final storage. The software will define appropriate arc bounds and unit costs to represent this function.

As with the diversion link, the analyst may specify also inviolable minimum and/or maximum storage for a final-storage link. The software will impose these constraints on the appropriate network arcs.

Channel-flow Link

A channel-flow link originates at any non-reservoir node, terminates at any other network node, and represents the flow in a channel reach. The flow along the link is a decision variable, selected to minimize total system penalty.

As with the diversion link, the analyst may specify inviolable minimum and/or maximum flow for a channel-flow link. The software will impose these constraints on the appropriate network arcs.

The analyst may specify also a multiplier for flow along a channel-flow link. The multiplier is a_k of Equation 2 for all arcs representing the link. If the multiplier is greater than 1.00, it represents increase of flow in the channel. If the multiplier is less than 1.00, it represents loss of flow.

Simple Reservoir-release Link

The reservoir-release link originates only at a non-hydropower reservoir node, terminates at any other node, and represents the total outflow from a reservoir. This includes release and spill. The flow along a reservoir-outflow link is a decision variable, selected to minimize total system penalty. In Figure C-1, the link from node 3 to node 4 is a simple reservoir-release link. It originates at a node representing a reservoir and terminates, in this case, at a node representing a demand point.

The analyst may specify inviolable minimum and/or maximum flow constraints. The analyst may specify also a multiplier for flow along a reservoir-release link. The software will apply the multiplier and impose the constraints on the appropriate network arcs.

Hydropower Reservoir-release Link

Link Description. A hydropower reservoir-release link (hydro-release link) originates only at a hydropower reservoir node, terminates at any other node, and represents the total outflow from the reservoir. This includes release and spill.

The flow along a hydro-release link is a decision variable, selected to minimize total system penalty. As hydroelectric energy is not a linear function of flow, however, determination of the release that minimizes total penalty requires consideration of storage.

Hydropower Computation From Link Flow. The nonlinear hydro-release problem will be solved via iterative solution of linear approximations. Such successive linear programming techniques are described by Martin (1982), Grygier and Stedinger (1985), and Reznicek and Simonovic (1990). In summary, these techniques convert the energy penalty functions to release penalty functions by assuming a value of reservoir storage. Given the storage, head can be estimated. Given this head, the unit penalty for release is used, and the flow allocation problem is solved. Then the head assumption is checked, using the storage computed for the optimal allocation. If the assumption is not acceptable, the heads corresponding to the computed storages are used, and the process is repeated.

The algorithm proposed by Grygier and Stedinger (1985) will be employed in the proposed model. This algorithm solves the hydro-release problem as follows:

1. **Initialize:** Set ITER (iteration counter) = 0. Set ITMAX = the maximum number of iterations allowed (must be > 1). Set CANDPEN (candidate optimal objective function value) = a very large number. Set $\Delta R_{max} = 0.50$. Set $R_{j,upper}$ = release corresponding to maximum power generation at maximum head for reservoir j. (ΔR_{max} and $R_{j,upper}$ are used in constraining release in step 3, and are subject to change as we collect information on performance with alternative values.) For each reservoir j, for each period t, estimate $S_{j,t}$, the end-of-period storage. Go to step 2.

2. **Set Up the Network:** Set ITER = ITER + 1. If ITER > ITMAX, declare the candidate solution the optimal solution and stop. Otherwise, use the elevation-capacity function for reservoir *j* to determine the end-of-period head. Average the beginning-of-period and end-of-period heads. Select the "closest" user-provided linear approximation of the hydropower penalty function for each period. Set up the system network with arc bounds and costs to represent these hydropower penalty functions, along with flow and storage penalty functions for other purposes. Go to step 3.

3. **Limited Variation:** If ITER = 1, go to step 4. Otherwise, constrain flow on the reservoir hydropower-release links so the total release does not vary from the candidate solution by more than ΔR_{max}. The link lower bound would be $R_{j,t}(1 + \Delta R_{max})$. If the candidate release is zero, set the upper bound equal $R_{j,upper}$. Go to step 4.

4. **Solve the Network:** Solve the resulting flow-allocation problem to find CURRPEN, the penalty associated with the current approximation. Use the best available network solver at this step. If a previous network solution is available, and if the solver can use it as a starting point, let it. Go to step 5.

5. **Check for Solution to Nonlinear Problem:** For each reservoir *j*, for each period *t*, determine $S_{j,t-1}$ and $S_{j,t}$ from the current solution of the network. Do these values differ from the values used in step 2 to select the approximation? If all are close enough, declare the current solution optimal and stop. Otherwise, go to step 6.

6. **Update Candidate Solution:** If CURRPEN < CANDPEN, it is an improvement, so save the current solution (storages, releases, etc.) as the candidate optimal solution, set CANDPEN = CURRPEN, and go to step 2. Otherwise, go to step 7.

7. **Decrease the Allowable Variation:** Set $\Delta R_{max} = \Delta R_{max}/2$. If ΔR_{max} < minimum value, declare the candidate solution optimal and stop. Otherwise, go to step 2.

Other Release Penalties. Due to the special nature of the hydro-release link, all other release-related penalties must be defined as a function of flow downstream. This is accomplished by defining a "dummy" node downstream of the hydropower reservoir. The hydro-release link connects the reservoir and this dummy node, and the hydropower penalty function is associated with this link. A channel-flow link connects the dummy node with the next downstream node. All penalty functions normally defined in terms of reservoir release are defined in terms of channel flow instead.

Reservoir-storage Link

Link Description. A reservoir-storage link originates at any reservoir node in a layered, multiple-period network. It represents the volume of water stored in the reservoir at the end of the period. The reservoir-storage link terminates at the node representing the same reservoir in the period following. The flow along a reservoir-storage link is a decision variable, selected to minimize total system penalty.

For example, in Figure C-2, the arc from node 3 in period 1 to node 3 in period 2 is a reservoir-storage link. Flow along the arc leaving the period 1 layer represents reservoir storage at the end of period 1. Flow along the arc entering the period 2 layer represents reservoir storage at the beginning of period 2.

Evaporation Computation With Link Flow. To approximate reservoir evaporation, a fraction of flow entering the reservoir-storage link may be "lost". For the network model, the relationship of storage and evaporation is given by

$$S_t = S_{t-1} - EV_{t-1} \tag{4}$$

in which:

S_t = reservoir storage at beginning of period t;
S_{t-1} = reservoir storage at end of period t-1;
EV_{t-1} = volume of reservoir evaporation. The evaporation volume is related to reservoir surface area with the following equation:

$$EV_{t-1} = (ED_{t-1})\,(A_{t-1}) \tag{5}$$

in which:

ED_{t-1} = evaporation rate in period t-1; and
A_{t-1} = reservoir surface area in period t-1.

The quantity ED_{t-1} is input to the model. It may be an historically observed evaporation rate, or it may be generated with a stochastic model. The relationship of surface area and storage can be approximated with a linear function as

$$A_{t-1} = \beta\, S_{t-1} \tag{6}$$

in which:

β = a linear coefficient.

The value of β is found from analysis of specified reservoir characteristics. Substituting Equations 5 and 6 into Equation 4 and simplifying yields

$$S_t = (1 - ED_{t-1}\,\beta)\,(S_{t-1}) \tag{7}$$

The quantity $(1 - ED_{t-1}\,\beta)$ is an arc multiplier. The flow out of the reservoir-storage arc, S_t, is the flow into the arc, S_{t-1}, multiplied by $(1 - ED_{t-1}\,\beta)$. This multiplier is the arc multiplier a_k of Equation 2.

If the magnitude of $(1 - ED_{t-1}\,\beta)$ is approximately 1.00 for all periods of analysis, S_t = S_{t-1}. That is, reservoir storage at beginning of period t = reservoir storage at end of period t-1. In that case, the network-flow programming is no longer a generalized network problem. Instead, it is a pure network problem. Faster solvers may be used.

If a_k = 1.00 for all k in Equation 2, the resulting problem is a *pure network-flow programming problem*. For this class of problem, faster solution algorithms are available. The well-known out-of-kilter (OKA) algorithm (Fulkerson, 1961) solves this pure network problem. A FORTRAN routine implementing the OKA has been available as shareware since 1967 (SHARE). Barr, Glover, and Klingman (1974) presented an improved formulation of the OKA and developed a FORTRAN code to implement their algorithm. They present results showing that the reformulated algorithm is faster than the share routine by a factor of 4 to 15 on large problems. This code, designated SUPERK, is published by the Texas Department of Water Resources (1975) and used by the California Department of Water Resources (Chung, et al., 1989). FORTRAN code for SUPERK is available at HEC.

Nodes

Nodes are included in the model to permit joining the appropriate links. Two or more of the links described may join at a node. The nodes represent system reservoirs, demand points, channel junctions, or diversion points. These may be existing facilities or proposed facilities. Additional nodes may be included in the network for convenience of description.

In addition to the analyst-defined nodes, the software will incorporate in the network a source node and a sink node to satisfy the mathematical requirements for defining a network. All water entering the system flows from the source node. All water leaving the system flows to the sink node. These hypothetical nodes have unlimited capacity.

TYPICAL PENALTY FUNCTIONS

The goals of reservoir system operation are identified by the analyst via penalty functions. The functions define, as a function of flow, storage, or both, the economic, social, and environmental cost for deviating from ideal operation for each of the system operation purposes. These purposes include flood control, navigation, lake and stream recreation, water supply, environmental protection, and hydropower.

Flood-control Penalty Function

A flood-control penalty function defines the cost of deviating from ideal flood-damage-reduction operation. This function typically will relate penalty to channel-link flow or reservoir release link flow.

Figure C-9 is a typical flood-control penalty function. In this example, no penalty is incurred for flows less that 600 cfs, the channel capacity. Between 600 cfs and 1100 cfs, the penalty is slight, increasing to 100 units. The penalty is much greater for flows exceeding 1100 cfs. This represents significant damage incurred as the flow moves out of the 10-25 year floodplain and into surrounding property.

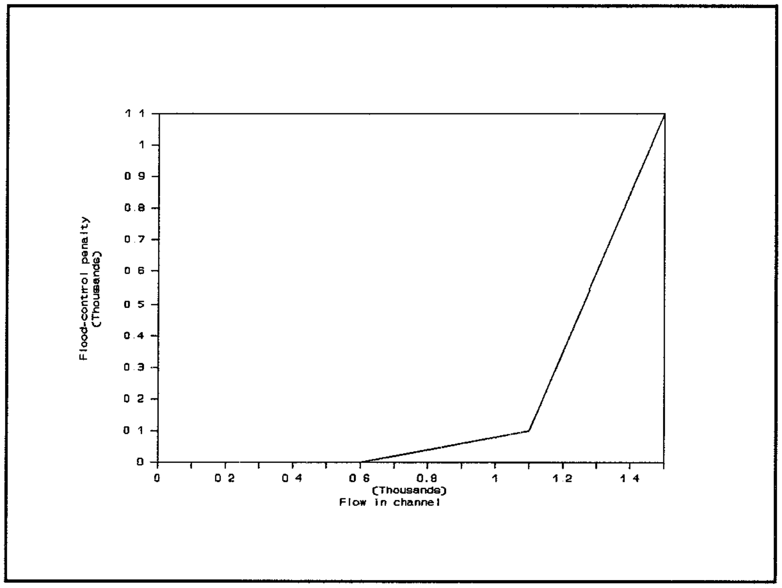

FIGURE C-9 Typical Flood-control Penalty Function

Navigation Penalty Function

A navigation penalty function defines the cost of deviating from flows desired for vessel traffic in a system channel.

Figure C-10 is a typical navigation penalty function. In this example, the penalty is great for flows less than 400 cfs; this represents the minimum desired flow for towing barges in the channel. Between 400 and 600 cfs, the penalty is zero, as this is the desired flow for navigation. Between 600 and 1100 cfs, the penalty increases slightly, representing the increased effort required for navigation. Finally, the penalty increases rapidly if the flow exceeds 1100 cfs. This is the upper limit on desired flow for navigation.

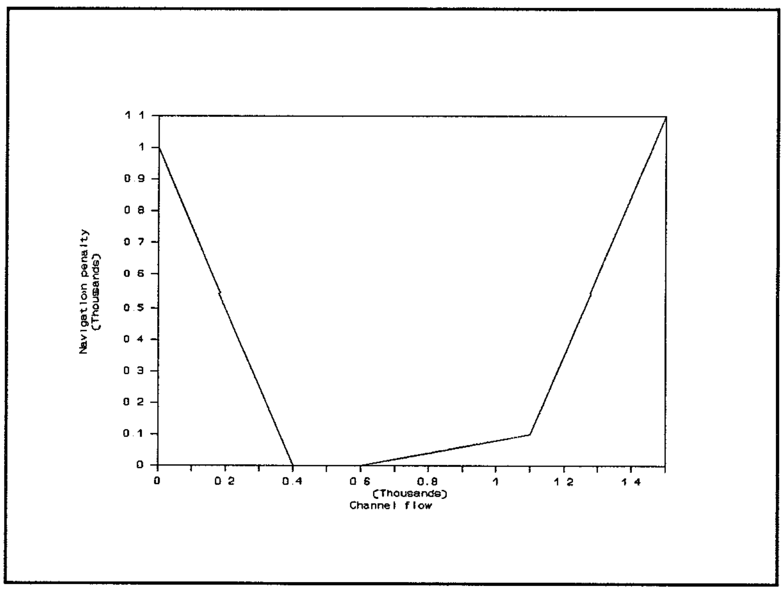

FIGURE C-10 Typical Navigation Penalty Function

Recreation Penalty Functions

A recreation penalty functions may represent the relationship of recreation to reservoir storage or channel flow. Figure C-11 is an example of a typical lake recreation penalty function. In this example, the desired range of active storage for recreation is 40 to 80 kaf. If the reservoir storage is less than 40 kaf, the boat ramps are inaccessible, and recreation is hazardous. If the reservoir storage is more than 80 kaf, the reservoir is in flood operation, and recreation is hazardous. Consequently, the function is shaped as shown.

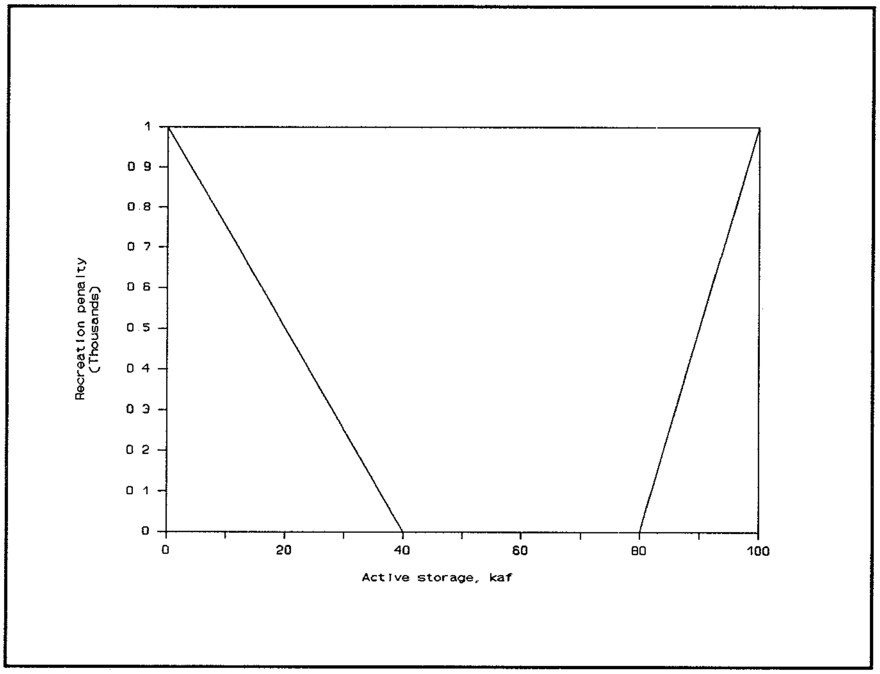

FIGURE C-11 Typical Lake Recreation Penalty Function

Figure C-12 is a typical river recreation penalty function. In this example, the desired range of flow for boating, swimming, and fishing is 400 to 500 cfs. If the flow rate is less than 400 cfs, boating and swimming are dangerous due to shallow depths and fishing is poor. If the flow rate exceeds 500 cfs, recreation is hazardous.

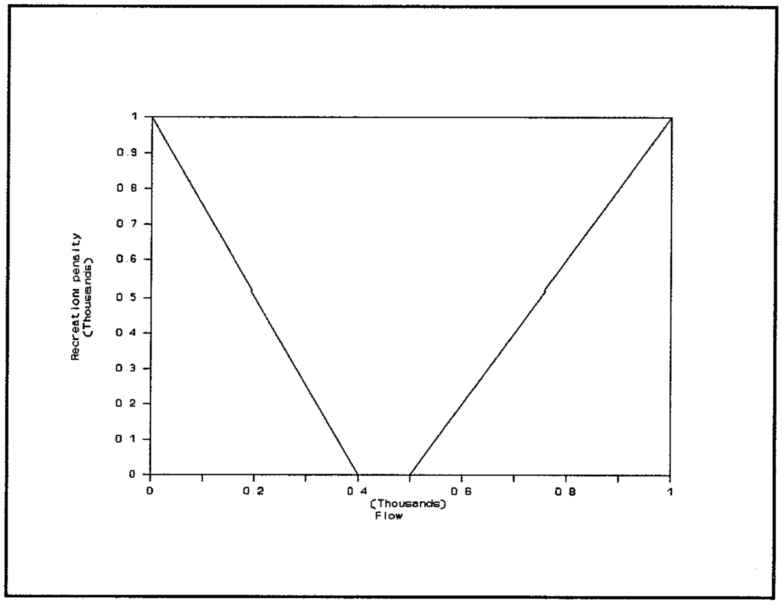

FIGURE C-12 Typical River Recreation Penalty Function

Water-supply Penalty Function

A water-supply penalty function describes desired operation for supply of water for municipal and industrial use or for irrigation. A water-supply penalty function may relate to channel-link flow, simple reservoir-release flow, or diversion flow. Figure C-13 is a typical water-supply penalty function. In this function, the desired flow for water supply is 100 cfs. If the flow is less, demands are not met, so the penalty is great. If the flow exceeds the desired rate, the water is used, but the benefit is not great, as it is not dependable supply.

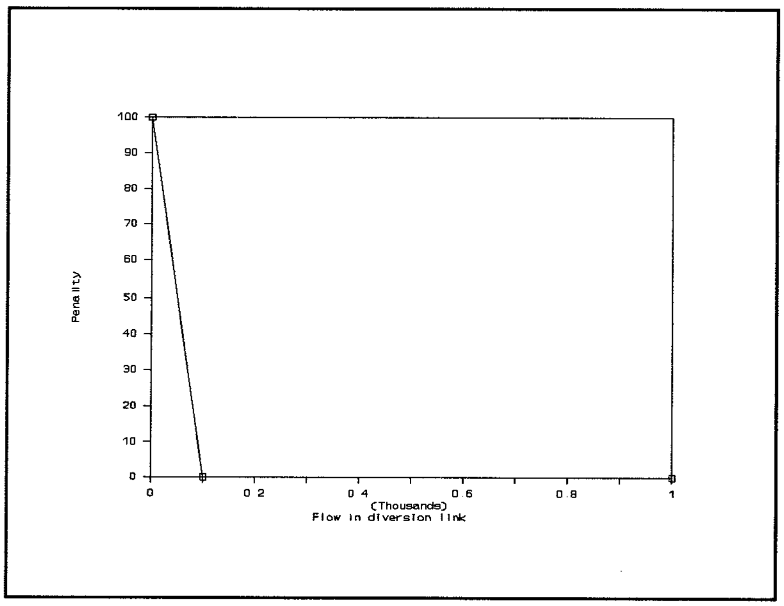

FIGURE C-13 Typical Water-supply Penalty Function

Environmental Penalty Function

An environmental penalty function represents the desired operation for environmental protection. The function may define penalty for flow or penalty for storage or penalty or both. A typical case is illustrated by Figure C-14. In this example, an average monthly flow of 100 cfs is required to preserve wildlife habitat. If the flow is less or more, the habitat is destroyed. In that case, only the desired value is assigned zero penalty. For all other flows, the penalty is positive.

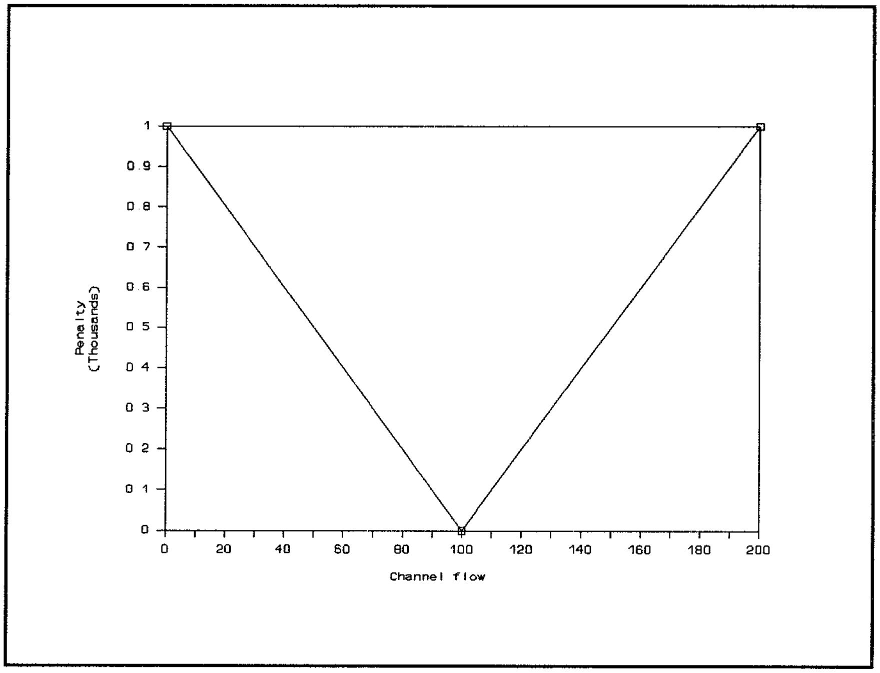

FIGURE C-14 Typical Environmental Penalty Function

Hydropower Penalty Function

A hydropower penalty function is assigned to a hydro-release link only and defines the cost of deviation from desired system operation for energy production. For the proposed model, Figure C-15 illustrates the acceptable form of the function. This function defines penalty as a function of release for a specified head (storage). If the head is less than the optimal head for the generator, the penalty is positive. Likewise, if the release is less than optimal for a specified head, the penalty is positive.

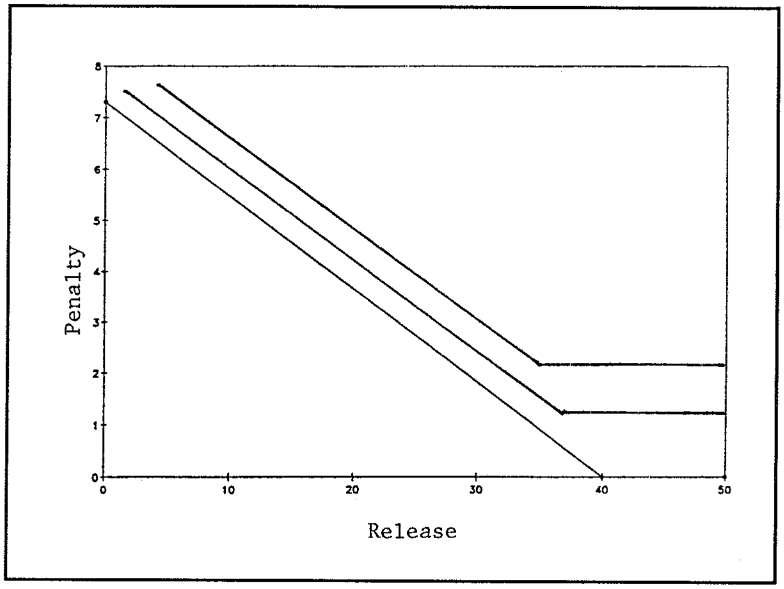

FIGURE C-15 Typical Hydropower Capacity Penalty Function

Combined Penalty Functions

If two or more penalty functions apply to a single stream reach or to a single reservoir, the functions are combined to yield a single penalty function. The combined penalty function then is used in the optimization. For example, a reservoir hydropower capacity penalty function, a reservoir recreation penalty function, and a water supply reservoir penalty function may apply for a reservoir. To combine the functions, the various penalties for a given storage are added. The resulting function is then edited or smoothed to yield a convex function. This convex function then is represented in a piecewise linear fashion for the network. Figure C-16 illustrates this.

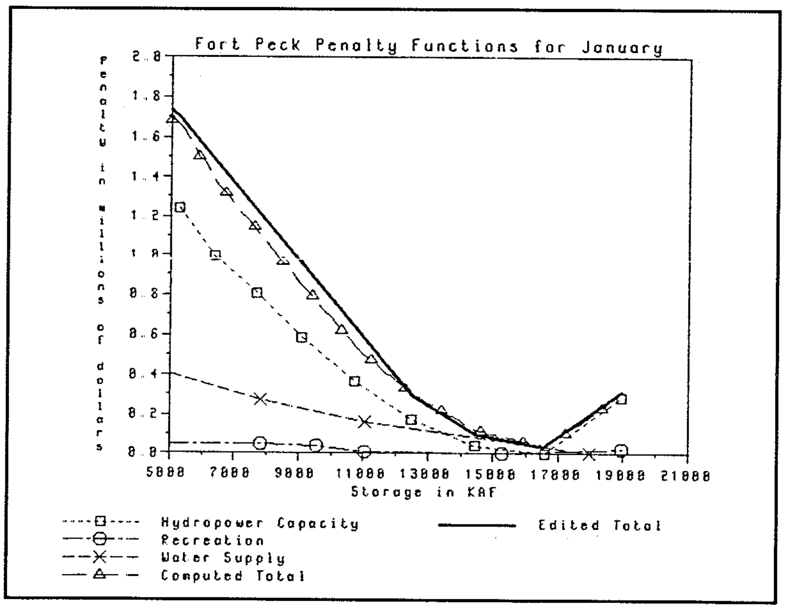

FIGURE C-16 Penalty Functions Combined

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GLOSSARY

ARC Connects two nodes of a network. In network-flow programming, each arc has three parameters: a lower bound, which is the minimal amount that can flow along the arc; an upper bound, which is the maximum amount that can flow along the arc; and a cost for each unit that flows along the arc. Arcs of a generalized network also have an arc multiplier.

CHANNEL-FLOW LINK Represents the flow in a channel reach. A channel-flow link originates at any non-reservoir node and terminates at any network node.

CONSTRAINT Limit the decision variables to their feasible or permissible values.

CONVEX FUNCTION A function $f(X)$ for which the following is true for any two distinct points X_1 and X_2 and for $0<\lambda<1$: $f(\lambda X_1+(1-\lambda)X_2) < \lambda f(X_1)+(1-\lambda)f(X_2)$

DECISION VARIABLE The unknowns which are to be determined from the solution of the model.

DIVERSION LINK Carries flow out of the system. A diversion link originates at any system node and terminates at the sink node.

FINAL-STORAGE LINK Carries flow out of the system, from a reservoir in the last period of analysis. It originates at a reservoir node and terminates at the sink node.

HYDROPOWER RESERVOIR-RELEASE LINK Represents the release from a hydropower reservoir. The penalty function for a hydropower reservoir-release link depends on both the release from the reservoir and the storage in the reservoir.

INFLOW LINK Brings flow into the reservoir-system network. An inflow link originates at the source node and terminates at any system node.

INITIAL-STORAGE LINK Introduces to the network the volume of water initially stored in a system reservoir. The initial-storage link originates at the source node and terminates at a reservoir node in the first period of analysis only.

NETWORK A collection of arcs and nodes.

NETWORK-FLOW PROGRAMMING An optimization procedure for allocating flow along the arcs of a network. Network-flow programming is a special class of linear programming.

NODE The junction of two or more network arcs. The node may represent a system reservoir, demand point, channel junction, diversion point. The sum of flow in arcs originating at a node equals the sum of flow in all arcs terminating at the node.

OBJECTIVE FUNCTION Defines the overall effectiveness of a system as a mathematical function of its decision variables. The optimal solution to the model yields the best value of the objective function, while satisfying all constraints.

PENALTY FUNCTION Defines the penalty for less-than-perfect operation as a function of flow, storage, or both.

PIECEWISE LINEAR APPROXIMATION Is an approximation in which a non-linear function is represented by linear segments, arranged sequentially.

RESERVOIR-STORAGE LINK Represents the volume of water stored in a reservoir at the end of a period. The link originates at any reservoir in a layered, multiple-period network and terminates at the node representing the same reservoir in the period following.

SIMPLE RESERVOIR-RELEASE LINK Represents the total outflow from a non-hydropower reservoir. Flow in the link includes release and spill.

SINK NODE Is the hypothetical absorber of all flow in the network. All diversion links and final-storage links terminate at the sink node.

SOLVER Finds the minimum-cost allocation of flow to the network arcs, subject to the upper and lower bounds on arc flows and to continuity at the network nodes.

SOURCE NODE Is the hypothetical provider of all flow in the network. All inflow links and initial-storage links originate at the source node. No user-defined links terminate at the source node.

APPENDIX D

COLUMBIA RIVER NETWORK MODEL DESCRIPTION

APPENDIX D

COLUMBIA RIVER NETWORK MODEL DESCRIPTION

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COLUMBIA RIVER NETWORK MODEL DESCRIPTION

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APPENDIX D

COLUMBIA RIVER NETWORK MODEL DESCRIPTION

SYSTEM DESCRIPTION *(adapted from EM 1110-2-1701)*

The Columbia River is primarily a snowmelt stream, with greatest runoff in late spring and early summer. Runoff is less during the remainder of the year. The coordinated system includes approximately 75 projects to control the temporal and spatial distribution of water in the basin. Figure D-1 shows the system and the location of these projects.

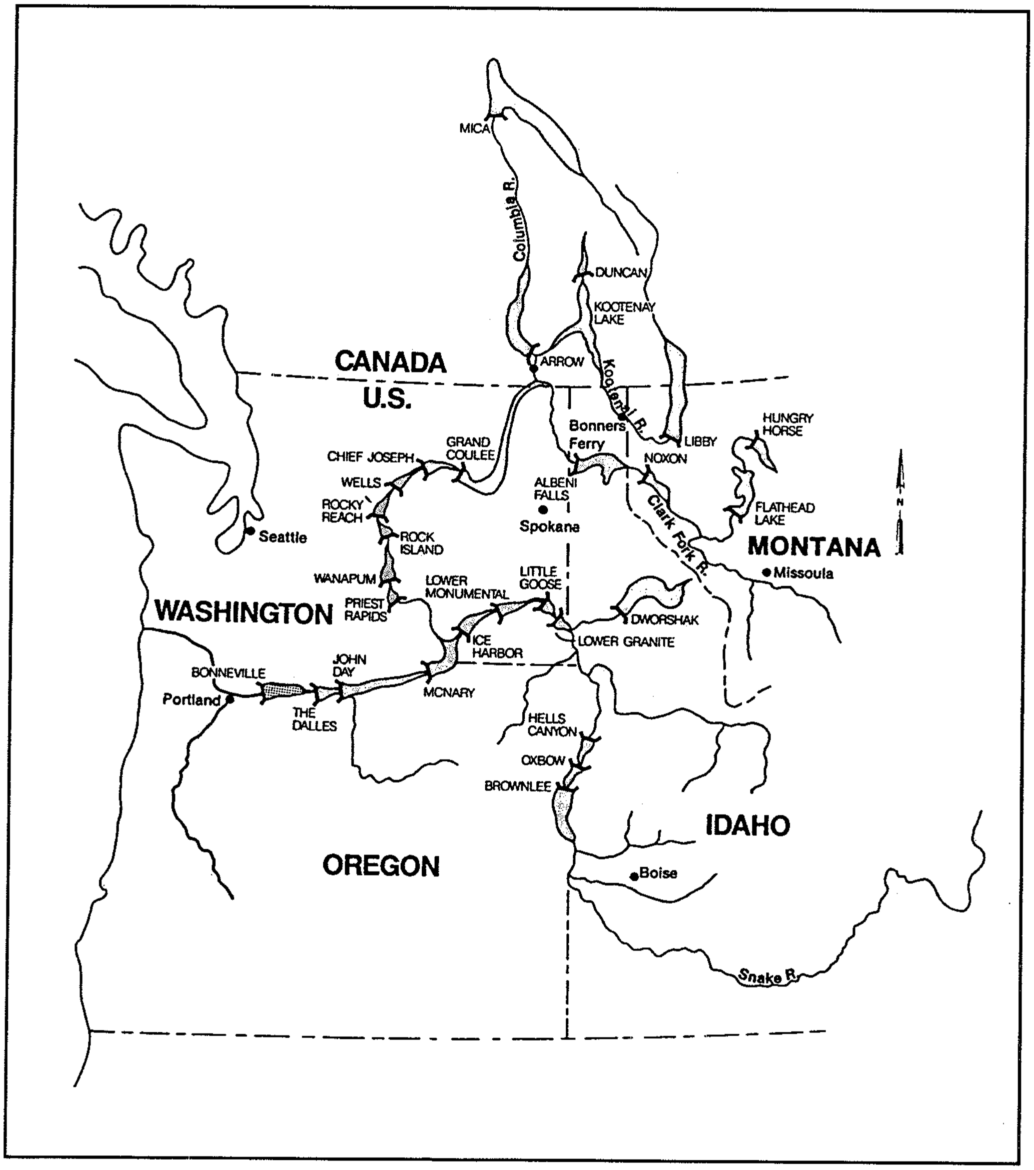

FIGURE D-1 Coordinated Columbia River System

Key system projects were constructed by the Corps of Engineers and the Bureau of Reclamation. Three major headwater reservoirs are in Canada and are operated by the British Columbia Hydro and Power Authority. System reservoirs have 42 million acre ft of storage. This storage represents 30 percent of the average annual runoff of the Columbia River upstream from The Dalles.

Historically, the dominant operation purposes are power generation and flood control. More recently, preservation of anadromous fish runs are equally important. The Bonneville Power Administration markets power generated from Corps and Bureau projects. The seasonal power demand is out of phase with the runoff supply. Consequently, storage is drafted from late summer through early spring to generate power. The releases also provide flood-control space for the subsequent runoff. Other operation purposes include navigation, irrigation, recreation, and fish and wildlife protection.

NETWORK REPRESENTATION

Summary

To analyze operation of the Columbia River system with HEC-PRM, Hydrologic Engineering Center's prescriptive reservoir model (USACE, 1990), the spatial configuration of the system is represented with a network. For multiple-period operating studies, the network is replicated. The replicates are interconnected to model the time variance of system storage.

Figure D-2 shows the network representation for Phase I studies. This network includes major projects on the Columbia, Snake, Clearwater, and Pend Oreille Rivers. For a single period, the network consists of 21 nodes and 20 links. Thirty storage or pondage projects are represented by 18 nodes. Three nodes represent non-reservoir system control points at which penalty functions are specified. Reservoir inflows or incremental local flows are introduced into the system at each of the 21 nodes.

Network Nodes

For the Phase I analysis, the network representation includes the following nodes:

Libby. This node represents Libby reservoir. An initial-storage link terminates at the node in the first period of analysis. An inflow link terminates at the node in each period; the link flow equals inflow to Libby. Reservoir storage links originate and terminate at the node each period. The upper bound of these links equals the capacity of Libby reservoir. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The hydropower penalty function, simplified by assuming constant head for Phase I, is associated with flow in the arcs representing this link.

Bonners Ferry. This node is included to impose flood control penalties for operation downstream from Libby reservoir. The penalties cannot be combined with those at Libby due to the local runoff downstream from the reservoir. An inflow link terminates at the Bonners Ferry node in each period; the link flow equals incremental local flow upstream of Bonners Ferry, but downstream of Libby reservoir.

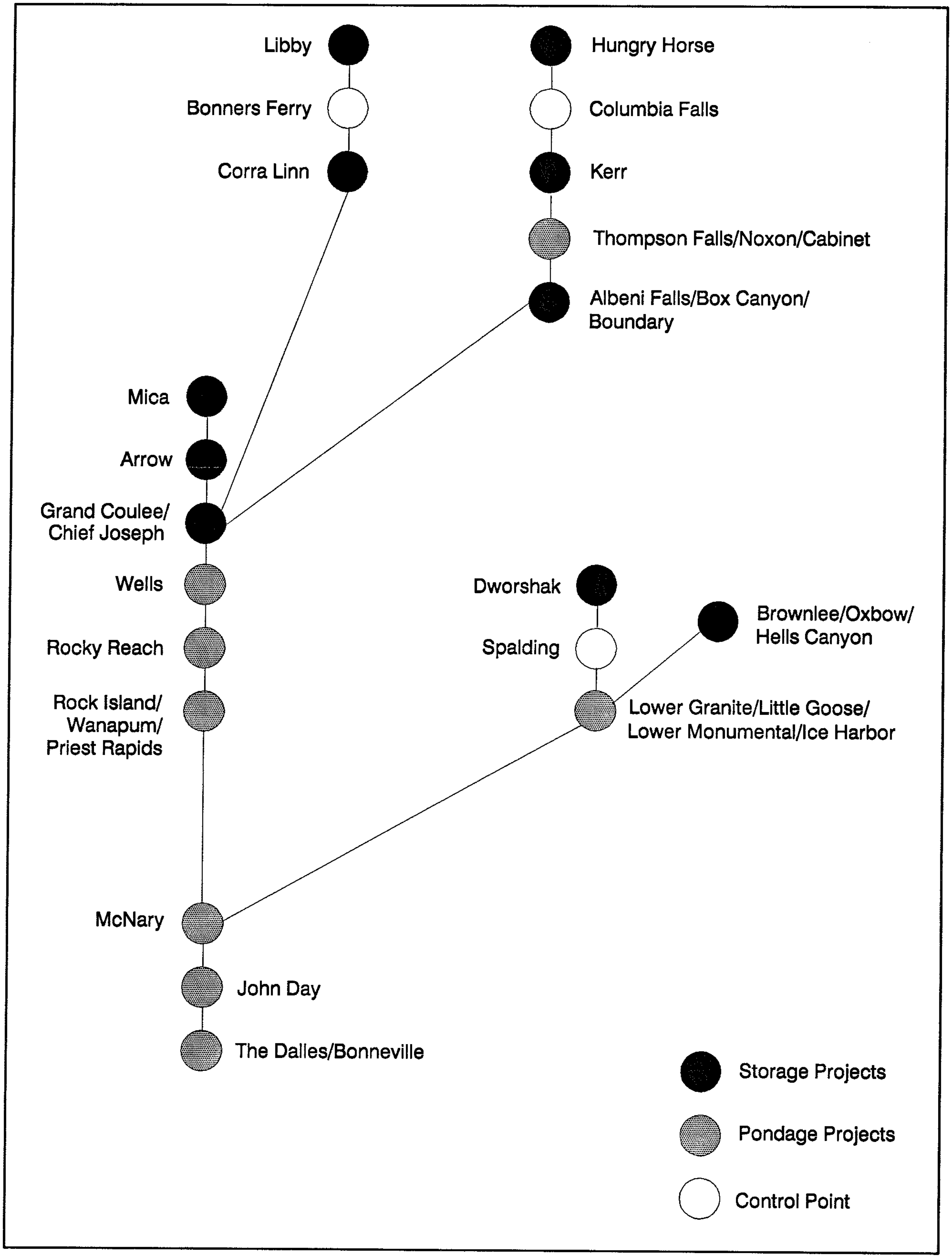

FIGURE D-2 Single-period Link-node Representation of Columbia River System

Corra Linn. This node represents Corra Linn reservoir (Kootenay Lake). An initial-storage link terminates at the node in the first period of analysis. An inflow link terminates at the node in each period; the link flow equals incremental local flow upstream of Corra Linn but downstream of Bonners Ferry. Reservoir storage links originate and terminate at the node each period and represent hydropower capacity and flooding. The upper bound of these links equals the capacity of Corra Linn. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The hydropower penalty function for Corra Linn, simplified by assuming constant head, is associated with flow on the arcs representing this link. The penalty functions for Upper Bonnington, Lower Bonnington, South Slocan, and Brilliant reservoirs are associated with the flow in the Corra Linn release link.

Hungry Horse. This node represents Hungry Horse reservoir. An initial-storage link terminates at the node in the first period of analysis. An inflow link terminates at the node in each period; the link flow equals inflow to Hungry Horse. Reservoir storage links originate and terminate at the node each period. The upper bound of these links equals the capacity of Hungry Horse reservoir. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The Hungry Horse hydropower penalty function, simplified by assuming constant head, is associated with flow on the arcs representing this link.

Columbia Falls. This node is included to impose penalties for operation downstream of Hungry Horse reservoir. The penalties cannot be combined with those of Hungry Horse due to the local runoff downstream from the reservoir. An inflow link terminates at the Columbia Falls node in each period; the link flow equals incremental local flow upstream of Columbia Falls but downstream of Hungry Horse reservoir.

Kerr. This node represents Kerr reservoir (Flathead Lake). An initial-storage link terminates at the node in the first period of analysis. An inflow link terminates at the node in each period; the link flow equals incremental local flow upstream of Kerr but downstream of Columbia Falls. Reservoir storage links originate and terminate at the node each period. The upper bound of these links equals the capacity of Kerr reservoir. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The Kerr hydropower penalty function, simplified by assuming constant head, is associated with flow on the arcs representing this link.

Thompson Falls/Noxon/Cabinet. This node represents combined operation of the Thompson Falls, Noxon, and Cabinet Gorge pondage projects. Penalties for operation of these cannot be combined with those of Kerr because of the impact of Clark fork flows and additional inflow downstream from Kerr. An inflow link terminates at the node in each period; the link flow equals incremental local flow upstream from Cabinet Gorge but downstream of Kerr reservoir including Clark Fork flows. Because these projects do not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is assumed equal to inflow and is modeled with a channel-flow link.

Albeni Falls/Box Canyon/Boundary. This node represents combined operation of Albeni Falls, Box Canyon, and Boundary reservoirs. Box Canyon and Boundary are considered pondage projects, with no monthly carry-over storage. Therefore, the capacity of the combined project equals the capacity of Albeni Falls. This is represented with reservoir storage links which originate and terminate at the node each period. The upper bound of these links equals the capacity of Albeni Falls, Box Canyon and Boundary. An initial-storage link terminates at the node in the first period of analysis; the flow in this link equals initial storage of Albeni Falls. The incremental flow between the projects is minor, so it is ignored for this analysis. Therefore, an inflow link with flow equal to the incremental flow upstream of Boundary reservoir but below Cabinet Gorge terminates at the node in each period. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The hydropower penalty function, simplified by assuming constant head, is associated with flow on the arcs representing this link. This penalty function represents power generated at all three projects.

Dworshak. This node represents Dworshak reservoir. An initial-storage link terminates at the node in the first period of analysis. An inflow link terminates at the node in each period; the link flow equals inflow to Dworshak. Reservoir storage links originate and terminate at the node each period. The upper bound of these links equals the capacity of Dworshak reservoir. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The Dworshak hydropower penalty function, simplified by assuming constant head, is associated with flow on the arcs representing this link.

Spalding. This node is included to impose penalties for operation downstream of Dworshak reservoir. The penalties cannot be combined with those of Dworshak due to the local runoff downstream of the reservoir. An inflow link terminates at the Spalding node in each period; the link flow equals incremental local flow upstream of Spalding but downstream of Dworshak reservoir.

Brownlee/Oxbow/Hells Canyon. This node represents combined operation of Brownlee, Oxbox, and Hells Canyon reservoirs. Of these, only Brownlee is a storage project. Therefore, the capacity of the combined project equals the capacity of Brownlee. This is represented with reservoir storage links which originate and terminate at the node each period; the upper bound of these links equals the capacity of Brownlee, Oxbow, and Hells Canyon. An initial-storage link terminates at the node in the first period of analysis; the flow in this link equals initial storage of Brownlee. The incremental flow between the projects is minor, so it is ignored for this analysis. Therefore, an inflow link with flow equal the Hells Canyon inflow terminates at the node in each period. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The hydropower penalty function, simplified by assuming constant head, is associated with flow on the arcs representing this link. This penalty function represents power generated at all three projects.

Lower Granite/Little Goose/Lower Monumental/Ice Harbor. This node represents combined operation of the Lower Granite, Little Goose, Lower Monumental, and Ice Harbor projects. An inflow link terminates at the node in each period; the link flow equals incremental local flow upstream of Ice Harbor but downstream of Spalding and Hells Canyon. This includes Salmon and Grande Ronde River flows. Because the projects do not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is assumed equal to inflow and is modeled with a channel-flow link.

Mica. This node represents Mica reservoir. An initial-storage link terminates at the node in the first period of analysis. An inflow link terminates at the node in each period; the link flow equals inflow to Mica. Reservoir storage links originate and terminate at the node each period. The upper bound of these links equals the capacity of Mica reservoir. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The system will not optimize storage or release from MICA. For Phase I, storage and release penalty functions have zero unit cost.

Arrow. This node represents Arrow reservoir. An initial-storage link terminates at the node in the first period of analysis. An inflow link terminates at the node in each period; the link flow equals incremental local flow upstream of Arrow but below Mica. Reservoir storage links originate and terminate at the node each period. The capacity of these links equals the capacity of Arrow reservoir. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The system will not optimize storage or release Arrow. For Phase I, storage and release penalty functions have zero unit cost.

Grand Coulee/Chief Joseph. This node represents combined operation of Grand Coulee and Chief Joseph reservoirs. Grand Coulee is a storage project, and Chief Joseph is a pondage project. Therefore, the capacity of the combined project equals the capacity of Grand Coulee. The storage is represented with reservoir storage links which originate and terminate at the node each period; the upper bound of these links equals the capacity of Grand Coulee. An initial-storage link terminates at the node in the first period of analysis; the flow in this link equals initial storage of Grand Coulee. An inflow link terminates at the node in each period; the link flow equal the incremental local flow above Chief Joseph but downstream from Arrow, Corra Linn and Boundary reservoirs. For the Phase I analysis, a simple reservoir-release link originates at the node each period. The hydropower penalty function, simplified by assuming constant head, is associated with flow on the arcs representing this link. This penalty function represents power generated at both projects.

Wells. This node is included to impose penalties for operation of Wells reservoir. The penalties cannot be combined with those of Grand Coulee/Chief Joseph due to the impact of local runoff downstream from the reservoirs and the Methow and Okanogan River flows. An inflow link terminates at the Wells node in each period; the link flow equals incremental local flow upstream of Wells but downstream of Chief Joseph reservoir including Methow and Okanogan River flows. Because this project does not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is assumed equal to inflow and is modeled with a channel-flow link.

Rocky Reach. This node is included to impose penalties for operation of Rocky Reach reservoir. The penalties cannot be combined with those of Wells reservoir due to the impact of local runoff downstream of Wells. An inflow link terminates at the Rocky Reach node in each period; the link flow equals incremental local flow upstream of Rocky Reach but downstream of Wells reservoir. Because this project does not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is assumed equal to inflow and is modeled with a channel-flow link.

Rock Island/Wanapum/Priest Rapids. This node represents combined operation of the Rock Island, Wanapum, and Priest Rapids pondage projects. Penalties for operation of these cannot be combined with those of Rocky Reach reservoirs due to the impact of

Wenatchee River flows and additional inflow downstream of Rocky Reach. An inflow link terminates at the Rock Island/Wanapum/Priest Rapids node in each period; the link flow equals incremental local flow upstream of Priest Rapids but downstream of Rocky Reach reservoir. Because these projects do not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is considered equal inflow and is modeled with a channel-flow link.

McNary. This node is included to impose penalties for operation downstream of McNary reservoir. An inflow link terminates at the McNary node in each period; the link flow equals incremental local flow upstream of McNary but downstream of Priest Rapids and Ice Harbor reservoirs, including Yakima and Naches River flows. Because this project does not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is assumed equal to inflow and is modeled with a channel-flow link.

John Day. This node is included to impose penalties for operation downstream of John Day reservoir. These penalties cannot be combined with those of McNary due to the impact of local runoff downstream of McNary and to the Umatilla and John Day River and Willow creek flows. An inflow link terminates at the John Day node in each period; the link flow equals incremental local runoff downstream of McNary including Umatilla and John Day River and Willow creek flows. Because this project does not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is assumed equal to inflow and is modeled with a channel-flow link.

The Dalles/Bonneville. This node is represents the combined operation of The Dalles and Bonneville pondage projects. An inflow link terminates at The Dalles/Bonneville node in each period; the link flow equals incremental local flow upstream of Bonneville but downstream from John Day reservoir. Because these projects do not have monthly carry-over storage, no initial-storage link or reservoir storage links are included. The reservoir release is assumed equal to inflow and is modeled with a channel-flow link.

Network Links

For the Phase I analysis, the network representation includes the following links:

Inflow links. Inflow links introduce reservoir inflow and incremental local flow at all 21 network nodes. For those nodes that represent combined storage or pondage projects, the flow in these inflow links equals the sum of the inflow for the component projects as described above. For each period of analysis, the network has 21 inflow links.

Initial-storage links. An initial-storage link carries flow equal the initial storage for each of the storage projects. The links terminate at the nodes representing Libby, Corra Linn, Hungry Horse, Kerr, Albeni Falls/Box Canyon/Boundary, Mica, Arrow, Grand Coulee/Chief Joseph, Dworshak, and Brownlee/Oxbow/Hells Canyon.

Diversion links. The network ends with a diversion link at The Dalles/Bonneville node. This link carries flow out of the network at its downstream end. For the Columbia system, the penalty associated with this link is the penalty assigned to The Dalles/Bonneville release. Irrigation diversions are not optimized but are included within the adjusted inflow data.

Final-storage links. A final storage link originates at each reservoir node in the last period of analysis. Final storage links are included from nodes representing Libby, Corra Linn, Hungry Horse, Kerr, Albeni Falls/Box Canyon/Boundary, Mica, Arrow, Grand Coulee/Chief Joseph, Dworshak, and Brownlee/Oxbow/Hells Canyon reservoirs.

Channel-flow links. The network includes the following channel-flow links:

1. Bonners Ferry to Corra Linn;
2. Columbia Falls to Kerr;
3. Thompson Falls/Noxon/Cabinet to Albeni Falls/Box Canyon/Boundary;
4. Wells to Rocky Reach;
5. Rocky Reach to Rock Island/Wanapum/Priest Rapids;
6. Rock Island/Wanapum/Priest Rapids to McNary;
7. Spalding to Lower Granite/Little Goose/Lower Monumental/Ice Harbor;
8. Lower Granite/Little Goose/Lower Monumental/Ice Harbor to McNary;
9. McNary to John Day;
10. John Day to The Dalles/Bonneville.

Here, the reservoir release links for the pondage projects are represented as channel-flow links.

Simple reservoir-release links. A reservoir-release link connects the node representing each storage reservoir with the next downstream node. Thus simple reservoir-release links originate at each of the nodes representing Libby, Corra Linn, Hungry Horse, Kerr, Albeni Falls/Box Canyon/Boundary, Mica, Arrow, Grand Coulee/Chief Joseph, Dworshak, and Brownlee/Oxbow/Hells Canyon. For Phase I analysis, the hydropower penalty function for each storage project is associated with flow in the reservoir-release link, as head is assumed constant.

Reservoir-storage links. Reservoir-storage links model the dynamic effects of system operation: they represent the carry over of water from one period to the next. A reservoir-storage link originates each period at each of the nodes representing Libby, Corra Linn, Hungry Horse, Kerr, Albeni Falls/Box Canyon/Boundary, Mica, Arrow, Grand Coulee/Chief Joseph, Dworshak, and Brownlee/Oxbow/Hells Canyon and terminates the following period at the corresponding node in the replicate network.

SYSTEM DATA

Reservoir-inflow and Local-flow Data

Reservoir-inflow and local-flow data are developed by NPD staff for the NPD HYSSR model. These were provided to HEC in computer-readable form. The data provided are "natural" flows (in CFS), from which "local-incremental" flows (in kaf/month) required for HEC-PRM were developed as shown in Table D-1. The flow data are shown in Appendix I.

TABLE D-1
Columbia System Flow Data Description

Node	Flow Data Description
Libby	Inflow to Libby Res. (Corps ID 003)
Bonners Ferry	Local flow between Libby and Bonners Ferry (Corps IDs 003 and 400)
Corra Linn	Local flow between Bonners Ferry and Corra Linn (Corps IDs 400 and 006)
Hungry Horse	Inflow to Hungry Horse Res. (Corps ID 010)
Columbia Falls	Local flow between Hungry Horse and Columbia Falls (Corps IDs 010 and 401)
Kerr	Local flow between Columbia Falls and Kerr Res. (Corps IDs 401 and 011)
Thompson Falls/Noxon/Cabinet	Local flow between Kerr Res. and Cabinet Res. (Corps IDs 011 and 056)
Albeni Falls/Box Canyon/Boundary	Local flow between Cabinet Res. and Boundary Res. (Corps IDs 056 and 058)
Dworshak	Inflow to Dworshak Res. (Corps ID 031)
Spalding	Local inflow between Dworshak Res and Spalding (Corps IDs 031 and 402)
Brownlee/Oxbow/Hells Canyon	Inflow to Hells Canyon Res. (Corps ID 084)
Lower Granite/Little Goose/ Lower Monumental/Ice Harbor	Local inflow between Hells Canyon, Spalding, and Ice Harbor (Corps IDs 084, 402 and 079)
Mica	Inflow to Mica Res. (Corps ID 001)
Arrow	Local flow between Mica and Arrow (Corps IDs 001 and 002)
Grand Coulee/Chief Joseph	Local flow between Arrow, Corra Linn, Boundary and Chief Joseph (Corps IDs 002, 006, 058 and 066)
Wells	Local flow between Chief Joseph and Wells (Corps IDs 066 and 067)
Rocky Reach	Local flow between Wells and Rocky Reach (Corps IDs 067 and 068)
Rock Island/Wanapum/Priest Rapids	Local flow between Rocky Reach and Priest Rapids (Corps IDs 068 and 071)
McNary	Local flow between Priest Rapids, Ice Harbor and Mc Nary (Corps IDs 071, 079 and 080)
John Day	Local flow between Mc Nary and John Day (Corps IDs 080 and 081)
The Dalles/Bonneville	Local flow between John Day and Bonneville (Corps IDs 081 and 083)

Inflow and Local Flow Depletions

According to NPD staff, the provided natural reservoir inflow and local flow data have been adjusted for 1980 level depletions. Thus, no further adjustments are required for use with HEC-PRM.

Reservoir Evaporation Data

According to NPD staff, flow data are adjusted to account for river and lake evaporation. Therefore, for analysis with HEC-PRM, no further adjustment or accounting is required.

With adjustments prior to analysis, lake evaporation is assumed constant with respect to lake area. The impact of assuming constant evaporation in the network optimization problem reduces to a pure minimum-cost network flow problem. Typically such problems can be solved in one-half to one-quarter the time required to solve the generalized minimum-cost network flow problem.

Hydraulic Capacities

For HEC-PRM, physical limits on reservoir storage must be defined explicitly. For the storage reservoirs of the Columbia system, the minimum and maximum capacities are shown in columns 2 and 4 of Table D-2.

For analysis of monthly operation of reservoirs with flood-control storage allocation, operation may be limited to the conservation pool. This forces the model to keep the flood-control pool empty on a monthly basis. The conservation pool capacities of the Columbia system reservoirs are shown in column 3 of Table D-2.

Initial Storage

Initial storage must be defined for each system reservoir. These values depend on the flow sequence to be analyzed. For analysis of the critical period, July 1928 to February 1932, the initial storages were set at full pool, they are shown in column 2 of Table D-3. For Phase I model validation the period of September 1969 through July 1975 was selected. Initial storages for the validation period are shown in column 3 of Table D-3. These data were derived by NPD staff with the HYSSR model run in a continuous mode.

PENALTY FUNCTIONS

Goals of and constraints on Columbia River reservoir system operation are represented with penalty functions. These functions represent the economic, social, and environmental costs associated with failure to meet operation goals. The costs are related to flow or storage or both at selected system locations. For the Phase I study, functions are developed by the Institute for Water Resources (IWR). These functions are presented in a separate document distributed by IWR.

TABLE D-2
Storage Capacities

Reservoir (1)	Top Inactive Storage 1000 acre-ft (2)	Top Conservation Storage 1000 acre-ft (3)	Maximum Storage 1000 acre-ft (4)
Libby	889.9	5,869.4	5,869.4
Corra Linn	144.0	817.0	817.0
Hungry Horse	486.0	3,647.1	3,771.8
Kerr	572.3	1,791.0	1,791.0
Albeni Falls	384.0	1,539.2	1,539.2
+			
Box Canyon	9.8	17.0	17.0
+			
Boundary	68.3	96.3	96.3
Sub Total	462.1	1,652.5	1,652.5
Mica	13,075.5	20,075.5	20,075.5
Arrow	219.3	7,327.3	7,327.3
Grand Coulee	3,921.9	9,107.4	9,107.4
+			
Chief Joseph	400.8	593.1	593.1
Sub Total	4,322.7	9,700.5	9,700.5
Dworshak	1,452.2	3,468.0	3,468.0
Brownlee	444.8	1,420.1	1,464.7
+			
Oxbow	48.8	59.8	59.8
+			
Hells Canyon	155.0	178.0	178.0
Sub Total	648.6	1657.9	1,702.5

TABLE D-3
Initial Storage

Reservoir (1)	**Critical Period Analysis July 1928 1000 acre-ft** (2)	**Validation Analysis August 1969 1000 acre-ft** (3)
Libby	5,869.4	5,869.4
Corra Linn	570.0	570.0
Hungry Horse	3,647.1	3,647.9
Kerr	1,791.0	1,789.7
Albeni Falls	1,539.2	1,539.2
+		
Box Canyon	17.0	17.0
+		
Boundary	96.3	96.3
Sub Total	1,652.5	1,652.5
Mica	20,075.5	20,075.5
Arrow	7,327.3	7,327.3
Grand Coulee	9,107.4	9,107.4
+		
Chief Joseph	593.1	593.1
Sub Total	9,700.5	9,700.5
Dworshak	3,468.0	3,468.0
Brownlee	1,420.1	1,420.1
+		
Oxbow	59.8	59.8
+		
Hells Canyon	178.0	178.0
Sub Total	1,657.9	1,657.9

REFERENCES

U.S. Army Corps of Engineers (1990). *Missouri River System Analysis Model: Phase I.* Hydrologic Engineering Center, Davis, CA.

EXHIBIT D-1 System Inflows

Location: Libby Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928	271	221	278	460	2651	1866	1509	542	301	371	215	81
1929	135	134	156	210	1201	2165	858	455	279	217	138	78
1930	133	151	154	624	1197	2013	1118	506	307	239	182	73
1931	145	119	142	204	1152	1327	665	340	261	197	159	76
1932	121	160	239	507	1896	2709	1053	516	333	273	270	104
1933	184	129	174	454	1567	3116	1646	653	467	537	509	262
1934	380	266	377	1648	2671	1809	874	443	281	238	313	98
1935	196	213	204	369	1488	2315	1490	621	320	236	185	78
1936	129	95	165	647	1789	1402	597	336	230	185	135	66
1937	103	108	130	225	1255	1659	900	431	268	267	325	97
1938	194	142	195	666	2061	2608	1097	415	298	268	200	78
1939	178	117	200	573	1622	1385	1064	407	274	330	292	117
1940	153	148	206	485	1668	1387	618	352	329	319	216	91
1941	157	127	207	498	1095	1094	561	340	467	484	333	207
1942	217	163	172	567	1816	2210	1732	704	411	327	250	103
1943	160	170	199	1157	1369	1963	1812	625	324	289	215	79
1944	140	128	139	237	973	1237	536	361	280	263	188	65
1945	134	119	136	180	1162	1913	1072	419	330	277	248	93
1946	165	134	201	659	2347	2425	1318	557	451	341	222	108
1947	159	186	275	712	2464	2101	1129	514	409	778	468	140
1948	201	167	189	561	2750	3266	1165	717	375	304	229	79
1949	154	151	213	605	1984	1368	663	425	295	263	265	112
1950	161	160	236	437	1469	2989	1829	661	362	441	393	189
1951	266	337	254	711	2705	2272	2081	754	582	665	380	134
1952	260	215	205	877	1889	1842	1166	550	344	264	181	82
1953	217	197	183	333	1398	2642	1589	619	346	294	253	100
1954	152	183	208	376	2345	2921	2569	916	590	392	341	130
1955	192	153	164	259	1082	2860	1765	642	354	432	392	137
1956	232	167	238	803	2758	3048	1507	604	341	328	240	100
1957	139	144	205	348	2540	1879	811	436	280	268	218	87
1958	151	149	192	367	2284	1702	930	442	329	317	252	113
1959	214	147	195	570	1785	3297	1757	708	891	686	478	180
1960	237	225	327	772	1311	2364	1399	586	373	288	248	88
1961	173	210	227	412	2303	3534	1020	574	389	444	281	103
1962	181	220	173	685	1445	2176	1089	565	335	318	294	125
1963	157	237	209	379	1520	2346	1569	621	386	307	268	95
1964	170	138	148	308	1492	3055	1476	602	415	484	321	109
1965	198	188	215	581	1587	2706	1410	676	453	419	328	119
1966	214	187	214	599	1945	2565	1479	592	353	282	242	114
1967	195	190	176	285	1566	3831	1819	657	355	300	251	90
1968	191	190	236	239	1464	2517	1413	605	440	410	330	110
1969	197	152	204	903	2420	2821	1545	557	351	348	251	92
1970	142	155	168	212	1247	1959	821	414	305	278	203	89
1971	175	253	184	478	2414	2825	1545	724	381	291	237	85
1972	155	176	385	401	2105	3690	1801	877	442	511	385	111
1973	188	168	207	312	1362	1905	993	455	343	287	320	122
1974	334	267	285	694	1738	4066	1942	785	413	290	268	104
1975	168	196	206	262	1231	2413	1431	640	459	361	392	213
1976	206	218	244	572	2285	1776	1661	1118	591	348	248	104
1977	167	147	167	329	964	1214	518	465	407	274	188	95
1978	210	165	244	482	1557	2276	1424	550	489			

Location: Bonners Ferry Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							245	247	228	77	108	156
1929	52	48	100	211	584	319	66	15	26	46	55	27
1930	43	58	102	448	409	343	115	35	34	55	53	20
1931	41	53	95	202	516	190	81	42	40	49	57	18
1932	51	87	193	524	1042	635	201	83	55	50	118	81
1933	93	60	101	450	938	1076	386	109	72	105	219	197
1934	387	245	342	1030	801	338	123	63	41	60	216	49
1935	147	147	144	337	918	610	201	79	58	57	50	21
1936	57	26	83	525	748	308	85	54	50	38	34	27
1937	22	31	46	220	706	530	152	61	46	38	118	50
1938	117	68	140	652	950	609	206	61	38	45	45	24
1939	63	42	96	394	624	304	129	62	41	33	46	36
1940	42	55	128	329	516	215	53	32	22	24	40	21
1941	41	36	89	230	352	188	73	33	65	138	137	183
1942	98	69	88	414	636	580	293	87	41	45	75	37
1943	52	55	96	975	790	696	325	106	39	34	37	22
1944	44	35	34	97	255	163	68	33	29	33	40	16
1945	53	53	55	116	681	397	116	42	37	51	85	38
1946	73	48	145	556	1012	602	213	66	51	69	75	63
1947	118	147	251	637	1066	456	138	65	52	261	195	64
1948	118	96	122	521	1202	878	246	127	65	61	50	26
1949	50	59	89	613	1099	342	91	42	29	52	111	60
1950	67	89	213	482	1106	1072	408	105	33	120	183	139
1951	197	362	169	543	1115	493	201	93	77	173	118	71
1952	81	86	95	760	936	437	233	96	52	43	45	17
1953	120	167	111	333	902	588	177	78	44	35	53	30
1954	41	64	120	436	1351	917	477	137	85	75	100	44
1955	59	46	52	170	774	856	288	95	52	133	213	95
1956	187	94	171	864	1464	710	237	102	63	65	46	30
1957	31	42	145	335	1151	370	122	54	36	44	42	21
1958	47	73	120	355	825	214	85	32	31	49	106	61
1959	165	89	96	588	943	772	248	60	120	187	201	100
1960	87	108	225	634	757	576	168	71	37	53	89	36
1961	90	181	196	396	1287	827	152	27	25	25	50	31
1962	67	52	70	508	725	418	116	67	45	61	120	81
1963	113	159	155	352	690	411	142	70	32	32	69	46
1964	88	66	63	283	906	818	171	72	47	40	67	46
1965	95	104	136	591	959	670	161	47	36	-38	-6	34
1966	223	23	14	517	879	483	42	-34	-44	9	38	36
1967	103	43	14	174	1046	913	104	-25	-33	14	57	77
1968	188	112	164	153	727	385	112	38	43	77	131	128
1969	362	283	129	926	1169	447	287	62	-8	26	31	38
1970	161	56	39	110	849	396	60	-16	-19	13	43	97
1971	328	319	17	468	1320	577	181	25	-3	30	158	108
1972	274	308	629	384	1242	789	245	92	-8	36	85	147
1973	287	141	88	212	624	276	34	-44	4	3	109	74
1974	506	159	257	741	1153	1349	357	98	10	63	116	26
1975	54	111	111	206	1123	935	192	42	12	8	109	190
1976	210	140	99	540	1195	472	116	67	45	3	56	19
1977	41	12	-8	154	244	46	-13	-37	-48	22	46	44
1978	-34	-23	177	395	917	457	92	17	17			

Location: Corra Linn Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							1591	524	196	361	196	-36
1929	100	70	174	227	1171	2034	994	620	305	183	97	70
1930	39	143	131	716	1227	1627	1246	697	374	213	150	56
1931	133	118	179	317	1538	1620	1009	552	415	187	192	88
1932	151	150	391	636	1994	2753	1529	724	306	267	331	159
1933	240	140	217	414	1578	3396	2585	999	405	510	475	232
1934	384	243	311	1287	2810	2317	1177	614	338	231	389	132
1935	247	244	236	339	1511	2585	1925	793	401	232	168	78
1936	156	100	164	763	2277	1929	1033	538	280	177	120	80
1937	89	131	114	264	1205	1899	1135	537	331	377	467	143
1938	258	163	295	713	1910	2479	1383	513	424	293	207	98
1939	204	119	208	724	2085	1597	1323	613	341	530	349	180
1940	217	202	333	640	1894	1710	969	557	476	414	229	111
1941	181	152	317	748	1485	1467	901	566	694	656	438	271
1942	248	193	199	532	1611	2012	1633	707	336	249	208	99
1943	146	142	204	1030	1333	2110	1959	713	305	289	192	87
1944	149	117	125	338	1213	1407	688	556	370	320	227	79
1945	167	149	179	233	1607	2185	1163	491	310	221	233	96
1946	187	171	261	693	2618	2781	1651	709	429	246	206	121
1947	184	224	316	728	2407	2331	1454	595	387	747	426	131
1948	196	186	200	507	1654	3658	1312	773	373	310	230	84
1949	118	141	205	591	2411	1559	836	537	326	240	296	153
1950	203	192	303	461	1358	3111	2262	809	399	541	443	221
1951	352	379	285	641	2462	2293	2171	756	421	525	311	136
1952	196	193	239	767	2226	2175	1292	598	303	186	111	77
1953	259	210	206	340	1697	2673	1856	789	379	358	337	134
1954	258	231	260	403	2231	2865	3044	1163	620	357	428	162
1955	218	163	164	355	1033	3399	2415	852	416	476	427	150
1956	248	169	274	899	2449	3315	1797	721	362	389	225	131
1957	173	185	204	454	3066	2131	965	550	320	317	201	103
1958	185	216	251	433	2719	2033	862	545	352	360	252	100
1959	238	161	219	533	1801	3269	2094	859	951	713	468	164
1960	205	172	328	842	1522	2734	1784	686	475	359	303	86
1961	211	290	310	511	2283	3953	1247	689	317	361	198	90
1962	133	193	194	767	1424	2514	1431	793	378	406	384	165
1963	229	320	303	543	1709	2490	1409	675	481	311	309	116
1964	211	151	179	385	1468	3106	2024	882	509	541	355	120
1965	213	198	244	663	1582	2497	1380	911	378	441	435	124
1966	57	167	377	653	2005	2752	1719	755	435	288	255	141
1967	239	289	353	410	1518	4095	2144	801	480	399	320	66
1968	78	267	501	392	1754	3030	1858	866	641	423	380	89
1969	-53	-43	217	838	2677	3184	1305	500	476	391	335	96
1970	98	153	220	377	1463	2550	1049	583	357	255	167	27
1971	-6	192	361	602	2449	3049	1889	908	398	299	127	11
1972	-33	-41	466	467	2228	3608	2172	1101	399	266	138	4
1973	-11	108	216	366	1506	1899	1178	607	311	329	378	162
1974	371	233	250	641	1708	3939	2275	1001	395	183	204	98
1975	147	113	152	325	1360	2570	1740	792	477	427	415	241
1976	185	188	186	553	2265	2146	2357	1489	767	283	139	107
1977	141	175	159	502	1249	1707	919	720	474	284	261	160
1978	291	202	327	679	1617	2440	1698	736	733			

Location: Hungry Horse

Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							344	112	64	48	44	32
1929	28	24	37	125	671	633	154	47	25	27	23	11
1930	19	30	29	505	565	408	116	40	29	57	60	23
1931	43	42	74	197	726	338	85	35	37	38	49	24
1932	34	83	131	326	889	731	215	67	39	51	136	59
1933	72	51	54	238	686	1489	333	85	48	178	246	108
1934	168	113	181	700	937	413	118	45	28	54	123	31
1935	57	57	79	182	785	715	199	57	30	28	24	10
1936	21	20	29	430	1074	426	97	39	25	27	21	13
1937	16	17	25	120	699	524	142	51	26	34	49	30
1938	59	53	58	316	715	624	162	52	30	35	33	25
1939	46	29	80	453	980	455	169	48	28	29	28	21
1940	34	33	85	271	650	344	83	34	26	31	29	15
1941	29	28	59	194	407	237	72	31	43	94	71	72
1942	59	34	38	325	570	546	218	60	37	32	65	34
1943	46	41	57	583	684	956	502	100	45	46	38	19
1944	28	22	28	154	546	323	104	43	36	39	36	18
1945	50	40	46	109	735	644	204	53	36	57	114	35
1946	54	40	82	427	867	647	217	67	38	95	103	60
1947	91	97	115	388	1091	696	230	73	54	153	85	29
1948	57	40	39	236	1116	907	187	74	34	30	28	13
1949	22	20	36	334	981	472	115	44	33	43	83	45
1950	59	48	67	208	764	1188	599	138	52	120	141	82
1951	100	123	68	321	938	659	384	93	63	143	99	34
1952	49	40	38	439	871	516	156	51	30	25	23	18
1953	66	58	53	212	646	991	326	68	32	27	43	22
1954	44	51	61	196	1104	880	515	100	60	88	88	37
1955	60	46	46	104	580	946	347	70	38	97	106	54
1956	80	62	83	356	1044	878	210	66	40	57	59	42
1957	62	40	49	172	1061	545	121	43	36	38	46	21
1958	32	39	49	178	1048	500	123	44	48	93	169	77
1959	133	83	84	367	740	1408	441	96	112	282	209	60
1960	69	53	119	342	568	882	246	71	38	42	57	20
1961	41	108	110	240	905	879	137	42	46	80	55	31
1962	56	61	53	462	845	805	215	66	37	82	95	51
1963	70	110	86	198	623	545	185	51	39	32	35	23
1964	56	32	42	127	738	1247	319	74	89	88	83	69
1965	95	84	109	361	840	1055	320	101	139	90	75	32
1966	55	39	74	284	777	648	201	58	37	43	52	38
1967	69	59	53	131	856	1186	319	65	36	65	100	32
1968	67	86	142	129	646	793	222	88	179	174	126	41
1969	104	56	61	437	795	549	235	63	52	60	44	22
1970	46	43	49	92	854	990	191	65	53	54	66	35
1971	102	221	86	291	1125	941	325	86	44	44	49	23
1972	51	49	209	231	916	1188	351	109	56	60	53	34
1973	63	28	56	137	586	526	127	43	32	40	132	51
1974	187	80	99	342	695	1450	447	95	52	38	48	21
1975	45	35	50	75	578	1205	485	108	76	96	134	85
1976	90	67	59	307	1030	696	310	101	45	34	35	19
1977	31	33	42	239	482	323	85	51	58	81	70	50
1978	54	39	128	362	667	853	341	91	80			

Location: Columbia Falls Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							817	261	166	155	127	91
1929	78	61	81	199	1111	1091	337	144	88	71	54	29
1930	63	63	71	693	930	818	302	133	92	102	91	32
1931	63	74	90	282	1141	596	204	104	93	80	86	32
1932	48	89	207	527	1716	1505	484	187	117	111	175	83
1933	69	54	75	375	1188	2196	703	214	139	321	412	170
1934	279	170	231	1216	1729	781	298	133	82	85	277	58
1935	157	129	94	248	1308	1364	540	178	97	74	62	25
1936	48	47	71	563	1578	730	223	113	77	61	49	24
1937	41	33	42	179	1182	1106	360	135	79	90	131	42
1938	95	69	95	588	1444	1317	431	158	101	100	82	45
1939	85	44	118	649	1417	735	357	135	85	69	66	44
1940	61	58	102	358	1068	623	191	92	88	93	70	33
1941	61	48	77	326	704	434	186	88	142	205	144	153
1942	145	86	72	451	1001	955	549	188	121	95	112	63
1943	99	99	105	876	1015	1335	746	209	106	96	75	32
1944	52	44	50	188	751	534	196	113	94	100	80	31
1945	67	59	68	126	1110	1057	411	138	109	112	184	58
1946	93	72	123	617	1566	1143	458	170	114	159	140	57
1947	73	93	142	626	1768	1156	469	205	155	372	201	58
1948	94	69	74	381	1703	1435	395	254	112	83	66	29
1949	56	53	68	448	1480	862	302	154	104	104	177	86
1950	98	84	125	291	1251	1888	948	284	135	272	263	131
1951	182	208	133	469	1759	1197	839	267	258	423	200	77
1952	102	82	79	724	1419	836	403	182	103	72	56	25
1953	115	119	91	313	1180	1704	706	229	114	74	87	44
1954	67	69	89	209	1871	1665	1122	324	224	202	183	68
1955	96	71	71	136	847	1596	713	221	113	267	244	79
1956	125	73	84	462	1683	1535	552	214	126	155	105	48
1957	73	66	92	259	1894	1031	328	146	82	78	70	31
1958	61	61	91	296	1606	733	242	127	109	169	177	89
1959	170	104	106	508	1178	1967	715	237	285	408	278	104
1960	120	104	186	592	924	1387	523	199	117	95	106	42
1961	70	105	132	318	1484	1551	368	152	112	170	108	38
1962	72	85	73	593	1180	1103	387	182	105	146	167	85
1963	106	159	130	333	1007	1110	564	174	109	88	81	33
1964	57	53	52	163	1252	2343	658	217	171	216	140	62
1965	106	93	73	471	1342	1703	635	262	187	161	117	54
1966	95	65	90	434	1222	1238	482	173	118	101	114	64
1967	109	109	91	178	1322	1907	697	202	100	98	149	43
1968	75	104	186	187	1077	1236	468	199	262	286	223	64
1969	112	77	82	702	1322	1036	487	156	92	122	87	32
1970	63	58	64	116	1283	1536	401	154	102	91	77	41
1971	95	246	111	413	1738	1538	701	265	118	98	93	36
1972	67	62	324	379	1567	1922	710	293	144	132	96	42
1973	93	77	74	221	1016	978	325	138	98	89	217	83
1974	302	145	138	562	1242	2385	963	300	151	89	88	38
1975	62	54	61	98	996	2076	876	269	188	153	210	150
1976	130	93	80	443	1584	1023	679	355	160	97	73	33
1977	59	52	55	286	720	483	189	136	137	117	93	54
1978	73	57	113	420	1116	1262	607	250	216			

Location: Kerr　　　　　　　　　　　　　　　　　Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							291	58	-7	120	67	-34
1929	44	60	84	70	233	404	63	1	-4	34	23	44
1930	4	57	72	87	169	204	43	-13	36	54	56	18
1931	44	52	72	58	210	188	29	-7	31	10	29	24
1932	50	20	71	182	152	207	92	30	-4	36	70	33
1933	78	46	69	88	230	448	144	58	35	66	126	102
1934	161	82	133	263	398	291	93	12	11	65	60	33
1935	34	61	71	127	264	368	120	21	5	24	42	26
1936	53	42	61	142	320	267	24	-15	-17	26	29	16
1937	43	48	64	70	150	219	52	5	6	35	36	23
1938	27	30	62	67	116	249	42	-20	7	19	21	13
1939	40	43	54	65	357	214	53	-23	-12	10	26	19
1940	18	53	78	125	185	155	24	-27	9	18	38	18
1941	44	42	53	72	119	95	-8	-19	1	43	64	35
1942	59	49	48	143	246	342	147	20	16	31	54	36
1943	67	39	31	307	295	422	272	31	11	55	62	21
1944	42	35	44	78	151	161	0	-25	-14	29	38	21
1945	49	35	55	73	197	310	115	-20	-7	46	45	41
1946	68	65	82	187	343	358	128	11	31	61	61	50
1947	80	46	120	166	452	386	116	58	55	94	101	41
1948	96	87	91	178	461	561	191	95	27	47	65	28
1949	53	75	101	183	323	232	50	5	6	23	63	22
1950	67	74	140	188	250	483	415	122	21	77	89	66
1951	126	136	93	224	563	393	279	47	59	121	97	36
1952	94	114	94	244	494	368	110	7	17	31	18	16
1953	79	51	69	103	265	457	155	19	-2	24	48	25
1954	63	71	90	126	415	408	352	84	46	35	67	18
1955	48	71	11	90	206	344	181	18	9	41	67	44
1956	68	60	68	262	431	477	170	37	28	30	52	36
1957	45	79	94	119	359	266	64	-11	-23	42	56	29
1958	77	79	57	156	364	278	79	-11	1	39	75	67
1959	129	123	67	258	489	605	293	63	88	162	158	56
1960	102	66	131	299	362	479	213	74	39	41	57	25
1961	52	68	91	156	465	558	93	27	14	42	73	18
1962	39	108	81	224	408	325	107	19	26	66	70	26
1963	69	92	93	123	181	273	125	18	41	23	31	21
1964	51	69	75	106	276	478	261	61	82	37	63	46
1965	93	80	138	258	481	568	230	107	84	76	76	29
1966	65	76	61	176	262	502	195	21	36	45	82	46
1967	84	94	92	133	289	550	158	4	8	43	48	30
1968	56	88	119	80	191	334	135	91	112	94	95	41
1969	103	71	106	252	350	314	171	15	41	38	37	21
1970	72	62	85	82	301	397	145	30	7	47	68	23
1971	83	139	83	127	437	419	194	55	2	38	42	25
1972	47	109	175	179	329	499	188	57	26	36	55	26
1973	46	48	65	81	133	178	30	-21	-3	-8	62	38
1974	106	80	87	221	325	529	232	46	21	27	22	18
1975	61	64	58	78	205	345	157	61	49	84	68	50
1976	145	73	69	181	374	252	164	84	43	17	35	15
1977	53	47	48	77	179	110	24	-9	46	23	33	53
1978	60	58	102	261	312	308	218	82	65			

Location: Thompson Falls, Noxon, and Cabinet | Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							989	597	523	243	270	313
1929	176	151	287	434	1186	1219	513	203	144	225	210	121
1930	179	296	316	1033	1194	888	372	199	179	272	253	114
1931	211	199	270	402	898	552	206	124	129	184	178	94
1932	192	237	427	827	2065	1623	704	266	197	223	280	121
1933	268	181	297	690	1486	3005	897	302	248	377	504	598
1934	984	683	967	2194	1701	877	340	186	163	263	348	153
1935	294	289	339	618	1433	1235	546	267	164	190	190	84
1936	173	134	315	1110	1815	1115	365	180	171	197	187	95
1937	113	140	204	340	1049	819	366	176	126	173	179	111
1938	227	175	325	898	1706	1773	845	243	177	251	246	120
1939	214	185	361	824	1604	953	421	195	160	209	207	113
1940	191	225	391	677	1124	711	242	144	134	229	204	104
1941	184	170	223	325	635	640	295	155	232	289	319	230
1942	325	235	325	781	1149	1476	675	237	210	232	287	146
1943	249	329	430	1817	1891	2620	1399	437	285	304	300	127
1944	204	195	218	328	741	913	473	226	189	219	222	79
1945	243	226	255	364	1274	1328	577	234	203	249	270	133
1946	287	222	371	853	1510	1220	588	235	263	385	442	335
1947	404	425	656	1036	2582	1764	748	319	297	438	411	195
1948	395	351	399	1021	3061	3418	929	479	294	321	308	102
1949	215	305	415	1043	2528	1556	511	260	237	277	284	160
1950	231	350	591	921	1679	2743	1449	521	317	385	524	243
1951	423	638	524	1162	2543	1931	1006	417	350	392	340	155
1952	282	256	348	1086	2156	1256	586	428	205	221	218	104
1953	315	337	326	506	1266	2283	870	364	215	235	225	149
1954	200	267	479	826	2240	1783	1131	421	340	332	338	147
1955	247	260	255	488	1473	2124	1253	415	288	361	376	300
1956	449	347	605	1770	3139	2241	847	422	295	323	291	172
1957	181	339	468	720	2566	1745	540	321	203	288	268	140
1958	243	259	364	690	2229	1615	652	311	221	322	452	253
1959	449	421	519	761	1827	2533	875	371	412	700	600	280
1960	342	287	563	1160	1572	1617	551	335	289	247	275	121
1961	249	429	489	732	1799	1885	489	260	229	306	255	123
1962	229	355	420	1248	1879	1774	677	389	246	348	371	208
1963	260	621	559	750	1461	1322	655	301	247	244	258	100
1964	224	218	296	585	1641	2836	998	408	361	330	336	267
1965	488	482	595	1453	2297	2485	987	490	516	451	368	172
1966	328	282	489	1065	1410	1098	547	265	247	251	319	158
1967	308	387	461	614	1825	2851	897	343	218	344	421	168
1968	342	560	674	697	1394	1799	733	320	395	449	438	159
1969	356	297	476	1594	2346	1482	924	320	294	346	298	138
1970	253	283	380	516	1875	2393	850	349	294	343	306	155
1971	404	792	574	1008	2955	2492	918	361	292	279	262	128
1972	268	432	1322	1121	2618	3476	1134	514	290	333	267	127
1973	330	266	430	454	815	795	343	172	165	220	367	170
1974	846	445	520	1199	1958	3127	1102	446	308	273	227	122
1975	268	243	369	465	1668	2997	1586	529	411	464	466	391
1976	519	449	535	1239	3022	2068	1014	514	370	322	281	126
1977	234	233	317	310	656	541	211	170	189	234	273	254
1978	335	315	657	1185	1839	1930	1114	368	382			

Location: Albeni Falls, Box Canyon, and Boundary   Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							185	-116	-178	130	99	-156
1929	19	71	148	246	367	426	196	84	26	22	5	47
1930	3	105	87	278	224	155	108	35	4	23	23	10
1931	72	103	225	352	427	226	133	26	24	28	66	33
1932	75	123	407	791	917	741	257	84	34	79	210	140
1933	222	145	220	557	715	676	568	157	94	128	283	307
1934	644	388	458	632	718	372	162	73	27	89	292	106
1935	255	230	304	532	785	605	300	104	49	91	101	54
1936	140	23	184	462	668	406	179	77	70	63	56	59
1937	42	71	138	421	503	494	243	104	79	110	263	143
1938	376	196	436	746	837	638	325	100	57	63	81	57
1939	132	66	197	455	539	336	127	39	41	57	85	95
1940	93	192	452	621	544	294	134	29	66	91	99	73
1941	159	152	354	395	570	299	130	67	144	210	239	266
1942	255	194	199	404	579	613	383	105	85	79	148	70
1943	41	141	238	820	724	559	493	165	43	94	83	62
1944	92	83	102	283	396	281	141	33	32	45	61	34
1945	123	149	277	320	905	595	283	78	70	92	183	89
1946	194	146	335	723	1060	808	372	116	86	81	175	153
1947	249	267	403	543	785	666	275	105	95	313	316	110
1948	222	186	232	592	1053	1363	651	282	105	109	138	53
1949	24	213	369	747	991	642	249	129	86	118	247	124
1950	155	236	575	749	946	966	749	256	111	248	319	235
1951	327	500	424	704	755	610	378	207	113	321	276	164
1952	192	259	307	850	1048	713	265	-35	4	16	133	101
1953	382	377	310	453	797	829	284	117	-14	171	170	106
1954	256	218	346	503	944	970	536	73	104	58	186	69
1955	107	116	85	519	666	887	507	85	35	266	240	195
1956	351	190	332	972	1152	899	269	67	45	83	132	103
1957	143	188	330	529	1064	606	169	46	48	121	118	109
1958	179	423	477	646	890	441	167	81	64	23	213	94
1959	325	212	275	623	896	824	327	78	109	190	308	189
1960	246	288	384	726	927	728	284	175	76	134	298	109
1961	233	571	439	561	1171	1043	230	24	3	139	104	113
1962	150	208	280	607	721	630	114	78	50	178	259	147
1963	186	225	265	482	648	413	138	40	43	62	228	77
1964	157	86	186	461	776	724	212	78	75	29	167	123
1965	146	176	209	656	827	538	138	35	-5	36	109	57
1966	117	57	295	481	602	356	142	0	-10	22	115	160
1967	308	235	291	287	654	843	155	-20	-37	107	134	43
1968	95	247	410	244	506	224	77	44	97	202	336	164
1969	204	192	259	920	1205	513	202	-4	52	95	143	59
1970	172	201	272	393	684	561	142	34	21	124	138	78
1971	210	250	267	529	891	623	243	50	35	108	171	79
1972	133	205	567	448	752	619	193	7	15	60	151	102
1973	160	90	222	188	523	223	43	12	58	59	350	250
1974	792	383	462	835	1116	1168	613	14	8	63	233	92
1975	122	159	218	429	923	758	308	67	69	103	228	149
1976	194	177	139	461	851	426	183	130	66	89	94	27
1977	74	67	95	245	241	109	0	65	93	68	154	130
1978	129	118	283	513	719	423	168	80	60			

Location: Dworshak | Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							193	97	78	79	82	68
1929	59	56	176	342	876	560	162	76	57	68	49	55
1930	56	172	263	865	608	304	121	63	60	88	102	36
1931	98	103	303	580	815	245	96	55	57	62	76	40
1932	80	95	387	948	1647	764	212	91	63	77	184	69
1933	145	80	214	683	1050	1425	278	102	88	207	317	563
1934	853	426	898	1250	691	247	105	61	56	98	167	69
1935	135	127	250	625	1106	578	177	78	54	60	58	31
1936	94	63	218	1134	1392	430	134	65	57	52	48	34
1937	42	50	124	419	943	490	148	74	51	56	111	77
1938	155	121	357	901	1072	560	169	82	60	76	87	58
1939	100	76	286	758	957	331	135	63	54	64	61	72
1940	136	251	490	693	751	289	104	57	59	83	102	89
1941	155	134	240	344	528	351	131	74	107	137	215	187
1942	182	142	193	618	530	394	192	83	63	64	183	86
1943	175	133	300	1188	1128	1016	401	115	70	83	84	58
1944	69	90	118	423	603	313	125	69	59	64	79	38
1945	197	179	208	411	1132	546	171	77	79	78	169	98
1946	214	128	377	809	1107	562	239	98	81	146	214	306
1947	246	318	451	732	1245	551	189	94	88	198	228	113
1948	322	234	264	782	1750	1115	276	150	90	93	125	50
1949	85	129	395	997	1682	624	193	88	72	94	133	67
1950	136	184	424	852	1281	1409	497	152	93	181	277	189
1951	274	423	279	921	1107	570	219	95	75	191	159	99
1952	117	151	192	933	1267	567	215	91	66	56	56	32
1953	260	276	252	514	940	899	279	102	65	61	89	68
1954	125	232	296	796	1401	903	407	140	101	103	126	55
1955	100	94	100	387	1106	1087	413	128	90	140	245	234
1956	298	163	328	1139	1660	828	287	121	85	100	123	96
1957	110	162	381	744	1530	700	196	96	65	81	81	55
1958	109	306	262	730	1346	535	167	84	80	122	367	226
1959	490	248	330	827	1117	951	258	104	171	356	405	135
1960	170	205	424	810	936	765	203	107	74	89	151	55
1961	128	504	448	690	1208	827	175	78	78	100	87	55
1962	172	190	217	1026	1111	694	205	94	76	170	223	137
1963	165	391	334	484	726	434	161	78	68	66	104	40
1964	80	79	124	530	1193	1328	356	141	122	122	177	305
1965	394	370	380	1089	1187	793	241	130	104	93	139	58
1966	141	91	298	700	825	459	166	78	54	73	124	102
1967	293	245	289	427	1050	968	250	87	64	123	155	68
1968	147	522	496	416	762	614	184	103	142	214	283	113
1969	386	176	308	992	1179	527	180	85	70	93	77	57
1970	256	276	292	360	1055	978	231	100	92	94	184	93
1971	307	489	335	723	1823	1120	386	135	98	93	100	46
1972	190	258	1011	757	1962	1539	431	164	92	85	86	85
1973	247	122	221	295	559	316	94	36	37	69	278	164
1974	685	303	504	1000	1325	1968	476	133	53	59	71	32
1975	139	109	260	418	1141	1307	476	162	71	150	222	308
1976	368	260	301	822	1569	827	306	160	77	80	74	32
1977	62	85	133	373	521	256	80	70	88	112	182	309
1978	244	262	523	656	824	648	229	115	61			

Location: Spalding Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							425	164	111	132	112	98
1929	90	72	270	564	1586	1399	342	98	63	70	72	79
1930	73	260	411	1176	1271	823	209	89	82	147	131	52
1931	136	139	439	921	1487	528	131	61	68	77	94	52
1932	109	155	879	1330	2751	1533	363	112	83	106	247	87
1933	172	108	475	973	1584	2950	445	116	95	237	374	460
1934	898	459	1075	1826	1208	395	134	62	54	102	184	86
1935	183	196	381	868	1612	1062	262	92	58	74	73	37
1936	130	99	508	1864	2546	800	179	78	66	64	59	38
1937	55	65	239	561	1640	938	214	87	56	68	94	96
1938	221	208	583	1269	1941	1283	285	101	66	94	120	77
1939	140	123	607	1137	1846	645	241	77	60	75	75	71
1940	187	406	638	1116	1526	627	140	60	73	145	160	124
1941	220	182	279	542	1001	798	262	107	193	287	392	246
1942	213	235	343	1128	1363	1109	392	118	84	76	208	144
1943	283	313	584	1988	2030	2186	885	172	97	95	125	55
1944	89	112	210	664	1310	882	271	110	78	77	95	46
1945	208	238	331	610	2078	1397	347	93	98	108	241	140
1946	326	230	688	1303	1885	1015	359	121	124	257	316	418
1947	364	477	586	1109	2607	1274	403	127	108	218	317	202
1948	492	417	485	1265	3534	2713	489	211	105	118	176	81
1949	142	249	828	1442	2990	1246	320	107	81	120	210	118
1950	221	452	836	1226	1886	2538	844	228	108	232	386	231
1951	380	619	437	1264	2164	1278	449	122	80	185	164	94
1952	138	239	394	1478	2525	1258	349	114	73	58	60	34
1953	279	337	350	719	1497	2027	551	127	65	67	96	76
1954	153	304	321	934	2139	1518	665	173	108	105	115	51
1955	102	103	138	732	1811	2318	826	172	97	143	316	302
1956	453	245	750	1721	2737	1508	384	138	93	122	171	126
1957	137	243	702	981	2929	1532	330	111	77	104	105	80
1958	153	441	315	1002	2257	992	284	108	97	154	435	351
1959	686	451	594	1193	1909	2082	457	130	208	697	588	187
1960	234	379	703	1282	1612	1626	317	125	82	92	158	68
1961	154	569	557	879	1949	1588	226	82	104	169	131	86
1962	315	323	398	1363	1818	1443	328	119	80	230	327	212
1963	197	554	504	790	1731	1258	380	123	92	81	121	58
1964	122	124	228	766	2055	3056	754	219	200	160	207	354
1965	729	672	500	1544	2098	1941	485	191	193	162	182	74
1966	166	136	488	925	1519	881	235	91	83	111	135	96
1967	339	256	392	596	1938	2105	445	109	67	198	314	141
1968	263	712	610	648	1525	1527	365	168	284	322	463	179
1969	747	301	639	1559	2207	1094	376	114	87	142	129	76
1970	494	441	449	545	1901	2120	492	134	154	172	226	111
1971	501	738	496	974	2668	2186	581	142	104	99	120	66
1972	280	614	1606	1076	2622	2726	705	147	101	96	107	121
1973	233	125	272	397	1152	783	219	69	83	79	256	206
1974	770	503	818	1430	1958	3352	704	166	91	71	97	52
1975	203	181	479	653	1936	3025	1171	255	163	283	349	460
1976	590	382	494	1306	2791	1835	657	223	144	124	115	52
1977	98	114	164	635	1034	601	174	117	128	183	265	438
1978	456	460	851	1231	1756	1759	701	190	156			

Location: Brownlee, Oxbow and Hells Canyon   Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							670	655	633	800	979	910
1929	895	710	1165	1107	869	825	543	545	602	728	769	468
1930	743	894	1024	795	763	611	483	507	604	769	690	405
1931	765	639	837	751	593	478	406	464	556	644	688	352
1932	710	629	1220	1275	1395	1118	574	541	671	793	781	430
1933	796	664	869	1005	1028	1297	550	579	669	757	740	394
1934	900	728	845	781	621	541	444	496	562	725	703	353
1935	735	645	744	977	828	742	466	490	558	740	693	352
1936	727	695	904	1512	1451	877	533	571	654	771	749	421
1937	769	653	809	871	868	682	490	501	588	786	771	530
1938	871	853	1252	1801	2115	1611	749	593	693	838	947	491
1939	809	835	1393	1151	1002	642	533	577	666	786	775	424
1940	837	956	1385	1463	1018	698	516	534	705	808	836	464
1941	913	933	1199	1021	1001	985	554	611	701	819	845	567
1942	909	908	978	1428	1219	1237	609	579	724	834	912	539
1943	1233	1315	2814	3963	2111	1651	1094	665	795	969	1066	575
1944	1060	897	1015	1076	839	850	563	587	703	794	855	473
1945	840	947	1139	1127	1500	1253	599	603	770	952	1007	612
1946	1196	1262	2083	2771	1781	1235	625	632	769	936	1117	590
1947	981	1271	1469	1353	1629	1194	595	591	728	840	970	494
1948	1048	1175	1182	1319	1759	1779	660	627	741	880	988	464
1949	814	1007	1865	1515	2004	929	553	562	679	810	855	483
1950	839	1260	1574	2258	1299	1311	898	651	786	1013	1233	706
1951	1362	1959	2002	2291	1985	1195	641	669	741	1007	1074	609
1952	1482	1886	2024	4250	3200	1641	783	651	765	860	949	469
1953	1114	1251	1319	1356	1362	2226	842	633	767	865	906	491
1954	941	1231	1411	1781	1534	1174	650	628	739	832	816	455
1955	825	678	789	1052	1017	910	591	564	694	829	839	692
1956	1411	1854	2434	2342	2271	1696	673	673	774	889	1073	529
1957	1112	1676	2006	2291	2757	1629	632	646	775	857	945	499
1958	1028	1468	1503	2136	3102	1628	651	663	780	853	844	503
1959	1007	830	921	990	1025	1086	583	627	828	927	836	501
1960	845	973	1547	1419	1127	1124	571	650	738	813	829	430
1961	780	913	948	815	907	822	491	529	660	765	776	434
1962	788	932	1073	1812	1364	1074	588	621	723	947	899	562
1963	872	1255	1091	1215	1169	1855	628	605	769	823	834	491
1964	836	949	1194	1654	1391	2112	639	661	784	841	950	800
1965	2257	2502	2394	2785	2376	1947	922	818	901	997	1244	690
1966	1224	950	1289	927	913	724	558	589	695	812	835	486
1967	934	804	881	947	1300	1793	715	632	756	794	985	485
1968	1077	1295	1211	874	819	896	582	765	804	977	1071	539
1969	1536	1930	2051	2665	2351	1261	686	699	798	904	803	513
1970	1460	1564	1493	1177	1886	2234	853	689	888	980	1170	645
1971	2951	2623	2700	3328	3096	2967	1328	698	882	1117	1484	783
1972	2376	2238	3996	2197	2136	2136	735	688	856	1016	1097	707
1973	1360	996	1306	1124	1344	779	590	617	763	885	1229	572
1974	1842	1680	2578	3259	2195	2615	1106	719	813	999	1047	639
1975	1381	1365	1824	2247	2592	2266	1264	727	842	1023	1121	720
1976	1663	1575	2072	2613	2455	1173	692	774	854	949	966	466
1977	967	792	785	557	545	479	391	455	563	725	726	528
1978	957	934	1240	1814	2103	1310	816	623	829			

Location: Lower Granite, L. Goose, L. Monumental and I-ce H Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							928	394	314	263	333	283
1929	317	309	603	707	1770	2427	809	276	197	325	252	202
1930	208	404	574	1323	1693	1715	547	288	215	296	230	112
1931	249	347	474	982	1624	948	275	94	103	277	218	117
1932	217	262	1134	1349	2674	2683	1109	328	219	306	370	178
1933	364	338	575	1024	1629	3642	1017	340	227	200	369	170
1934	689	599	717	1569	1679	862	366	177	155	303	338	182
1935	312	421	454	903	1723	2079	642	230	168	286	276	131
1936	356	273	779	1653	2792	1803	545	276	216	272	238	135
1937	186	326	525	776	1925	1493	508	199	135	262	265	195
1938	389	510	826	1294	2767	3200	1257	389	252	345	350	211
1939	384	436	905	1352	2262	1186	528	220	179	309	270	183
1940	395	667	1085	1632	2591	1646	493	203	205	396	350	220
1941	373	453	617	832	1975	1947	781	364	331	397	536	473
1942	527	618	625	1708	2272	2667	1175	354	240	301	377	241
1943	526	677	895	2555	2636	3506	2359	613	324	349	368	172
1944	291	427	518	866	1701	1955	823	345	243	313	330	146
1945	352	557	567	849	2052	2662	1005	360	244	311	338	211
1946	510	461	870	1659	2825	2311	869	359	361	487	565	567
1947	519	837	991	1447	3762	2550	971	405	325	502	570	314
1948	699	730	720	1671	3978	4732	1418	538	316	418	428	211
1949	415	739	1368	1898	3884	2304	704	312	248	399	425	224
1950	446	829	1210	1616	2407	3753	1974	567	351	492	639	344
1951	595	964	874	1873	3169	2664	1337	504	288	490	464	293
1952	478	683	709	2120	4022	3179	1327	479	317	353	341	182
1953	791	864	776	1272	2321	4079	1996	550	339	379	387	232
1954	444	725	736	1231	2961	2430	1394	479	324	356	360	161
1955	319	391	405	891	2098	3191	1272	379	244	318	379	458
1956	746	549	1066	2264	4466	3980	1208	527	361	407	427	255
1957	358	591	1067	1282	4457	3538	1005	406	307	397	368	235
1958	420	828	708	1270	3991	2926	928	455	277	392	554	396
1959	800	714	713	1338	2176	3223	1028	419	464	727	619	255
1960	376	536	967	1514	2069	2599	759	395	318	376	438	191
1961	335	824	830	960	2175	2627	585	300	311	380	379	218
1962	482	593	671	1646	2318	2814	1023	455	174	655	612	373
1963	441	1127	686	963	2645	2910	1204	466	387	406	462	196
1964	449	476	563	1412	2556	4184	1627	546	437	397	357	484
1965	1066	1134	1092	1750	3652	5052	2126	803	582	489	438	220
1966	444	461	653	1362	1869	1559	642	308	277	321	381	211
1967	457	571	625	790	2701	4144	1534	439	281	464	462	200
1968	452	791	944	812	1830	2694	788	413	385	450	598	254
1969	747	404	783	2026	3576	2403	817	273	218	309	267	147
1970	675	662	644	633	2548	3793	1431	401	367	391	435	216
1971	768	859	728	1290	3945	4542	1890	519	347	342	359	184
1972	558	792	1933	1083	2901	4407	1178	476	324	471	379	250
1973	621	367	599	508	1588	1390	492	244	221	335	762	502
1974	1530	871	1117	1904	3133	5738	2115	587	308	326	349	165
1975	477	463	802	747	2046	4095	2376	652	446	512	516	477
1976	799	558	801	2004	4075	3069	1363	575	392	428	357	205
1977	259	314	315	588	874	1018	259	159	257	382	390	433
1978	610	554	1021	1614	2485	3087	1592	553	408			

Location: Mica — Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							3886	3181	1934	837	292	271
1929	233	177	193	176	1099	3448	2771	2444	1357	510	239	110
1930	157	151	246	794	1476	3453	3905	2819	1375	538	308	109
1931	174	144	198	354	1727	3583	3473	2417	1517	682	482	145
1932	197	155	206	494	1982	4104	3431	2771	1159	658	421	161
1933	263	189	202	328	1584	3726	4463	3005	1340	762	544	165
1934	303	173	244	1293	3224	3700	3478	2518	1211	741	529	156
1935	224	216	239	270	1385	3514	4362	2453	1347	641	341	132
1936	232	191	201	638	2562	3626	3211	2551	1225	631	308	115
1937	191	147	172	327	1194	2819	3271	2149	1361	741	551	169
1938	224	157	210	447	1792	3648	3520	1982	1590	720	351	156
1939	314	171	252	588	2601	2632	3491	2617	1267	734	493	204
1940	246	205	243	574	2151	3388	3698	2264	1524	1129	410	155
1941	216	185	234	804	1679	2876	3288	2397	1208	847	482	184
1942	223	168	175	396	1658	2806	3749	2669	1107	665	312	122
1943	176	164	183	785	1182	2329	3884	2546	1083	679	309	100
1944	165	176	177	373	1484	2906	2628	2283	1455	779	468	140
1945	234	204	211	212	1342	2841	3017	2162	1079	559	287	113
1946	165	149	186	403	2718	3922	3635	2429	1246	524	280	145
1947	273	209	226	613	2338	3615	3659	2023	1242	970	466	151
1948	238	178	175	331	2400	4835	2897	2568	1284	700	409	126
1949	172	133	174	416	2055	2330	2306	2006	1016	489	370	124
1950	150	131	180	282	1090	3966	4520	2442	1361	593	369	143
1951	247	197	215	400	2240	2836	4200	2306	980	644	316	100
1952	164	147	162	499	2099	3139	3309	2332	1004	626	266	98
1953	193	168	184	237	1576	3163	3420	2348	1230	773	521	150
1954	223	212	212	240	1742	3562	5037	3035	1706	718	547	189
1955	252	200	214	287	906	3503	4317	2378	1254	552	328	136
1956	225	155	186	504	2154	3883	3494	2328	1147	675	341	129
1957	203	186	209	339	3261	3342	2713	1729	1141	632	329	124
1958	230	198	222	367	2566	4068	2934	2343	1147	724	353	143
1959	249	192	196	371	1650	3657	4262	2296	1564	822	478	185
1960	260	222	240	537	1108	2868	4213	2360	1253	755	468	140
1961	265	216	239	373	2191	5020	3094	2523	1046	779	369	142
1962	223	229	192	564	1508	3146	3371	2596	1111	669	508	168
1963	270	275	285	524	1552	3491	3371	2471	1605	767	391	142
1964	244	193	183	312	1133	3658	4097	2192	1129	921	520	148
1965	252	218	218	504	1465	3324	3685	3032	879	767	557	180
1966	265	234	277	641	1988	3313	3851	2588	1367	785	453	165
1967	273	221	218	318	1453	5229	4687	2959	1748	822	483	126
1968	242	233	280	284	1521	3563	4325	2426	1439	705	444	141
1969	172	171	210	663	2259	4194	2898	2127	1201	712	427	129
1970	209	189	185	245	1158	3587	3089	2247	879	488	245	94
1971	193	183	174	373	2154	3557	3102	2945	1219	656	345	94
1972	170	156	231	359	2210	5384	3772	2952	1141	644	354	132
1973	217	177	218	335	1573	2915	3063	2232	1087	705	565	130
1974	226	192	194	478	1256	4108	3913	2751	1662	662	353	152
1975	220	197	140	390	1179	2670	3757	2162	1090	676	691	165
1976	257	212	188	487	2164	2693	4404	3555	1924	721	361	138
1977	270	187	269	493	1400	2935	2459	2449	964	441	306	132
1978	226	167	221	454	1173	3097	3714	2223	1690			

Location: Arrow　　　　Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928	826	644	883	1606	6854	6966	2859	1051	228	376	450	-1
1929	171	101	225	488	1912	3182	2030	1665	745	513	352	139
1930	312	294	251	1293	2217	2756	2176	1635	990	367	258	98
1931	224	182	275	574	2458	3250	1986	1280	1014	747	510	201
1932	308	363	668	1294	3181	4366	2551	1775	878	616	552	233
1933	329	221	281	729	2472	3970	3185	1890	1090	937	846	269
1934	441	372	574	2074	3463	3056	2019	1383	885	631	736	232
1935	388	429	340	626	2228	3468	3078	1537	1006	571	301	136
1936	200	108	219	1086	3425	3415	1990	1253	740	458	200	84
1937	104	131	162	361	1730	2902	2011	1014	831	656	589	167
1938	329	242	350	853	2504	3572	2186	752	959	560	333	103
1939	198	171	219	971	2869	2481	2129	1154	728	804	498	276
1940	305	282	452	1021	2668	2856	2002	1292	1185	962	420	152
1941	281	221	467	1166	1959	2316	1607	1051	948	1109	592	265
1942	288	230	235	650	2060	2522	2191	1224	585	492	268	123
1943	189	177	185	849	1559	2303	2388	1071	532	509	268	138
1944	249	151	173	577	1822	2376	1232	1043	832	698	499	125
1945	257	191	246	379	2175	2838	1636	886	597	385	325	116
1946	259	201	289	863	3429	3751	2440	1153	744	337	225	112
1947	160	202	324	1022	2772	3414	2405	1157	737	881	510	160
1948	242	207	214	599	3225	4408	1805	1496	957	742	430	138
1949	239	255	261	1025	3249	2645	1853	1407	769	472	480	231
1950	255	256	286	515	1878	4319	3402	1642	945	678	540	254
1951	346	274	213	798	3173	2839	2631	1036	632	668	343	151
1952	261	238	228	995	2868	3161	2413	1363	712	493	261	124
1953	264	240	252	532	2443	3177	2453	1369	816	828	694	240
1954	330	316	323	458	2708	3617	4138	1918	1286	734	856	278
1955	387	291	245	495	1587	4194	3585	1445	680	702	590	173
1956	315	229	282	1115	3218	3724	2521	1214	907	764	451	181
1957	267	216	260	679	4313	3471	2105	1245	757	557	428	175
1958	292	304	421	845	3710	4147	1919	1300	984	1014	529	210
1959	363	254	344	912	2713	4355	3542	1628	1568	1181	783	247
1960	351	328	427	1058	2109	3883	3405	1476	965	956	627	197
1961	327	338	359	716	3108	3927	2287	1508	795	765	396	135
1962	232	263	262	998	2265	3718	2927	1934	950	808	650	250
1963	319	369	379	859	2265	3433	2724	1616	1045	624	463	178
1964	298	225	253	504	2118	4873	4169	2151	1182	1251	680	187
1965	336	252	284	977	2364	3599	2675	2004	825	691	666	177
1966	316	219	256	708	2806	4087	3431	1806	1003	722	467	222
1967	355	295	299	495	2271	5444	3333	1613	1045	826	568	190
1968	377	360	568	566	2800	4730	3898	2044	1434	854	591	197
1969	399	260	291	1196	3198	4042	2159	1265	889	857	713	269
1970	393	220	244	415	1897	3249	1922	1190	713	548	457	185
1971	327	382	302	748	3304	3853	2809	1864	748	637	592	283
1972	406	259	527	661	3185	5711	3959	2157	880	569	464	184
1973	445	274	400	607	2327	2945	2267	1170	692	688	512	233
1974	406	335	384	1004	2354	4630	3628	1857	936	499	352	233
1975	424	334	281	544	2147	3613	3110	1418	934	918	990	378
1976	542	354	496	888	3155	3029	3964	3189	2041	860	579	212
1977	548	330	323	980	2202	3039	1964	1555	959	478	502	167
1978	379	367	581	1113	2324	3201	2747	1561	2067			

Location: Grand Coulee and Chief Joseph Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928	774	552	1385	1643	3925	1859	1102	213	127	189	258	127
1929	242	206	469	688	1346	1135	235	28	96	174	138	93
1930	-56	267	319	838	934	1050	833	289	284	304	280	126
1931	277	297	679	1275	1781	1160	779	323	268	85	141	84
1932	267	369	1179	2673	2943	1096	576	162	247	279	492	287
1933	498	251	811	1900	2756	2774	1775	698	419	387	730	1098
1934	1953	1061	1354	2467	1933	1625	604	365	240	269	470	270
1935	655	658	915	1729	2843	2335	1298	518	284	274	265	126
1936	333	256	611	2110	2502	1958	805	366	208	216	221	120
1937	155	161	452	1179	2291	1907	1180	628	265	263	413	281
1938	781	507	1342	2650	3212	2612	1232	552	181	332	294	147
1939	334	296	788	1918	2462	1726	1215	582	236	116	355	211
1940	309	623	1272	2063	2046	1476	646	279	175	211	355	235
1941	517	444	960	1464	2069	1290	502	178	608	647	634	658
1942	588	597	696	1863	2319	2384	1249	533	237	223	420	221
1943	388	351	697	2843	2492	2539	1558	514	215	275	231	148
1944	268	334	381	948	1600	1477	522	330	224	300	354	136
1945	465	496	767	1167	3596	2666	1037	330	242	226	399	276
1946	666	467	1042	2586	4170	2427	1079	486	307	282	498	478
1947	531	689	969	1639	2289	1287	759	484	284	661	667	308
1948	785	641	676	2096	5036	4011	1092	724	343	314	359	179
1949	320	531	1216	2619	3359	1044	403	134	142	227	342	194
1950	454	733	1486	1899	2971	3448	1727	178	73	313	501	464
1951	897	1373	925	2531	3824	2389	1431	708	292	619	498	293
1952	587	678	931	3256	3947	2232	1279	474	315	197	249	181
1953	825	912	855	1532	2737	3407	1734	785	524	381	384	275
1954	588	842	939	1628	3537	3171	1953	1146	707	536	519	278
1955	416	491	596	1260	2451	2985	1819	605	399	489	691	591
1956	853	517	1101	3511	4512	2495	1251	487	300	360	314	244
1957	384	619	991	1642	4373	1694	487	308	200	278	287	175
1958	553	1194	1070	1968	3230	1562	476	128	159	243	531	334
1959	1250	553	934	1983	3007	2528	1016	326	444	634	828	291
1960	424	661	1029	2236	2522	2133	744	170	256	232	375	176
1961	512	1693	1389	1846	3756	3328	380	121	172	225	244	182
1962	455	645	699	2229	2350	1987	346	97	187	297	453	374
1963	649	1060	887	1548	2044	1449	392	79	150	194	292	182
1964	387	475	581	1373	2817	2996	1148	251	391	351	478	648
1965	897	920	1055	2554	2787	2012	523	79	307	283	359	219
1966	564	448	1016	1592	2047	1406	568	154	172	181	340	327
1967	918	802	1011	1311	2867	2812	1261	377	125	216	350	237
1968	592	1156	1529	1237	2039	1933	790	466	452	540	717	391
1969	1106	893	1430	3639	3878	1753	892	378	376	240	203	157
1970	568	895	956	1266	2493	1867	439	248	126	151	198	140
1971	674	976	888	2245	4046	2620	1198	540	419	348	181	119
1972	539	982	2434	1924	3860	2561	1185	476	377	430	246	239
1973	494	370	915	1154	1903	1314	574	370	108	144	542	679
1974	2480	1505	1637	3388	3788	3949	1544	574	254	46	376	83
1975	274	464	1305	1643	3952	3018	1101	185	150	32	129	398
1976	692	1015	770	1902	3254	2356	1537	420	198	116	52	78
1977	246	168	220	627	1369	884	32	-31	-97	172	207	514
1978	687	730	1251	2429	3091	2345	1025	245	312			

Location: Wells

Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928	290	233	141	157	396	897	523	239	152	136	132	59
1929	117	86	61	30	129	517	297	111	124	142	124	47
1930	106	56	71	124	291	350	223	114	128	73	69	32
1931	61	48	26	46	307	265	128	123	104	69	71	29
1932	60	69	133	120	371	467	203	64	89	72	148	88
1933	108	99	76	53	186	831	667	150	97	181	290	114
1934	212	206	236	630	766	483	109	60	91	109	155	63
1935	157	254	156	96	329	656	269	180	108	113	106	50
1936	79	62	43	28	285	376	34	26	91	96	88	43
1937	83	58	63	59	164	562	151	47	93	105	110	58
1938	94	72	83	108	430	384	145	85	61	114	99	53
1939	85	51	53	86	139	178	71	44	86	90	137	72
1940	105	39	75	137	272	136	44	68	61	102	130	41
1941	70	61	101	242	141	222	95	56	90	142	119	66
1942	145	111	77	191	382	345	75	110	101	149	137	70
1943	147	121	136	274	464	784	651	320	160	148	135	74
1944	99	95	101	114	289	429	243	151	128	137	136	68
1945	153	114	97	125	317	676	234	141	132	143	156	53
1946	130	103	113	134	591	559	389	176	158	164	119	70
1947	125	119	164	269	624	508	236	140	129	99	176	70
1948	118	132	97	75	393	1383	620	333	274	222	189	82
1949	146	136	144	264	961	862	382	204	158	149	212	107
1950	131	118	155	205	636	964	668	404	186	160	222	112
1951	256	294	261	390	833	725	363	262	182	132	192	80
1952	184	139	159	191	307	290	159	85	51	45	48	20
1953	81	87	87	128	413	403	360	120	78	104	112	61
1954	92	91	93	119	413	571	553	241	184	144	188	90
1955	121	112	141	145	277	760	700	340	141	124	212	63
1956	110	112	121	285	837	1021	492	192	118	134	138	89
1957	109	115	96	138	685	528	205	102	76	83	87	46
1958	83	73	126	170	573	462	186	78	78	115	135	84
1959	155	155	186	265	562	778	533	208	140	257	263	147
1960	140	147	127	310	420	604	358	165	94	232	227	106
1961	106	88	96	402	708	1904	452	93	130	115	182	92
1962	178	274	113	219	340	642	339	82	31	265	260	191
1963	150	214	193	184	692	752	480	310	67	238	248	147
1964	260	8	80	123	378	1397	752	340	-116	154	240	134
1965	246	88	-12	239	638	942	368	260	69	107	123	16
1966	90	105	40	262	665	445	434	338	321	321	255	98
1967	207	148	245	281	815	1820	242	76	158	47	151	67
1968	163	174	246	155	839	975	389	111	99	114	97	48
1969	123	128	86	390	1245	767	310	80	60	39	40	7
1970	66	26	84	39	637	1065	-9	-106	-38	172	-24	51
1971	204	272	609	263	1701	1339	189	52	-197	44	166	146
1972	298	93	154	502	1492	2227	934	291	17	-184	-92	77
1973	105	104	84	107	475	421	197	23	35	76	47	125
1974	314	433	234	432	1062	1937	831	458	65	-44	58	104
1975	110	300	326	197	614	1283	475	116	106	133	142	107
1976	320	311	713	792	2194	1384	839	696	475	184	193	61
1977	86	142	84	43	322	93	-176	-118	123	15	52	7
1978	8	0	73	158	627	1013	300	34	30			

Location: Rocky Reach | Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928	227	153	127	162	502	704	371	153	40	68	19	-3
1929	-45	-54	23	42	306	604	240	30	-20	-25	-40	-15
1930	-11	56	92	247	375	403	178	30	23	-21	-29	-31
1931	-18	30	42	100	485	235	104	16	-14	-58	-2	-6
1932	46	92	152	176	318	390	174	49	10	-26	170	23
1933	50	-18	-33	110	268	618	486	121	49	92	130	65
1934	60	38	245	594	505	366	96	12	-14	-9	161	46
1935	101	29	43	106	413	511	219	95	3	-31	-36	-24
1936	-25	-35	36	162	538	355	32	-45	-37	-50	-63	-18
1937	-25	-10	30	50	324	801	126	-32	-24	-18	8	16
1938	29	28	56	190	503	339	110	-6	-39	-29	-44	-13
1939	51	16	20	158	336	278	81	-29	-39	-41	-1	12
1940	-13	3	51	188	485	228	22	-28	-38	12	-9	7
1941	3	11	86	343	305	203	57	-16	12	123	83	43
1942	35	21	13	199	376	298	58	54	-6	-8	23	34
1943	42	34	30	315	511	645	460	182	24	-4	-24	4
1944	-11	69	83	164	417	456	178	60	12	-3	-4	-2
1945	72	112	84	93	465	569	162	45	-7	13	52	13
1946	28	-11	30	125	772	484	274	79	11	17	-5	20
1947	1	36	100	286	699	442	177	29	-1	86	110	29
1948	-18	17	5	73	560	983	450	190	107	86	50	0
1949	-30	18	71	264	1007	682	270	95	28	6	183	77
1950	-6	28	70	158	474	888	469	275	94	127	154	70
1951	133	55	90	303	660	593	259	173	67	109	51	9
1952	-76	9	47	225	537	453	189	60	-46	-49	-76	-26
1953	24	32	-6	109	605	665	383	112	-1	39	32	11
1954	-5	16	-4	129	606	730	532	224	124	34	141	40
1955	3	10	16	94	438	1027	654	278	52	94	255	26
1956	30	-52	4	366	957	978	463	171	47	45	39	52
1957	-5	11	9	174	1055	499	191	95	-15	-23	-23	-8
1958	-28	31	45	176	978	506	176	79	-23	36	87	77
1959	81	-18	78	334	682	868	501	192	115	226	227	110
1960	1	36	41	310	541	652	338	153	-9	-67	-58	-43
1961	-77	-37	-47	101	422	483	60	17	-36	-46	-73	-41
1962	-59	-11	-66	167	233	286	65	4	-27	-22	-10	-8
1963	-73	37	-26	55	333	178	71	40	10	-61	-49	-25
1964	-51	-95	-79	7	260	514	121	48	-12	-36	-901	-33
1965	-60	-33	-2	115	300	209	64	33	-12	-72	-72	-48
1966	-91	-86	-80	89	348	320	78	41	-27	-47	-901	-24
1967	-54	-56	-55	-10	387	590	48	13	-42	112	134	19
1968	79	70	31	-176	49	419	197	-2	-139	-134	-60	-1
1969	-116	-83	-196	-376	293	376	-281	-181	-96	177	141	38
1970	49	26	76	198	136	449	128	9	81	29	119	54
1971	75	107	-105	71	361	880	864	87	193	258	20	-67
1972	-175	197	636	303	1198	1773	1016	443	255	321	284	45
1973	66	-134	-106	39	261	43	-145	-233	-83	-13	-24	-46
1974	-191	-171	-110	-154	374	1397	939	-232	-41	-59	-141	-50
1975	-50	-278	-295	-202	384	432	257	222	-38	-5	243	252
1976	94	-397	-429	-233	-64	149	337	425	-12	233	73	3
1977	-27	-103	300	432	426	582	519	203	114	-21	-50	57
1978	2	-7	197	137	292	777	111	-38	-171			

Location: Rock Island, Wanapum, and Priest Rapids   Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928	297	239	149	168	411	910	554	270	174	154	143	65
1929	128	96	71	45	152	540	334	145	146	159	136	54
1930	118	66	81	136	309	378	261	148	150	92	83	39
1931	73	58	38	60	325	294	168	157	127	89	85	36
1932	73	80	142	132	387	490	241	99	113	91	159	93
1933	119	108	86	67	207	845	692	182	120	197	298	119
1934	220	213	243	629	772	506	149	95	114	127	167	69
1935	167	259	164	109	346	674	304	212	131	132	119	56
1936	92	73	54	43	303	401	74	61	114	115	101	50
1937	95	68	74	73	185	581	188	82	116	124	122	64
1938	106	82	93	121	445	408	182	118	85	132	113	59
1939	97	62	64	99	160	208	109	78	109	109	149	78
1940	117	51	86	149	290	166	82	101	86	122	143	48
1941	82	72	110	251	163	250	132	90	114	160	132	72
1942	155	120	88	201	397	369	113	142	124	167	149	76
1943	158	130	145	283	477	796	673	346	182	167	148	80
1944	111	105	110	127	307	451	275	182	151	156	148	74
1945	163	123	107	137	334	691	266	171	155	162	168	60
1946	141	112	123	146	600	577	417	206	180	182	132	77
1947	136	128	172	277	632	526	267	170	152	119	188	76
1948	129	141	107	88	407	1379	640	358	293	239	200	88
1949	157	145	153	273	960	870	408	232	180	168	223	112
1950	142	127	163	216	644	969	686	426	207	179	232	117
1951	263	299	267	395	835	736	388	287	203	152	203	85
1952	193	148	167	254	410	397	240	142	92	80	76	32
1953	116	122	121	177	543	538	490	185	123	150	154	83
1954	128	124	126	163	541	746	730	336	255	201	249	120
1955	164	151	186	196	371	982	912	459	201	176	278	85
1956	148	150	161	370	1070	1307	651	273	172	187	185	118
1957	149	153	129	187	879	690	291	159	119	123	122	64
1958	114	100	167	226	740	608	268	129	121	165	182	112
1959	204	202	241	345	724	1002	700	290	198	371	340	196
1960	136	217	99	408	517	813	556	212	93	31	11	23
1961	172	245	389	39	185	291	379	243	-32	-14	-103	-44
1962	-94	-129	35	77	190	493	237	263	30	-6	43	-10
1963	172	91	170	30	133	480	296	-139	12	-6	-48	14
1964	-78	230	56	177	371	687	670	272	281	229	-89	27
1965	29	194	439	393	522	922	587	104	166	40	211	148
1966	-8	201	240	184	356	564	297	66	-216	-262	-17	64
1967	88	16	136	13	299	915	747	191	-22	78	214	153
1968	269	347	169	271	434	504	464	-60	196	258	139	88
1969	138	176	79	586	913	765	524	60	3	152	-19	115
1970	77	131	120	159	289	459	331	163	24	-76	62	-2
1971	-110	133	9	-21	479	617	488	260	-1	-203	86	16
1972	14	38	72	223	259	643	379	9	-102	60	-9	6
1973	63	218	232	63	314	350	183	166	-75	304	183	118
1974	150	124	168	311	451	398	346	456	21	253	152	72
1975	219	167	68	146	397	707	450	154	175	336	253	186
1976	205	218	264	293	258	277	143	-2	152	-98	167	87
1977	88	289	99	64	-7	126	-162	35	13	64	219	140
1978	34	87	94	253	422	429	424	274	304			

Location: Mc Nary Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							-933	-441	-184	106	170	-563
1929	295	482	601	91	-435	-1053	-74	-84	-72	-63	26	117
1930	248	886	195	-777	-516	-933	-400	-184	-167	226	157	193
1931	419	235	195	598	-764	-559	-144	-20	-26	258	356	228
1932	666	280	953	715	262	-103	891	530	559	335	500	182
1933	769	490	600	435	356	194	349	886	634	385	726	367
1934	617	560	152	-691	-648	-31	552	549	417	139	393	255
1935	384	462	317	285	-362	-456	292	882	460	208	251	189
1936	561	459	599	-356	-179	204	519	467	386	161	228	172
1937	363	410	537	594	-79	-66	755	608	401	243	302	374
1938	630	519	778	462	69	685	749	677	380	410	321	142
1939	250	194	240	-17	-485	128	506	580	408	106	345	83
1940	343	110	467	70	-454	3	478	555	383	356	659	256
1941	579	395	348	165	30	419	351	304	467	466	562	116
1942	504	739	560	434	63	219	439	652	582	174	361	420
1943	927	854	376	178	-282	-774	-16	699	343	117	280	118
1944	199	172	192	-95	-540	-700	68	-19	3	72	161	87
1945	254	200	157	258	-582	-532	396	253	136	101	184	131
1946	739	193	429	31	-182	354	447	447	369	274	214	164
1947	342	243	83	-181	-885	-170	289	501	209	70	518	190
1948	403	371	481	124	-564	2352	785	244	392	292	266	138
1949	104	682	724	-49	-92	666	71	286	226	162	69	162
1950	293	662	668	500	-526	108	977	472	301	155	526	298
1951	775	551	678	238	-449	281	-2	318	378	206	252	114
1952	211	422	168	9	-691	-57	148	286	195	92	185	70
1953	457	439	241	240	-227	-127	-112	383	199	215	313	252
1954	494	528	501	520	-218	17	68	304	362	195	412	101
1955	283	97	121	98	191	-873	-251	110	165	257	567	381
1956	835	413	788	783	499	1608	366	239	279	361	454	270
1957	131	137	623	526	254	551	194	32	236	241	279	155
1958	357	425	349	522	-264	315	35	154	141	179	384	294
1959	737	397	384	314	-87	79	208	216	73	299	568	263
1960	218	319	121	370	169	-155	-135	119	210	167	295	125
1961	252	541	652	596	8	820	4	91	252	241	347	204
1962	407	348	358	322	-107	93	32	324	485	205	248	220
1963	310	489	359	274	4	-72	154	412	178	167	177	93
1964	306	107	386	114	-173	278	-359	97	72	175	279	262
1965	736	800	387	328	46	-73	-27	-47	86	245	103	89
1966	279	104	207	69	-126	-225	-8	135	133	220	232	178
1967	411	352	132	222	67	-662	42	190	129	223	138	141
1968	463	628	350	270	-52	97	282	106	298	262	348	111
1969	367	345	369	541	538	393	199	50	176	202	268	88
1970	441	405	281	218	277	383	102	90	187	215	196	145
1971	377	528	272	489	318	96	141	165	237	248	229	153
1972	479	307	1204	1090	692	59	429	103	266	181	228	233
1973	514	209	217	58	132	36	115	126	115	48	245	212
1974	732	634	460	834	860	682	374	178	140	167	174	151
1975	506	495	291	355	674	581	324	220	222	148	289	528
1976	561	300	239	469	553	598	287	360	300	108	202	60
1977	89	178	54	141	58	232	62	147	283	248	376	471
1978	542	623	811	743	533	295	241	251	199			

Location: John Day Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928	624	258	477	242	514	458	213	63	51	32	42	-35
1929	-139	-61	108	107	62	384	157	83	82	56	66	-34
1930	-209	60	47	349	123	357	193	90	78	67	69	-38
1931	-82	-6	120	136	154	326	178	101	93	78	90	-23
1932	-57	20	519	384	336	485	203	82	71	62	65	75
1933	163	17	195	233	173	551	239	66	36	51	116	452
1934	1126	488	640	768	383	379	183	84	78	50	82	37
1935	148	220	180	170	157	431	217	75	60	58	58	-49
1936	-126	-115	95	316	314	365	150	67	62	58	68	-59
1937	-254	-76	-10	22	53	316	165	76	65	49	56	32
1938	117	3	196	170	216	484	201	65	43	29	35	-23
1939	-23	-39	226	349	286	328	195	84	73	62	98	46
1940	-19	88	354	317	253	354	181	94	63	62	93	41
1941	67	70	227	298	135	342	181	94	47	67	117	288
1942	240	127	115	312	205	434	235	93	76	70	38	-20
1943	-9	0	164	397	97	419	218	43	33	6	5	-31
1944	-147	-61	-34	149	90	335	166	96	79	68	94	-39
1945	51	78	139	101	167	441	197	82	74	54	85	19
1946	155	42	292	325	355	443	191	63	20	-1	38	198
1947	180	243	339	369	456	448	200	71	50	5	79	120
1948	269	156	138	252	409	612	178	48	8	-3	67	-14
1949	-55	68	337	268	291	303	111	43	37	26	77	80
1950	43	171	427	217	126	476	239	14	-4	-8	105	56
1951	218	341	264	331	292	275	192	187	32	-8	66	43
1952	-25	162	160	443	443	418	223	40	60	13	49	19
1953	198	206	194	203	226	618	313	-52	77	77	-3	7
1954	-38	142	117	82	-225	105	54	115	24	34	44	28
1955	40	-2	-7	144	110	-73	400	196	136	101	115	184
1956	557	196	234	163	247	436	125	75	106	-65	-16	85
1957	68	-32	615	401	37	993	61	95	27	52	65	76
1958	123	459	336	510	601	939	169	5	-19	4	-19	75
1959	194	177	193	199	494	405	752	81	-91	16	44	49
1960	12	161	144	306	99	128	115	0	-53	5	72	41
1961	18	194	343	91	308	770	305	15	-1	-27	69	20
1962	63	126	198	247	753	1136	285	46	5	17	20	84
1963	82	354	180	294	303	272	115	52	-9	6	59	18
1964	-80	29	120	200	-22	203	329	44	-43	0	8	313
1965	392	667	326	252	284	700	232	7	33	25	-36	11
1966	74	24	151	190	-141	5	56	44	4	2	20	75
1967	128	206	124	172	-29	399	230	44	-32	-5	-19	35
1968	32	43	-248	150	-422	-857	-602	-208	-168	-102	1	26
1969	279	28	127	852	893	529	164	-57	-110	22	-49	-45
1970	526	360	460	203	383	267	48	59	56	52	91	52
1971	673	163	282	304	1071	812	-3	-28	88	92	137	62
1972	246	311	1032	236	227	968	-247	-349	-11	-32	-34	-97
1973	-150	-59	140	84	100	25	-63	49	131	176	205	227
1974	497	165	370	503	-61	263	-207	-210	-202	-208	-113	-54
1975	67	-66	152	168	144	-115	-301	-305	-209	-190	-154	-46
1976	71	110	148	167	177	-346	-388	-466	-353	-199	-157	-122
1977	-260	-242	-241	-144	-160	-245	-351	-336	-309	-265	-292	-30
1978	-92	-140	-151	-291	-492	-346	-573	-502	-521			

Location: The Dalles and Bonneville | Data: Local Inflow (kaf/month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1928							631	1941	1992	655	463	2191
1929	469	448	688	644	882	677	517	409	363	368	349	290
1930	407	896	628	636	592	377	435	345	353	360	369	189
1931	446	404	603	886	720	491	496	342	322	363	407	205
1932	605	633	1144	929	986	730	530	427	400	396	625	303
1933	689	505	758	861	1005	1156	717	504	450	489	518	958
1934	1501	770	886	770	611	526	454	421	394	488	705	419
1935	835	700	726	754	920	728	524	436	399	385	399	224
1936	955	530	828	939	976	696	487	416	399	372	347	236
1937	403	449	769	1013	955	836	536	404	386	396	696	552
1938	1158	758	1305	1297	1106	740	533	438	408	416	462	288
1939	582	583	728	668	640	464	411	367	360	361	339	284
1940	517	962	1087	810	685	443	403	381	368	379	430	271
1941	623	554	631	545	573	416	367	335	375	399	464	451
1942	537	812	636	724	675	542	407	348	335	356	731	564
1943	1067	1139	1093	1673	1078	861	650	475	407	460	494	272
1944	516	544	556	546	550	441	380	337	332	344	387	198
1945	581	695	594	627	857	512	397	338	337	320	468	426
1946	1041	695	933	848	923	687	545	404	373	424	640	609
1947	714	843	794	664	592	494	406	362	349	610	641	306
1948	990	828	761	774	1009	889	504	416	371	442	565	392
1949	480	943	1163	1095	1251	759	539	436	413	438	567	324
1950	644	944	1279	1090	1057	1039	666	499	440	616	927	671
1951	1302	1486	1043	1171	1063	682	525	468	437	666	673	434
1952	595	1024	821	1136	930	693	542	453	416	398	401	237
1953	1671	1184	807	777	918	754	560	465	420	444	592	530
1954	986	1103	1039	1031	930	793	616	483	440	474	558	299
1955	616	583	574	666	812	878	601	451	423	577	941	768
1956	1408	769	1153	1321	1415	993	663	532	484	528	559	401
1957	559	681	1194	1024	912	556	464	427	409	460	491	412
1958	963	1387	867	981	919	668	494	424	405	339	835	412
1959	1074	691	814	604	31	-103	-135	415	416	638	511	351
1960	493	1003	960	1017	638	658	469	375	400	510	934	372
1961	1055	1898	1328	753	29	72	704	529	466	462	611	526
1962	891	742	923	954	93	-20	304	327	352	389	790	443
1963	607	1002	639	756	346	325	252	314	337	275	665	311
1964	1235	768	640	468	439	375	995	355	412	377	560	1048
1965	1284	1048	661	636	465	33	415	484	608	506	542	272
1966	886	582	992	920	555	429	227	381	435	414	577	446
1967	935	777	389	426	309	-107	122	140	412	515	524	322
1968	788	1453	917	665	564	952	656	365	389	485	809	355
1969	795	676	828	528	123	-38	-17	388	412	371	467	351
1970	1538	904	694	484	157	82	19	109	211	290	422	341
1971	1368	860	583	590	179	124	203	79	209	235	606	401
1972	1387	1228	1152	350	-178	-1276	192	669	416	494	662	582
1973	1004	576	585	483	413	328	238	156	285	315	965	753
1974	1626	866	839	525	602	-345	500	634	598	691	747	445
1975	1389	1016	1050	808	536	359	859	691	613	677	1005	761
1976	1459	835	1032	695	13	377	624	600	715	703	653	425
1977	840	555	711	716	559	664	591	624	584	700	1075	1066
1978	1198	1106	1073	1007	942	743	1096	871	1035			

APPENDIX E

PENALTY FUNCTIONS USED IN PHASE I ANALYSIS

APPENDIX E

PENALTY FUNCTIONS USED IN PHASE I ANALYSIS

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APPENDIX E

PENALTY FUNCTIONS USED IN PHASE I ANALYSIS

INTRODUCTION

The following plots depict the edited penalty functions used in Phase I of the study. The penalties are in thousands of dollars, the storage in 1,000 acre-feet per month, and flow in cubic feet per second (cfs). These edited composite penalty functions were derived by manually editing the computed function developed by IWR. Appendix E contains the convex, composite functions used as input to HEC-PRM.

From the standpoint of network flow programming, the reservoir storage arcs contain flow volume per month. The beginning-of-period storage comes into a node through arcs connected to the same node in the previous time period and the end-of-period storage leaves the node through arcs connected to the same node in the next time period.

The graphs are plotted on 2 scales: (1) reservoir storage, penalty from 0 to $90 million, storage from 0 to 10 million acre-feet per month; (2) reservoir release and channel flow, penalty from 0 to $50 million, release from 0 to 800,000 cfs.

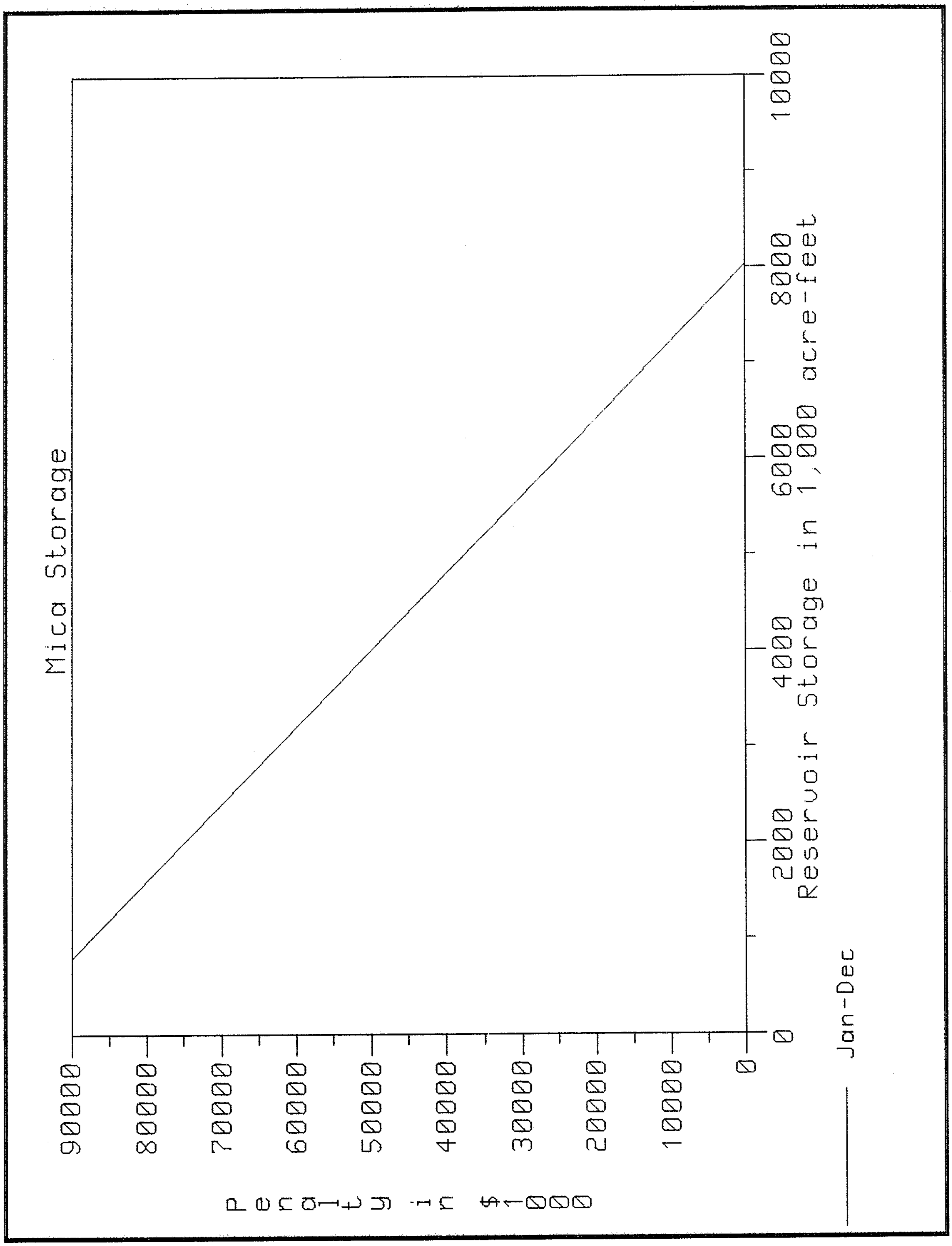

FIGURE E-1 Mica Storage

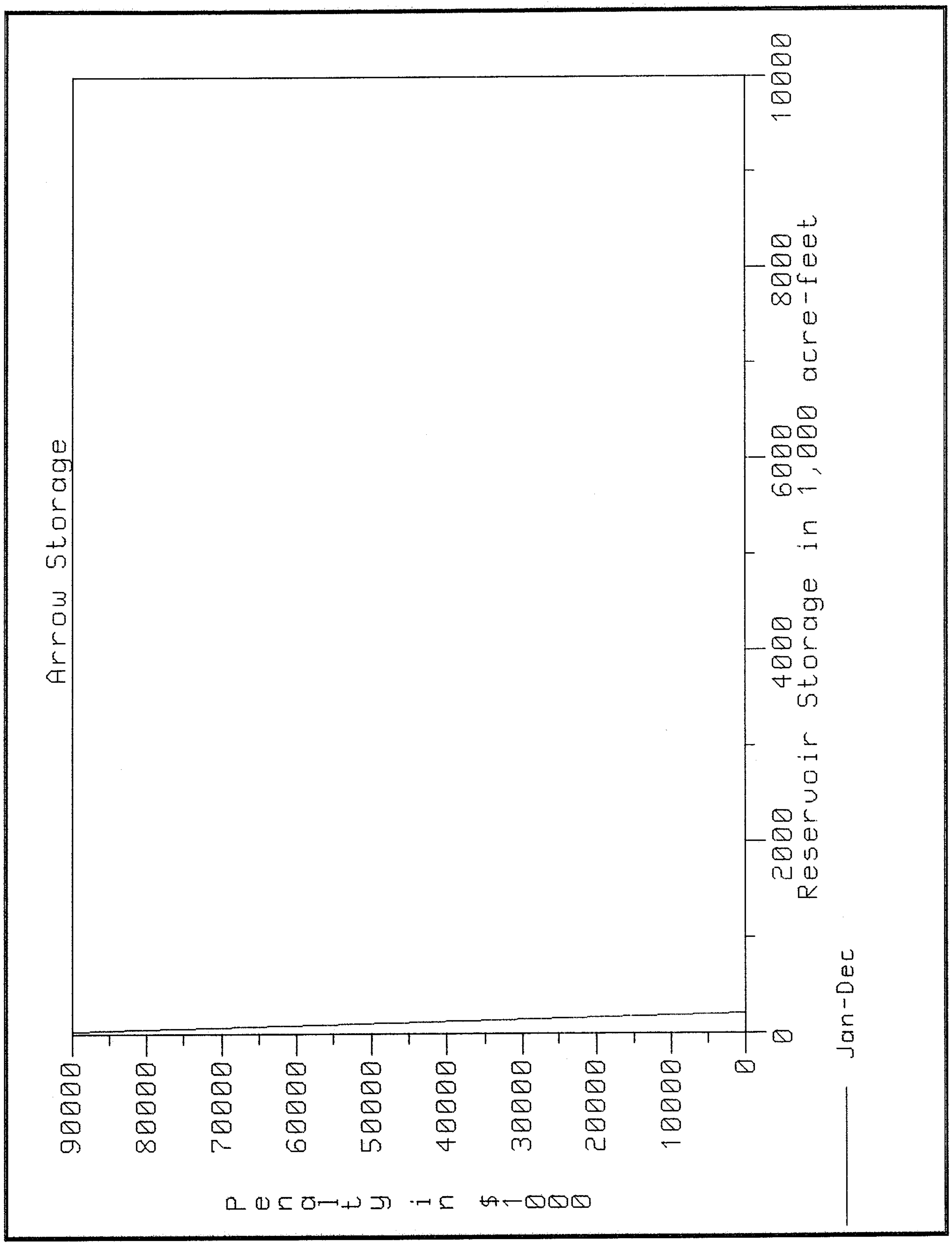

FIGURE E-2 Arrow Storage

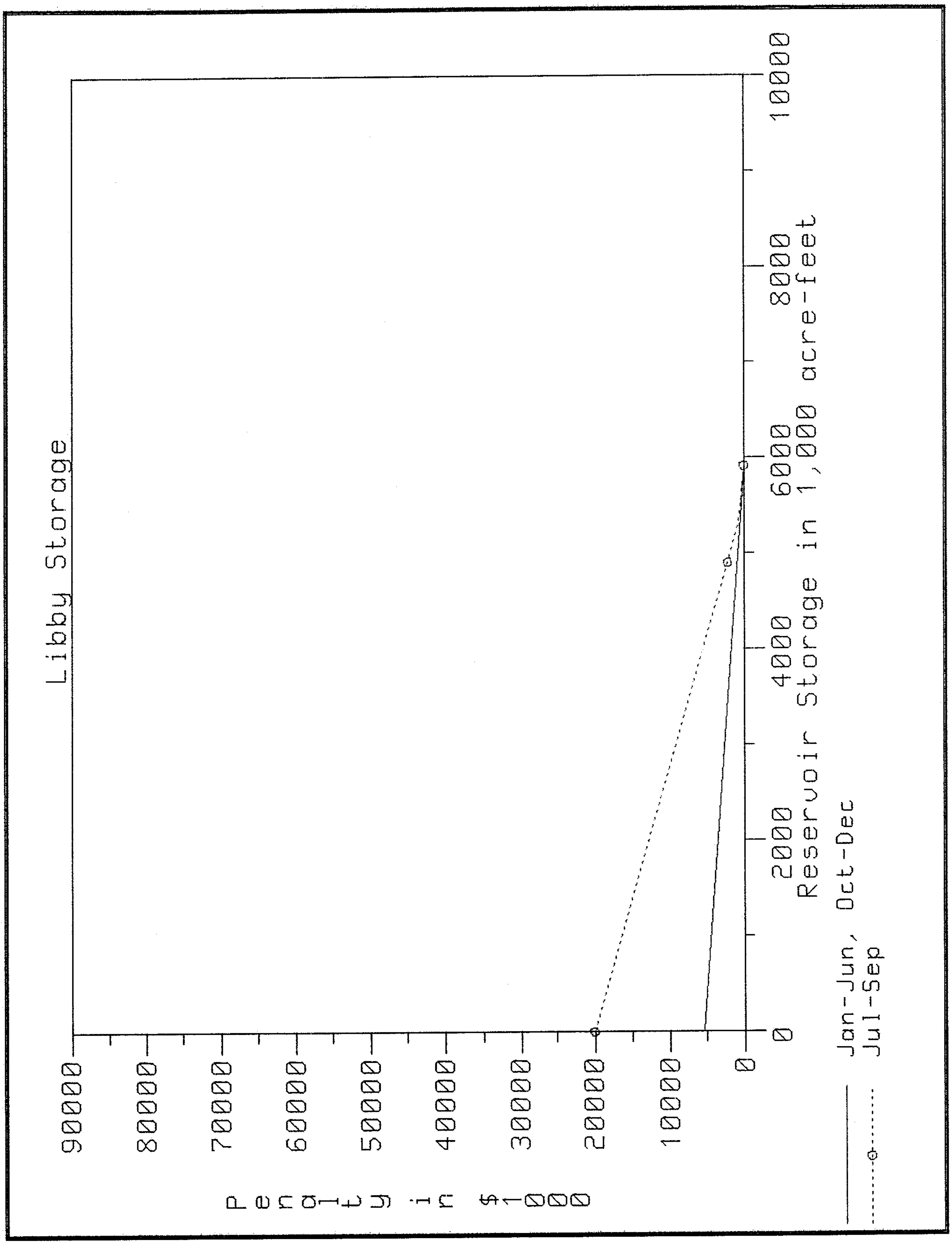

FIGURE E-3 Libby Storage

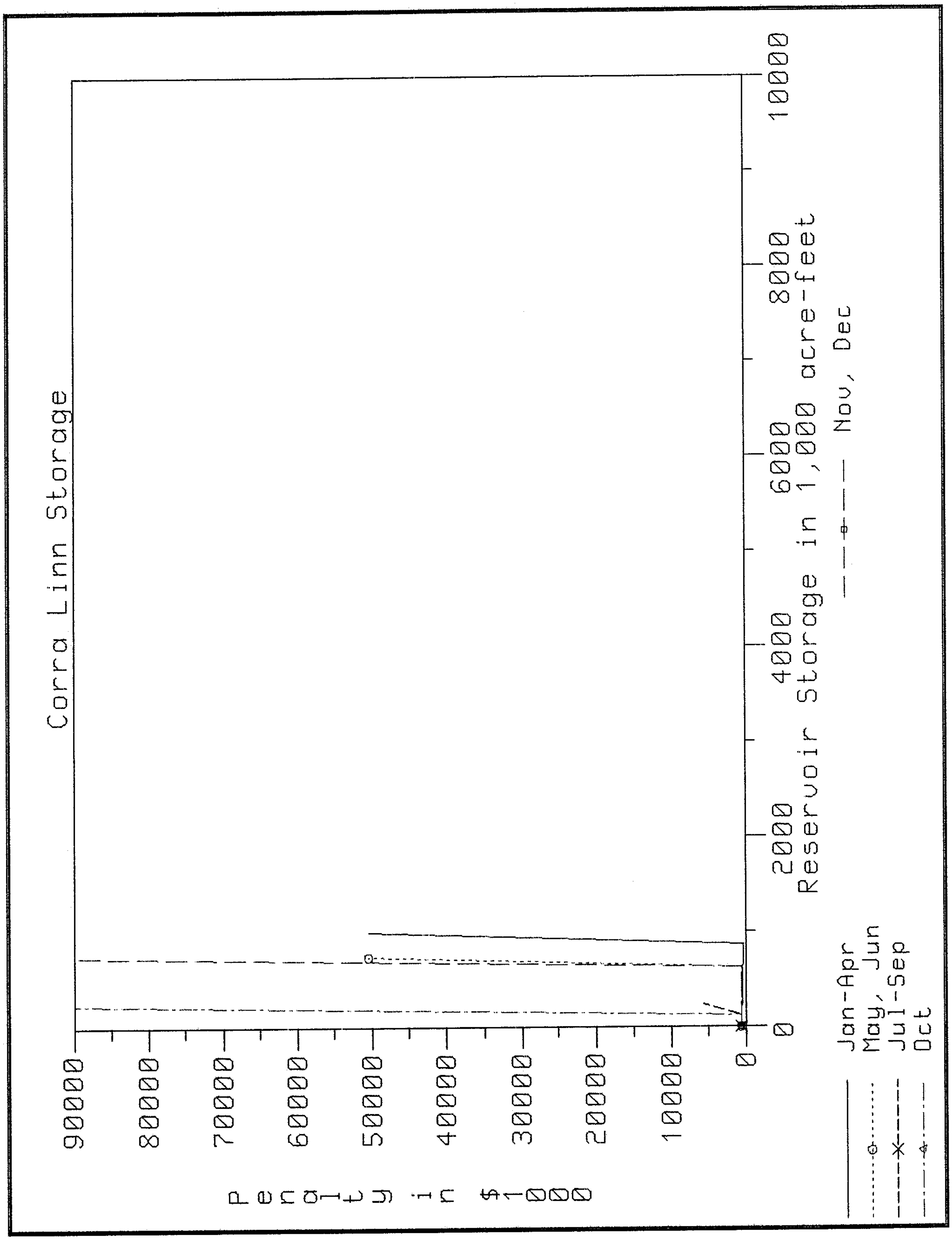

FIGURE E-4 Corra Linn Storage

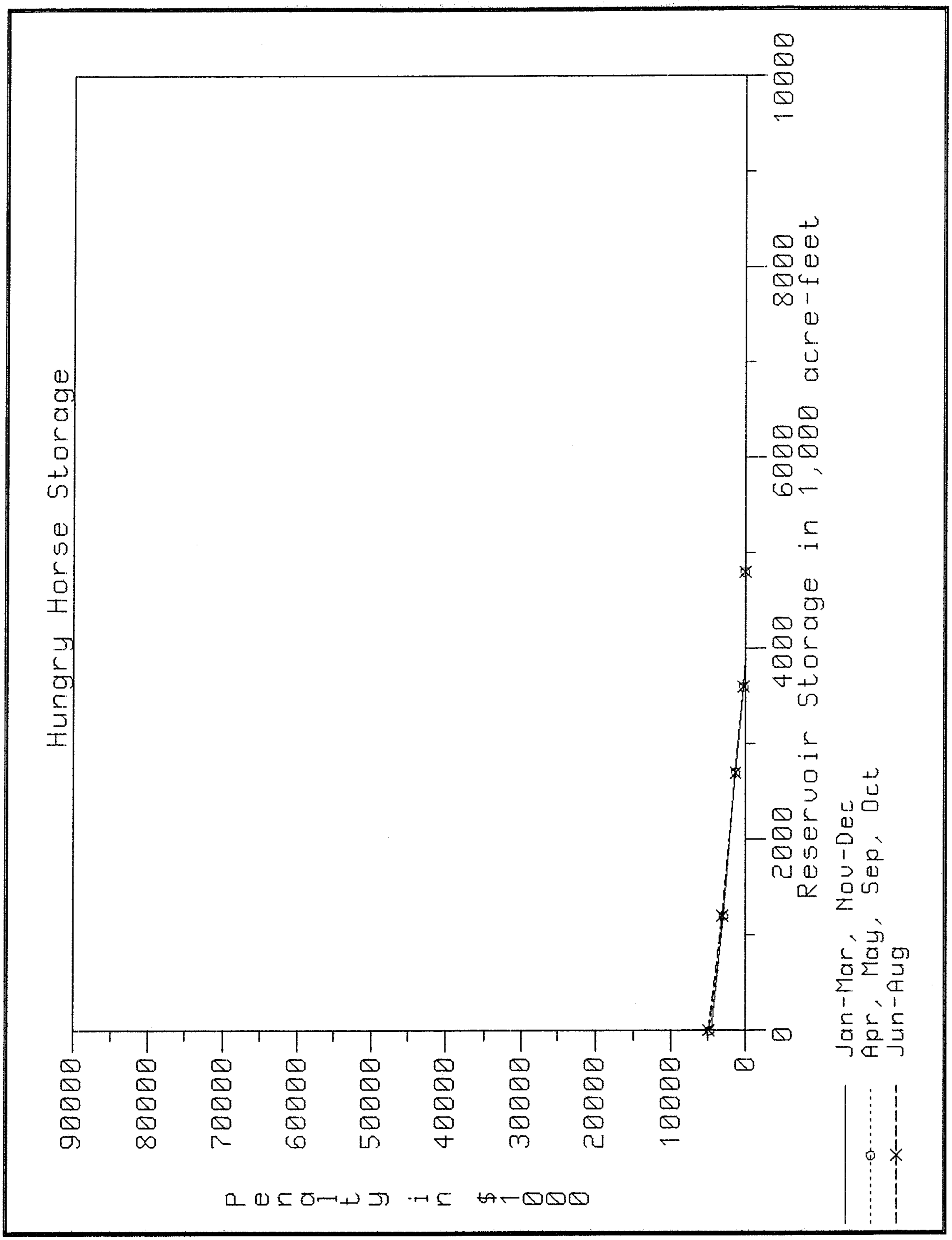

FIGURE E-5 Hungry Horse Storage

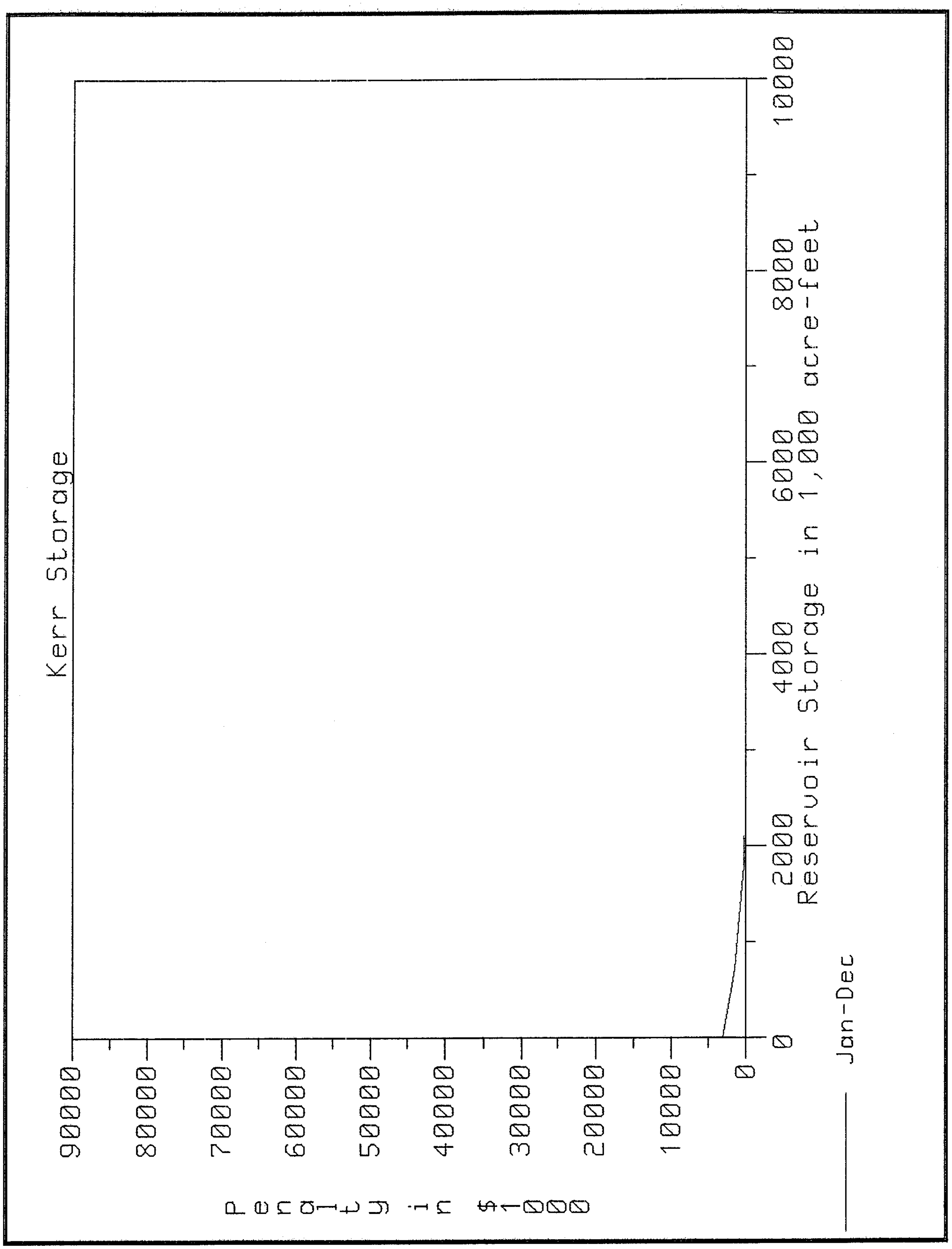

FIGURE E-6 Kerr Storage

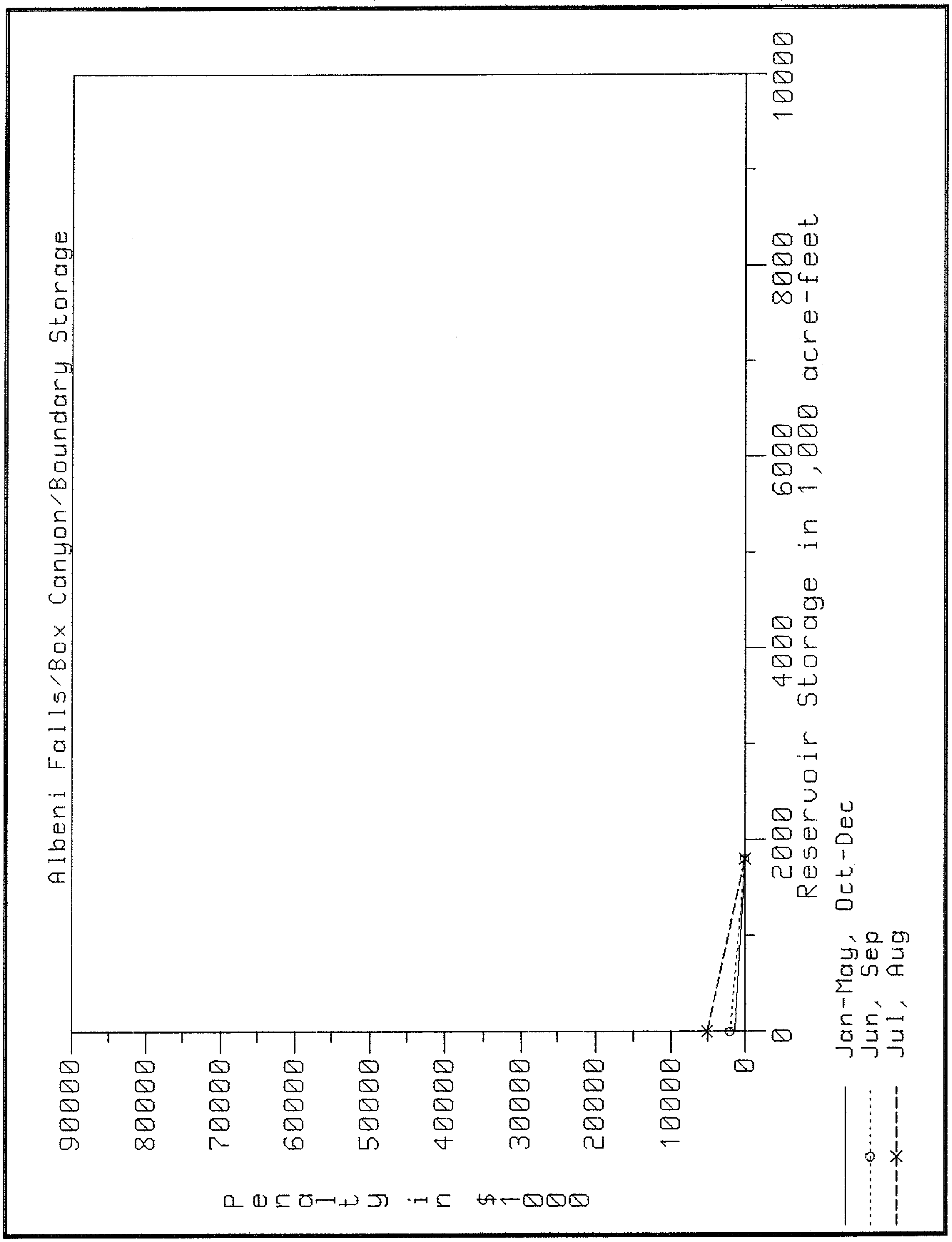

FIGURE E-7 Albeni Falls/Box Canyon/Boundary Storage

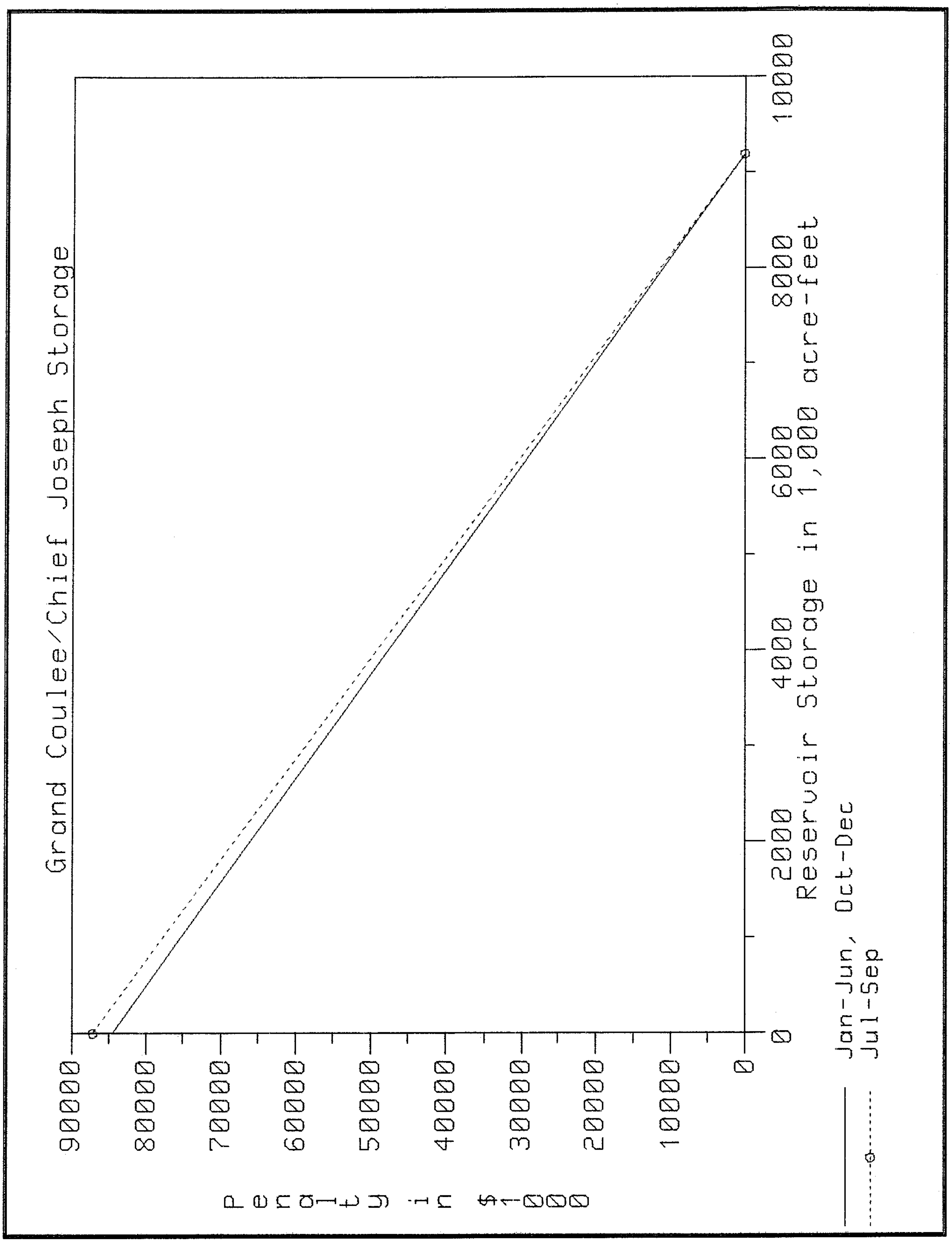

FIGURE E-8 Grand Coulee/Chief Joseph Storage

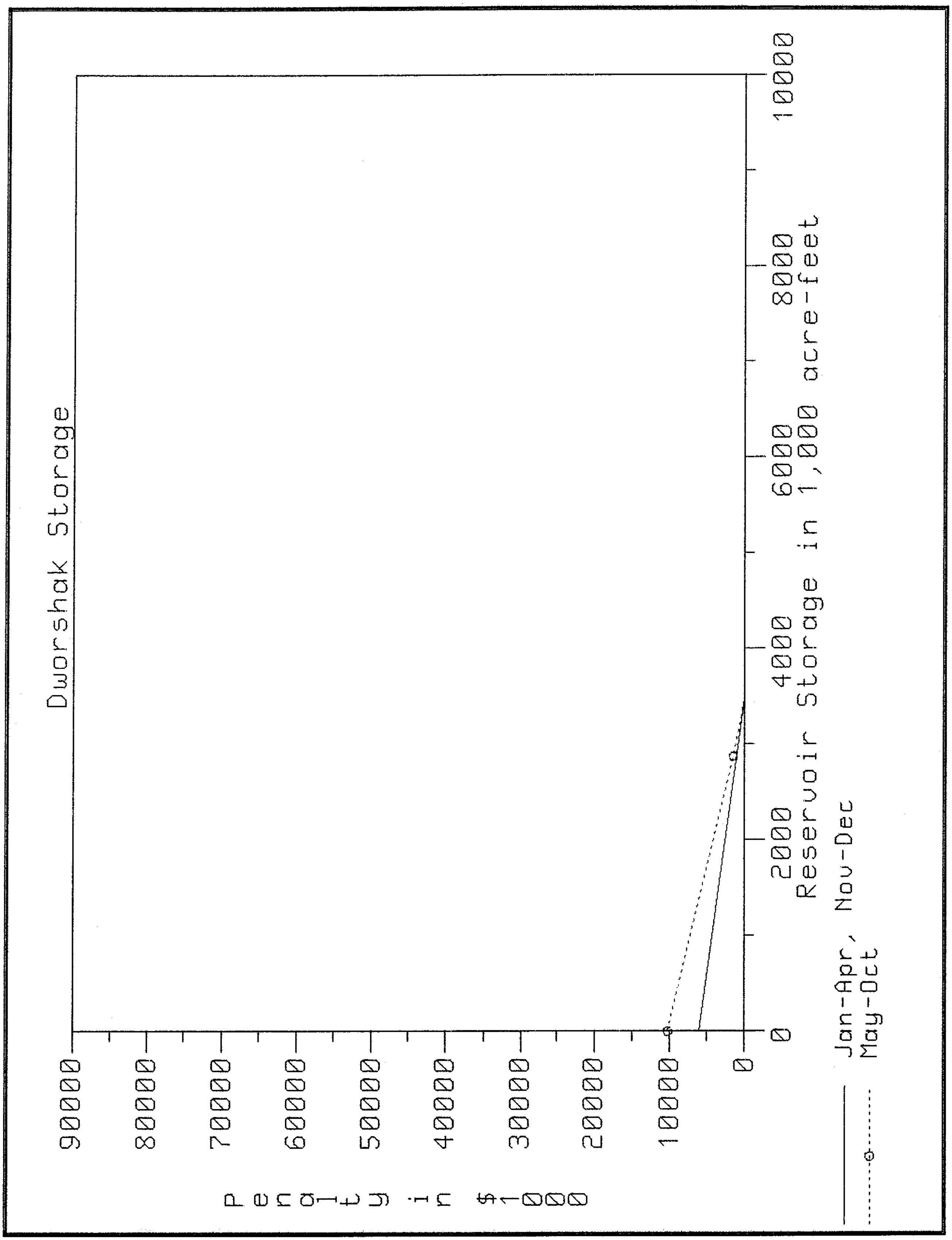

FIGURE E-9 Dworshak Storage

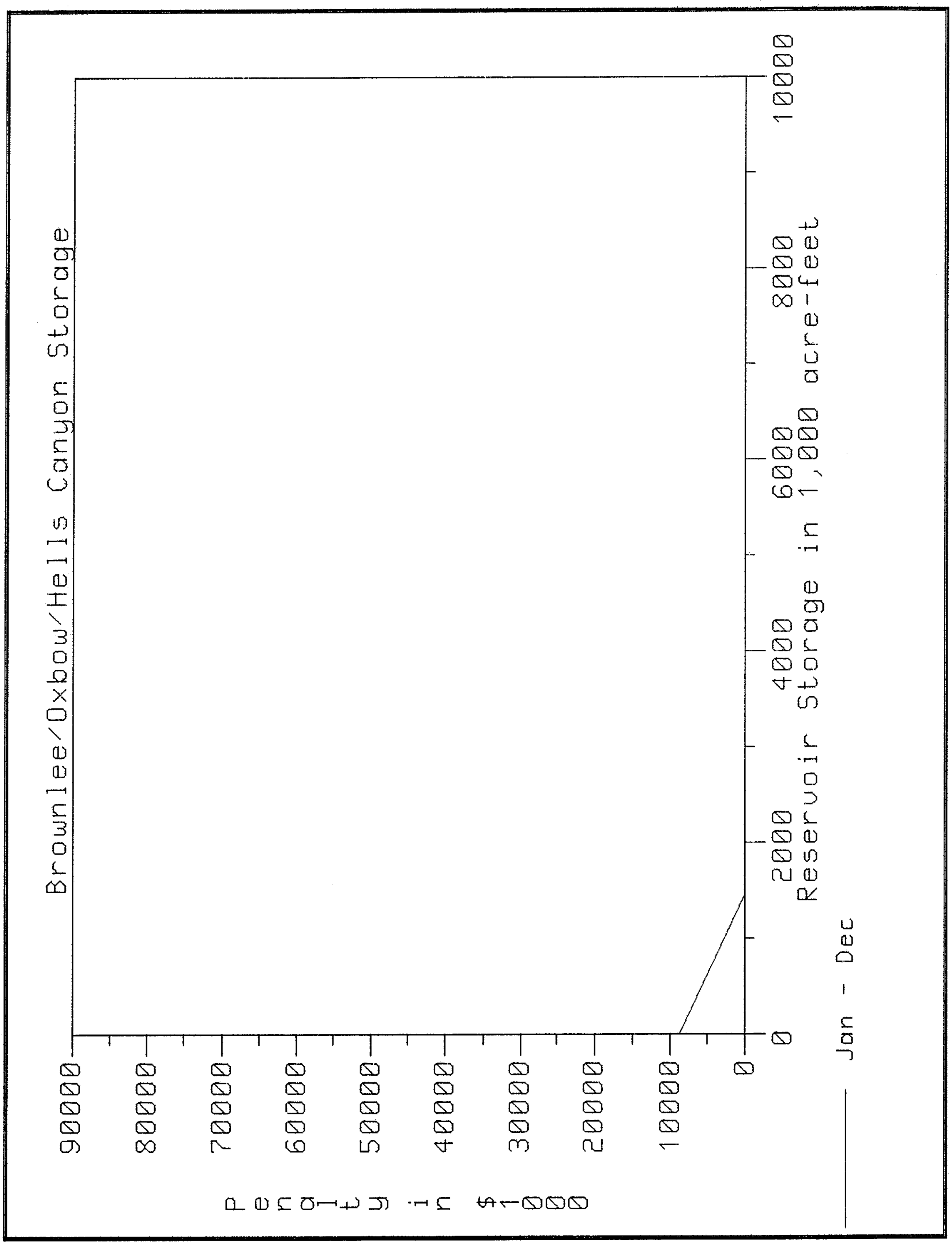

FIGURE E-10 Brownlee/Oxbow/Hells Canyon Storage

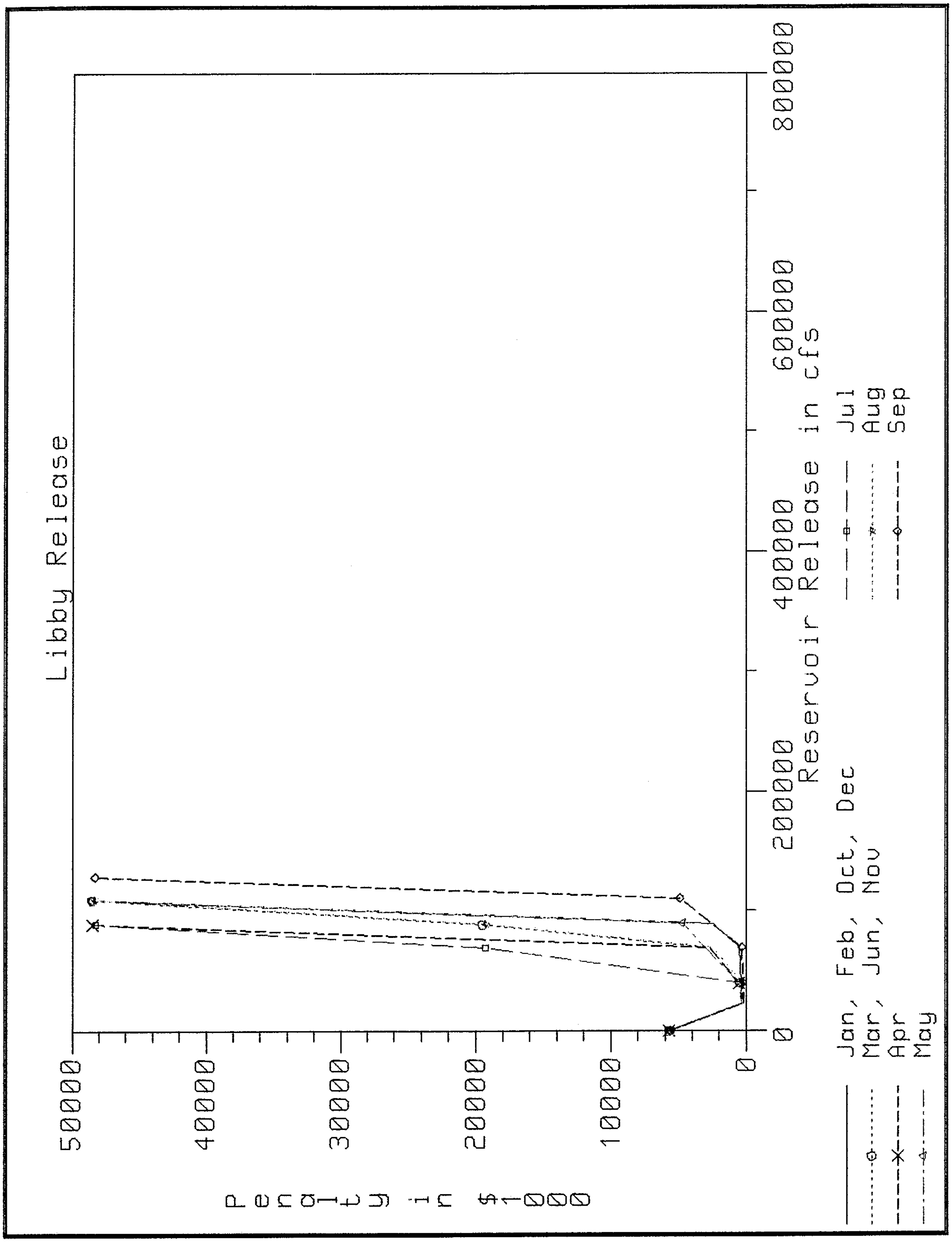

FIGURE E-11 Libby Release

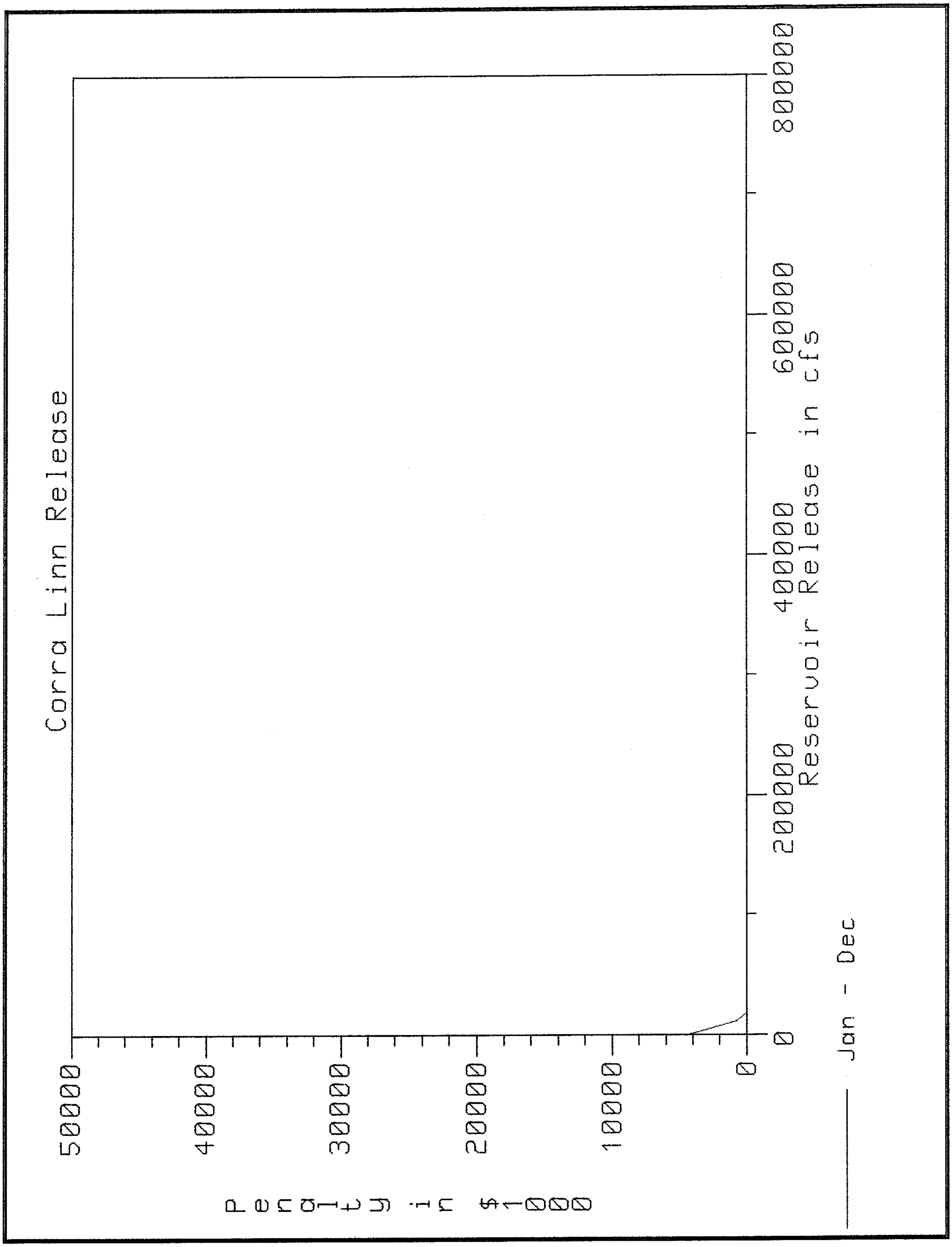

FIGURE E-12 Corra Linn Release

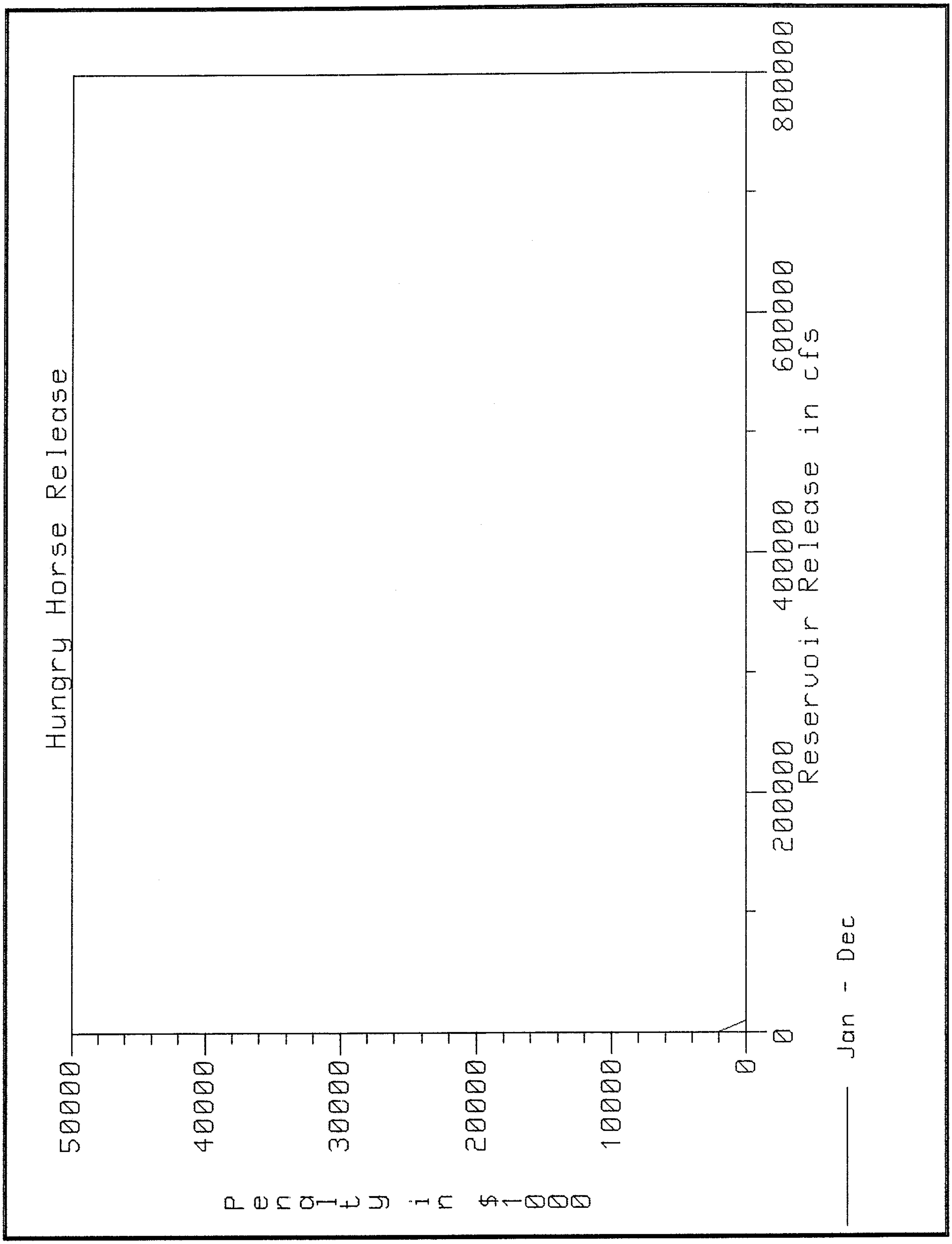

FIGURE E-13 Hungry Horse Release

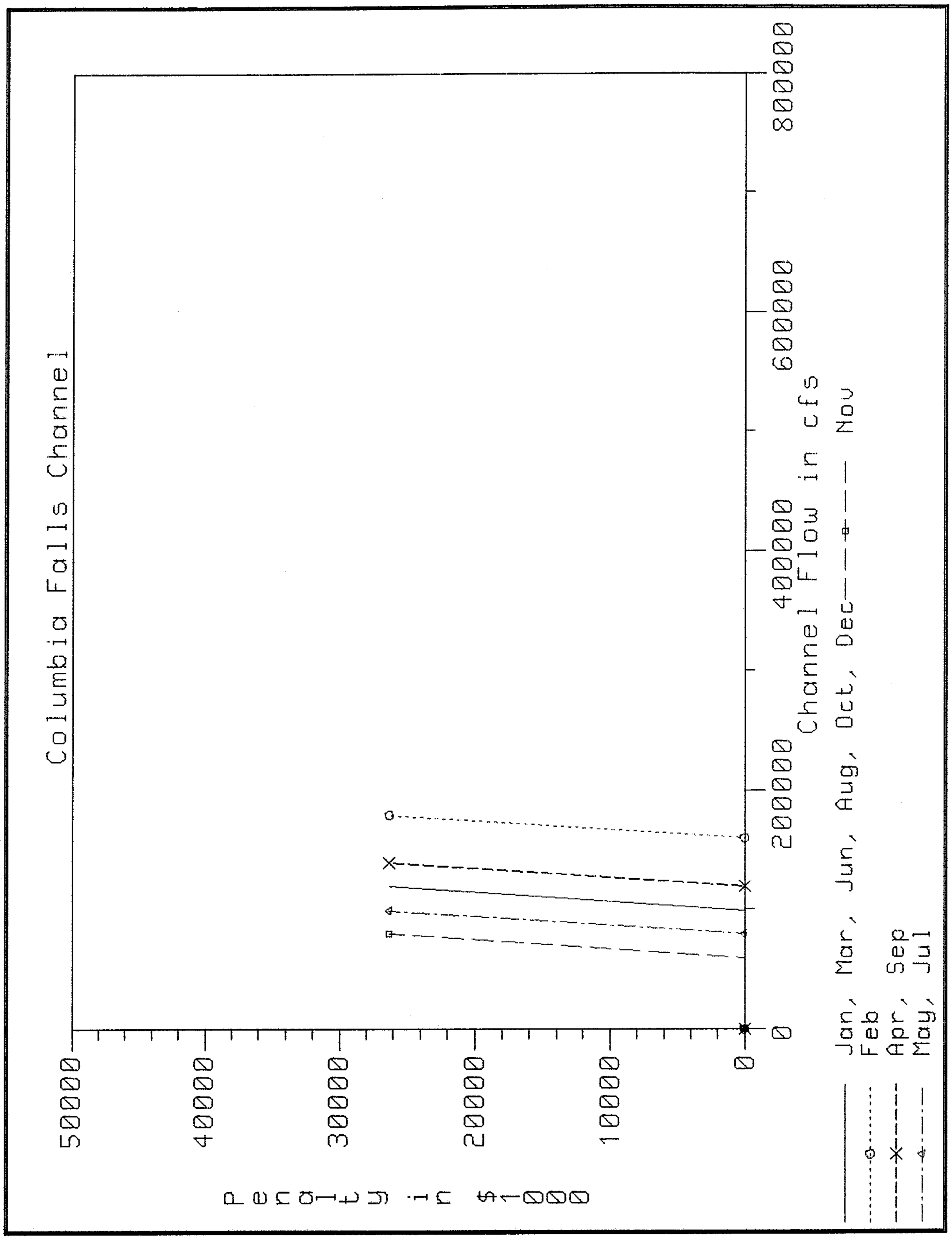

FIGURE E-14 Columbia Falls Channel

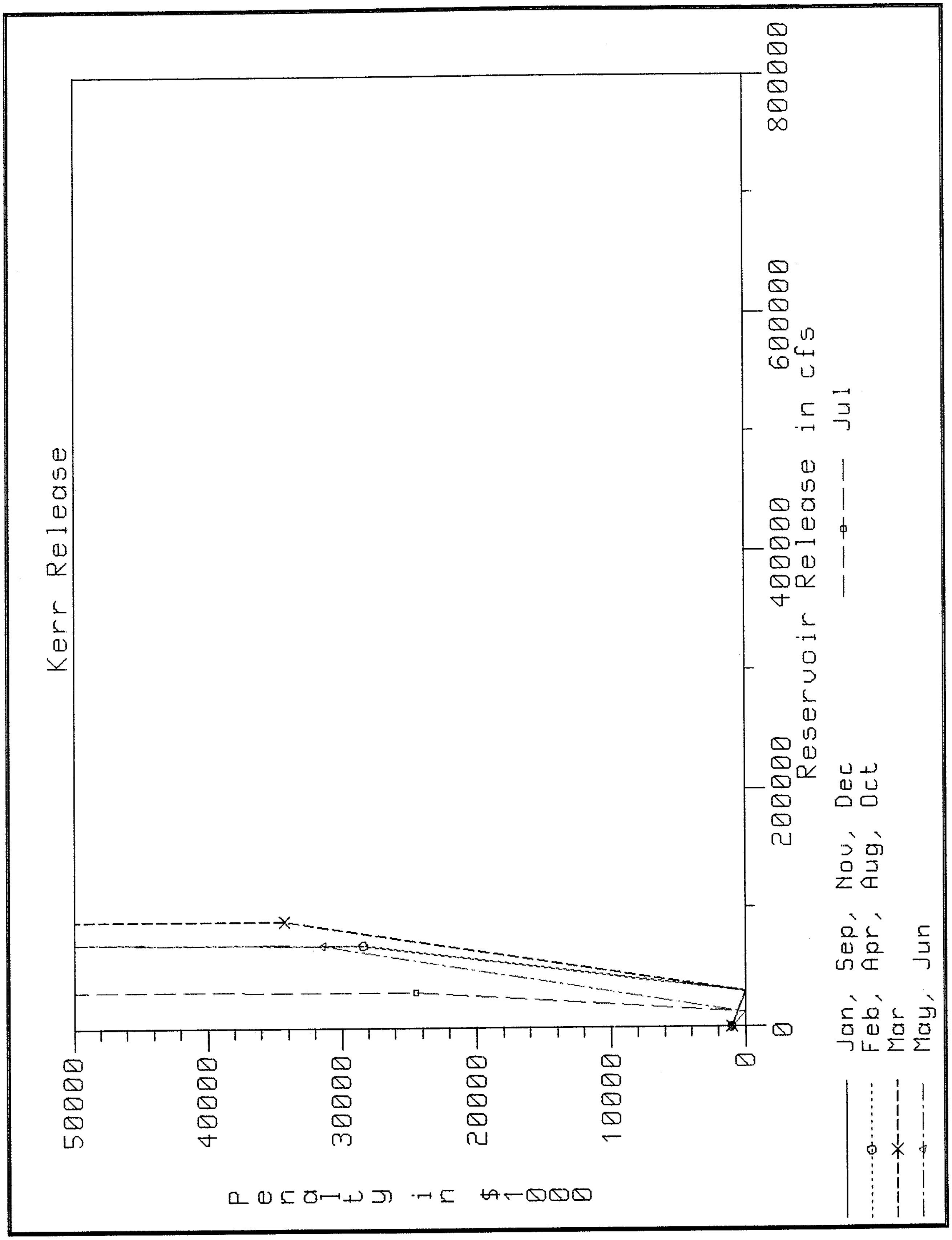

FIGURE E-15 Kerr Release

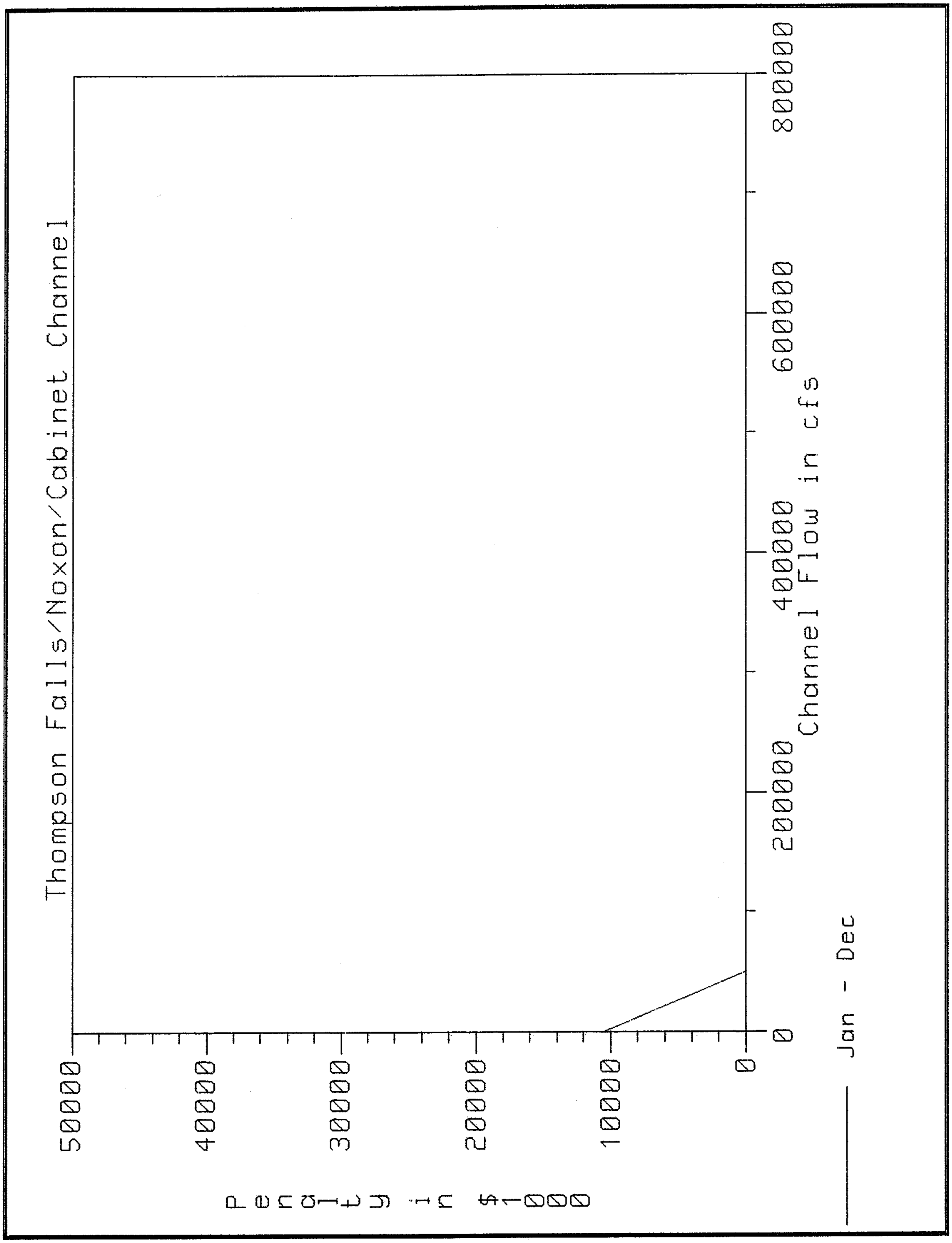

FIGURE E-16 Thompson Falls Noxon Cabinet Channel

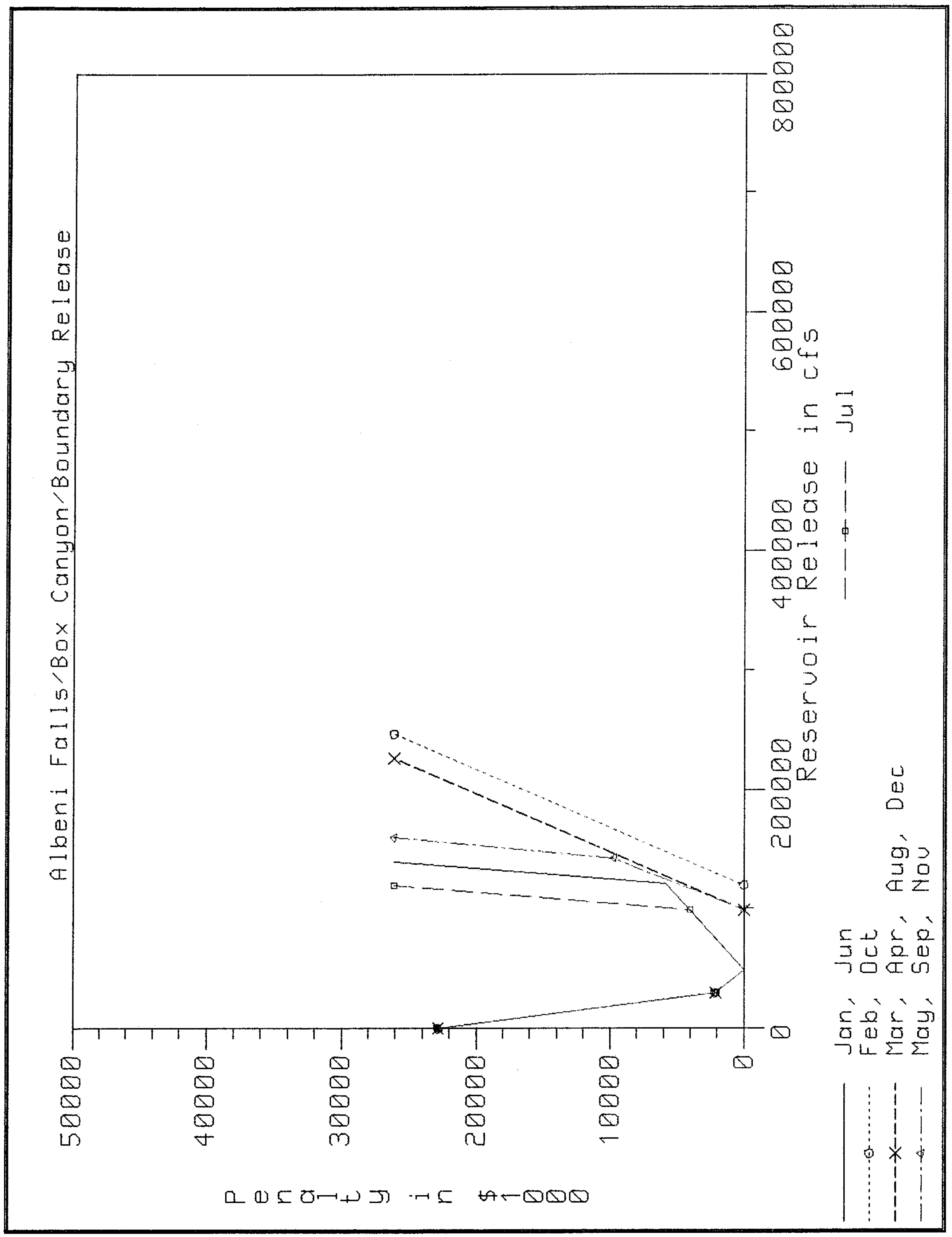

FIGURE E-17 Albeni Falls Box Canyon/Boundary Release

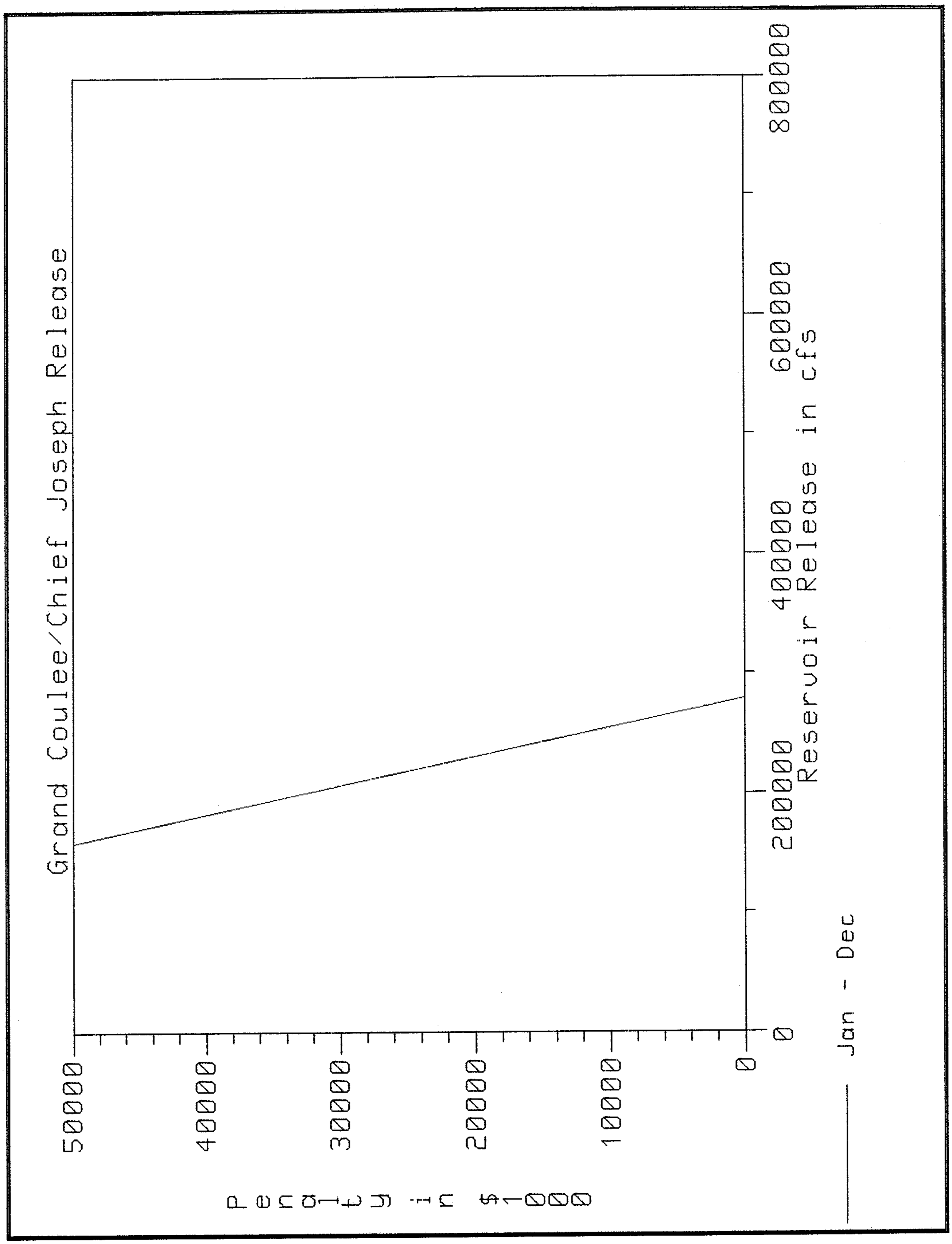

FIGURE E-18 Grand Coulee/Chief Joseph Release

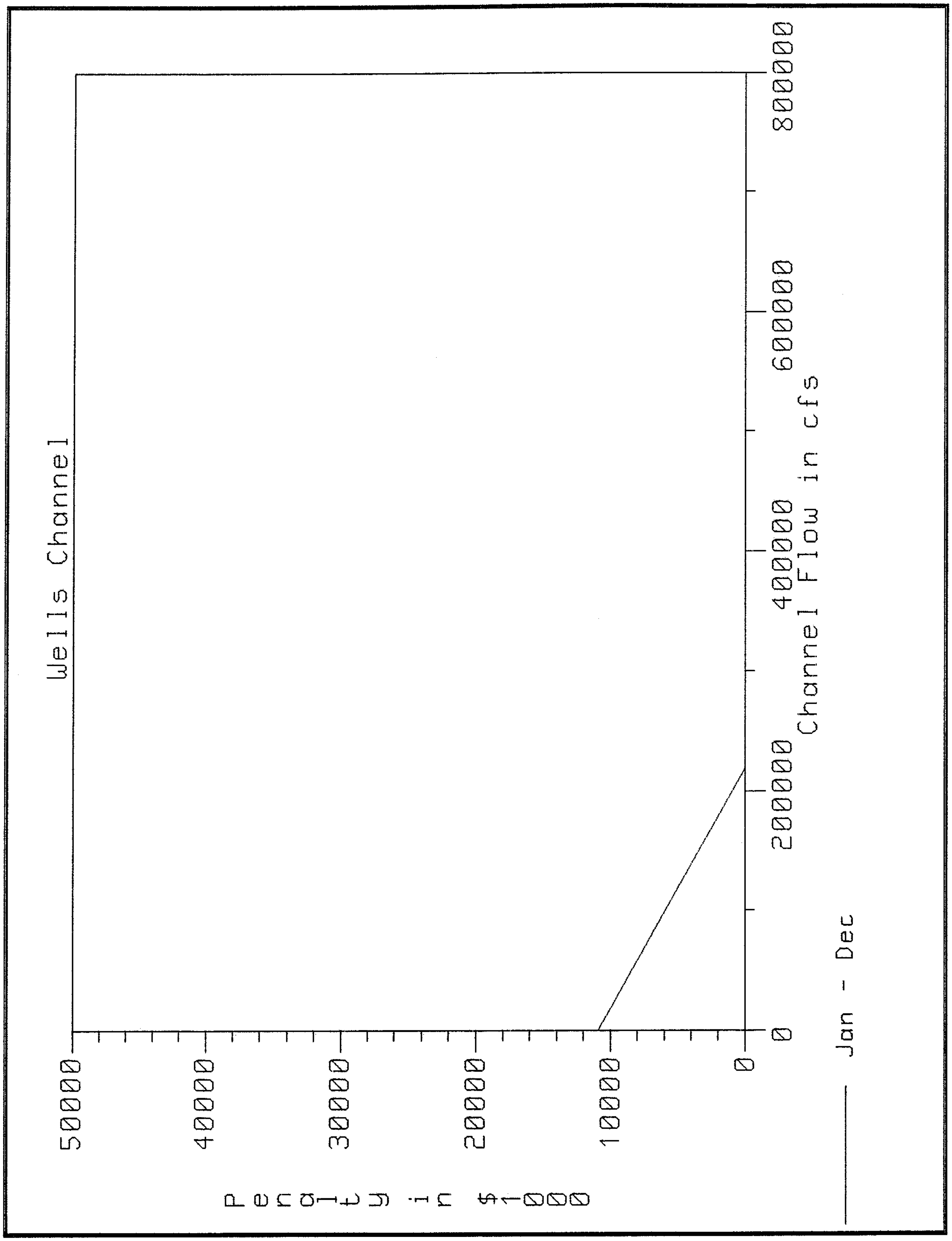

FIGURE E-19 Wells Channel

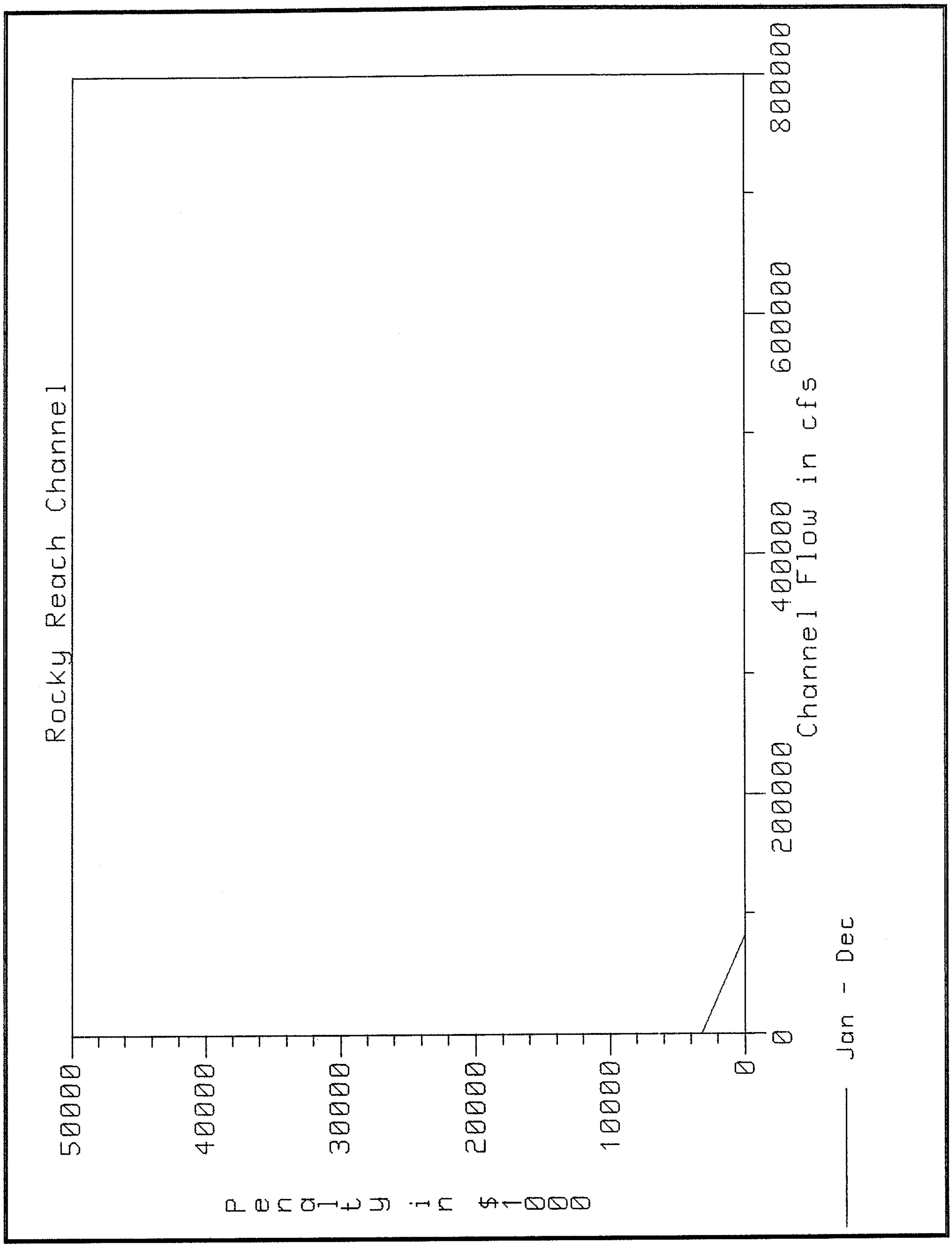

FIGURE E-20 Rocky Reach Channel

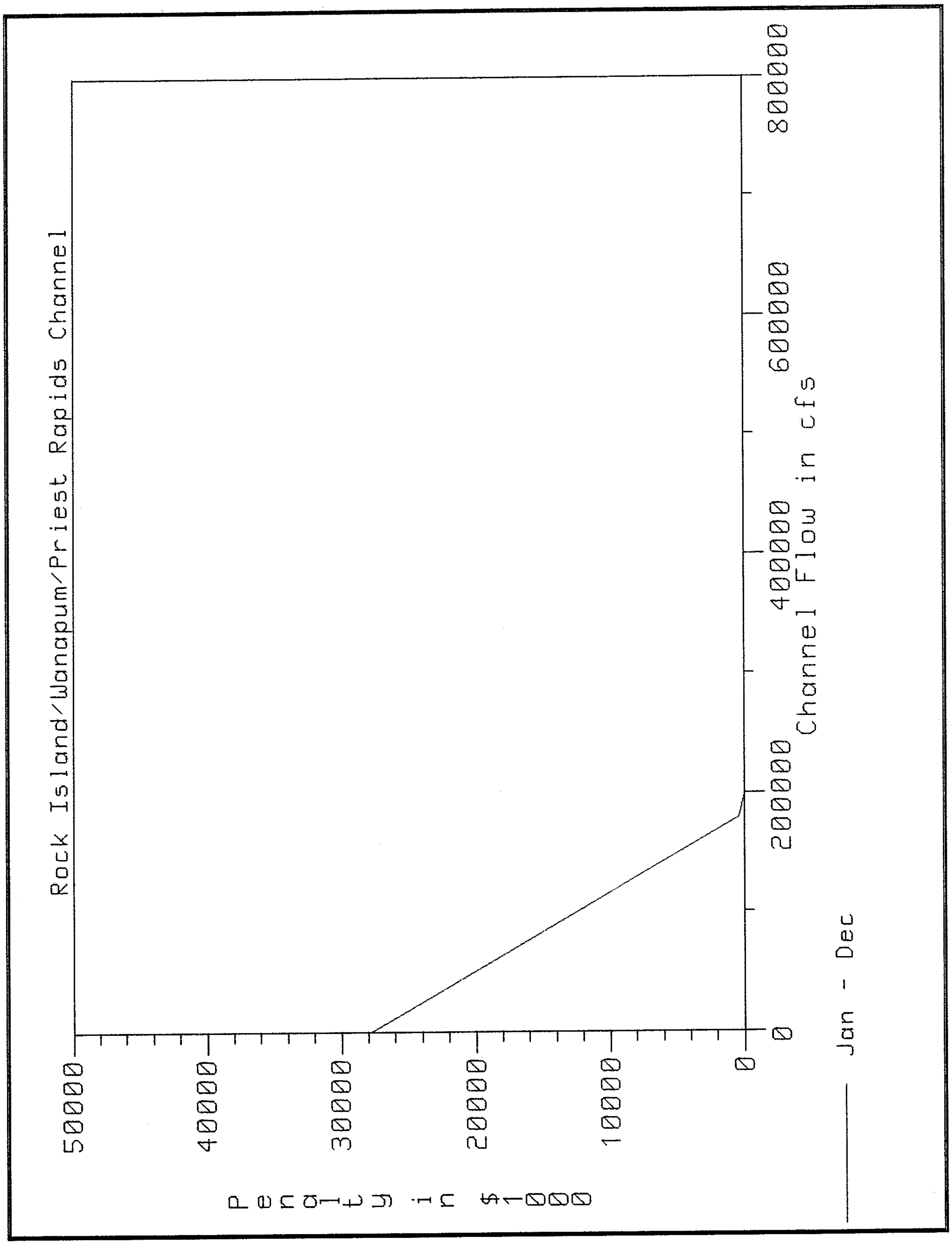

FIGURE E-21 Rock Island/Wanapum/Priest Rapids Channel

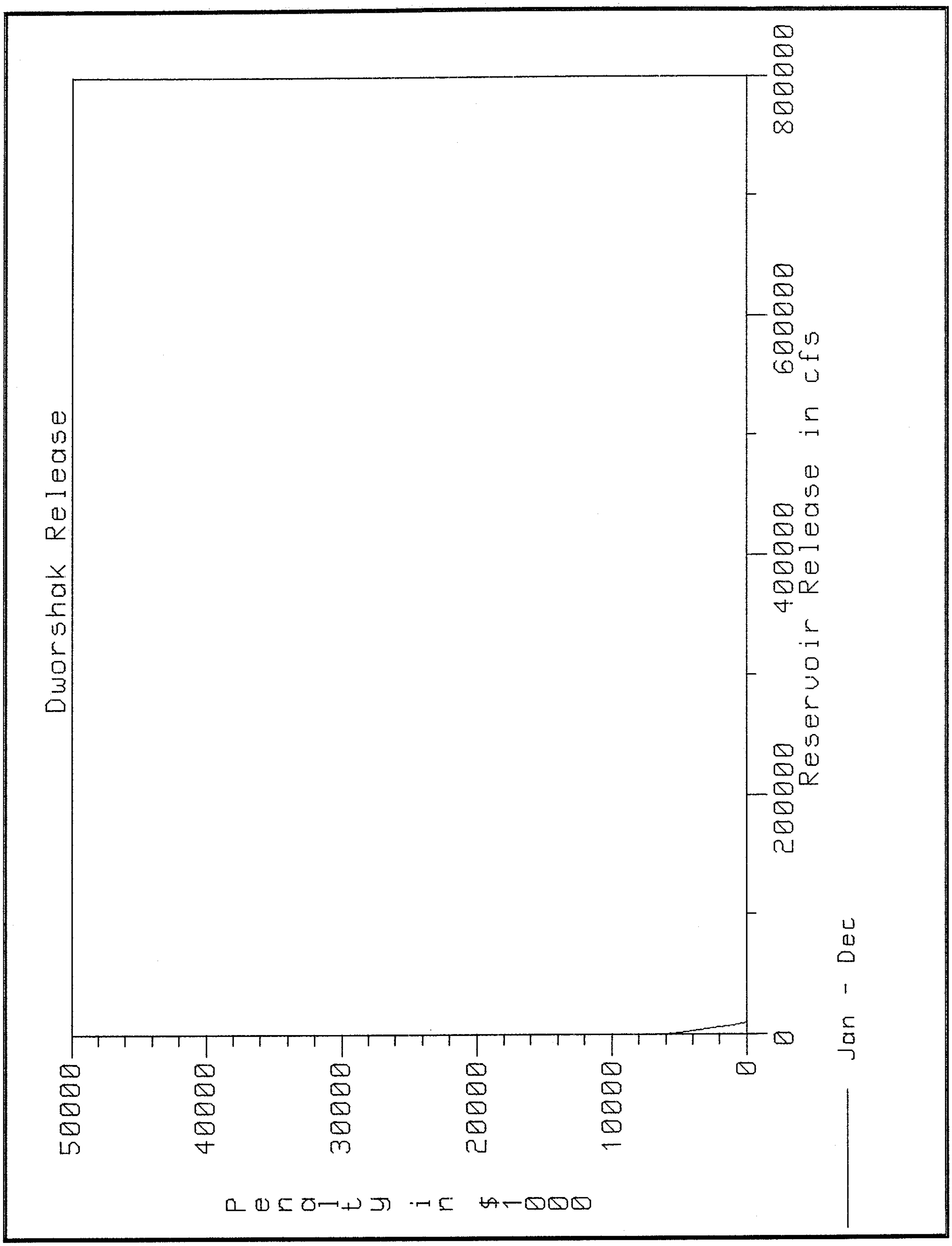

FIGURE E-22 Dworshak Release

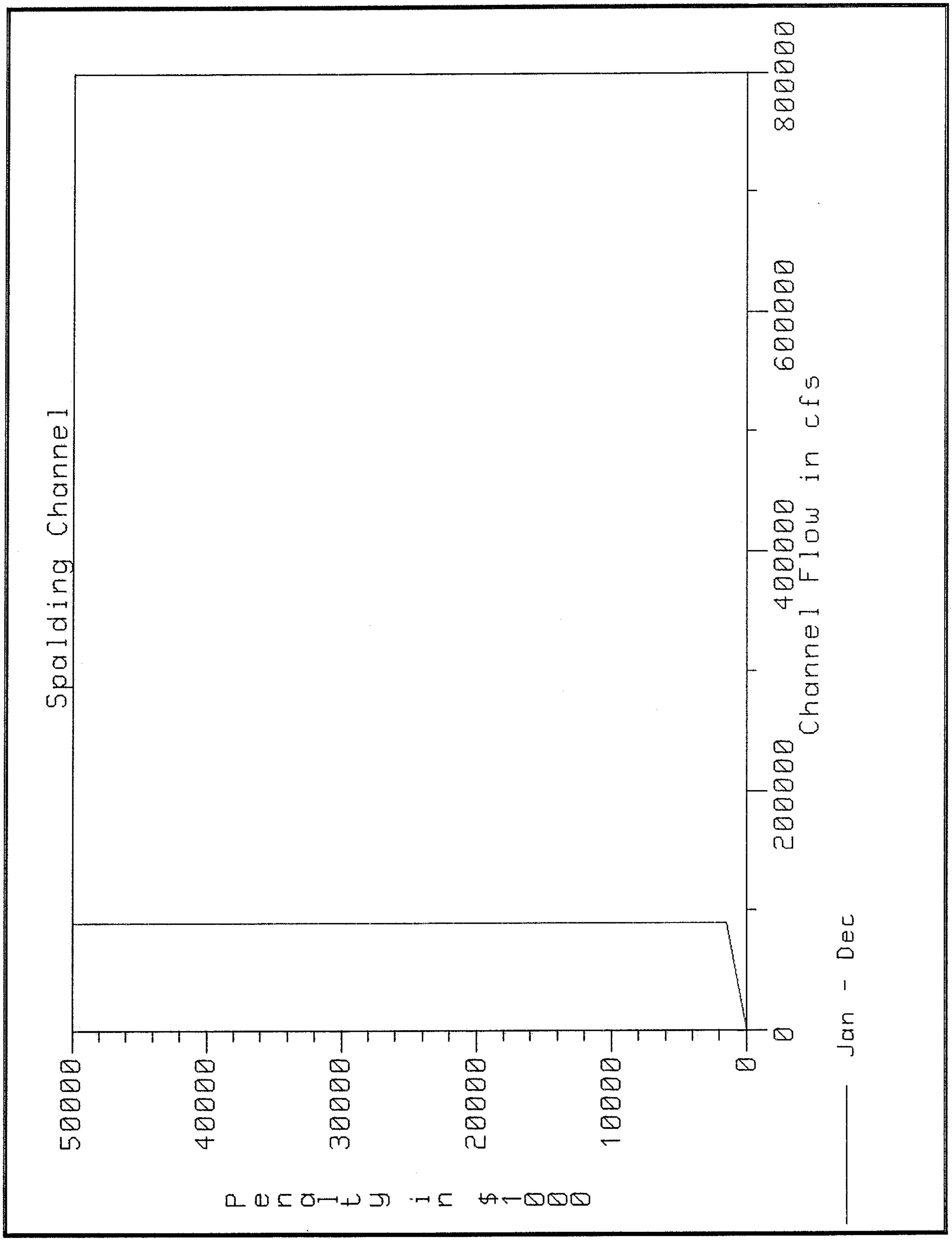

FIGURE E-23 Spalding Channel

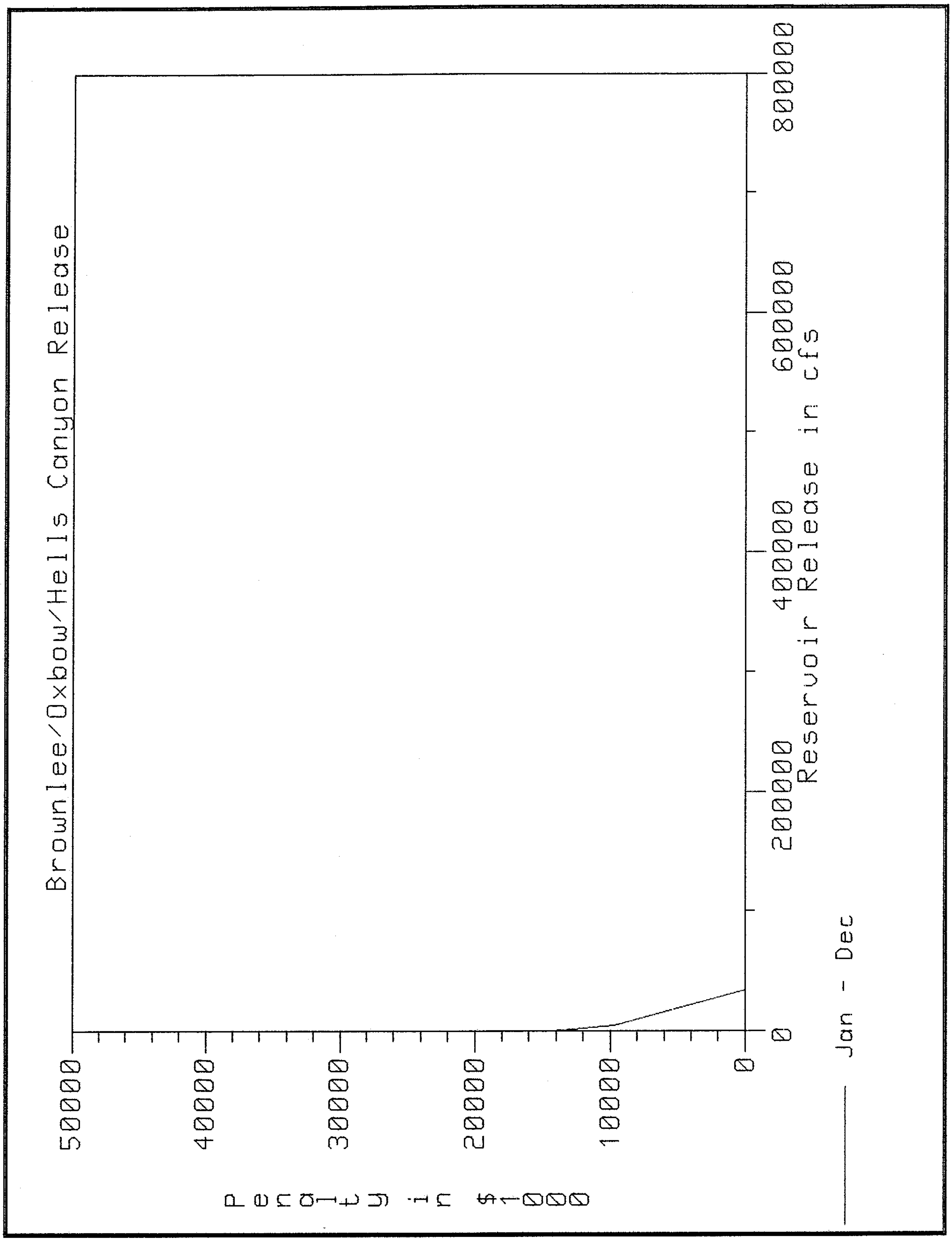

FIGURE E-24 Brownlee/Oxbow/Hells Canyon Release

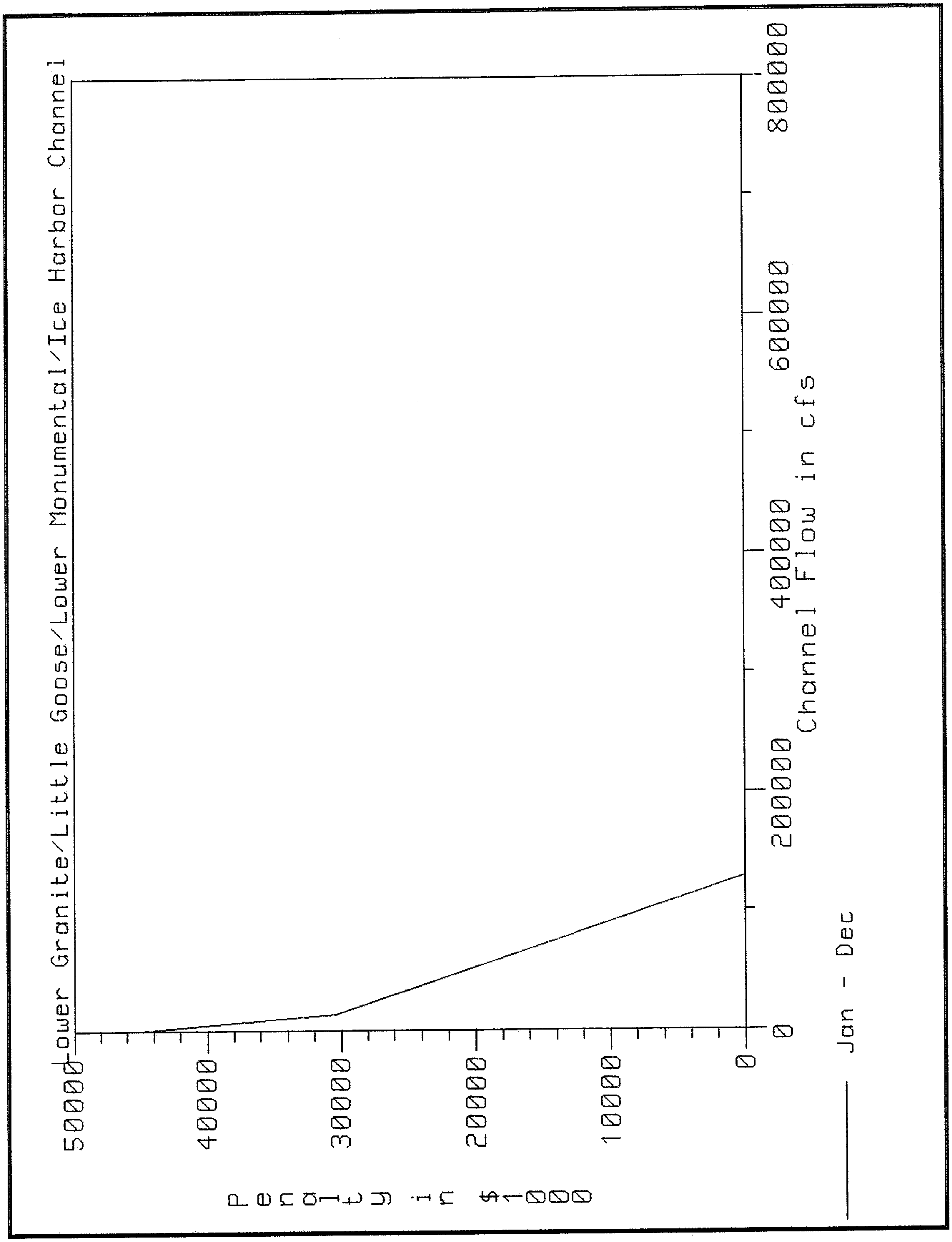

FIGURE E-25 Lower Granite/Little Goose/Lower Monumental/Ice Harbor Channel

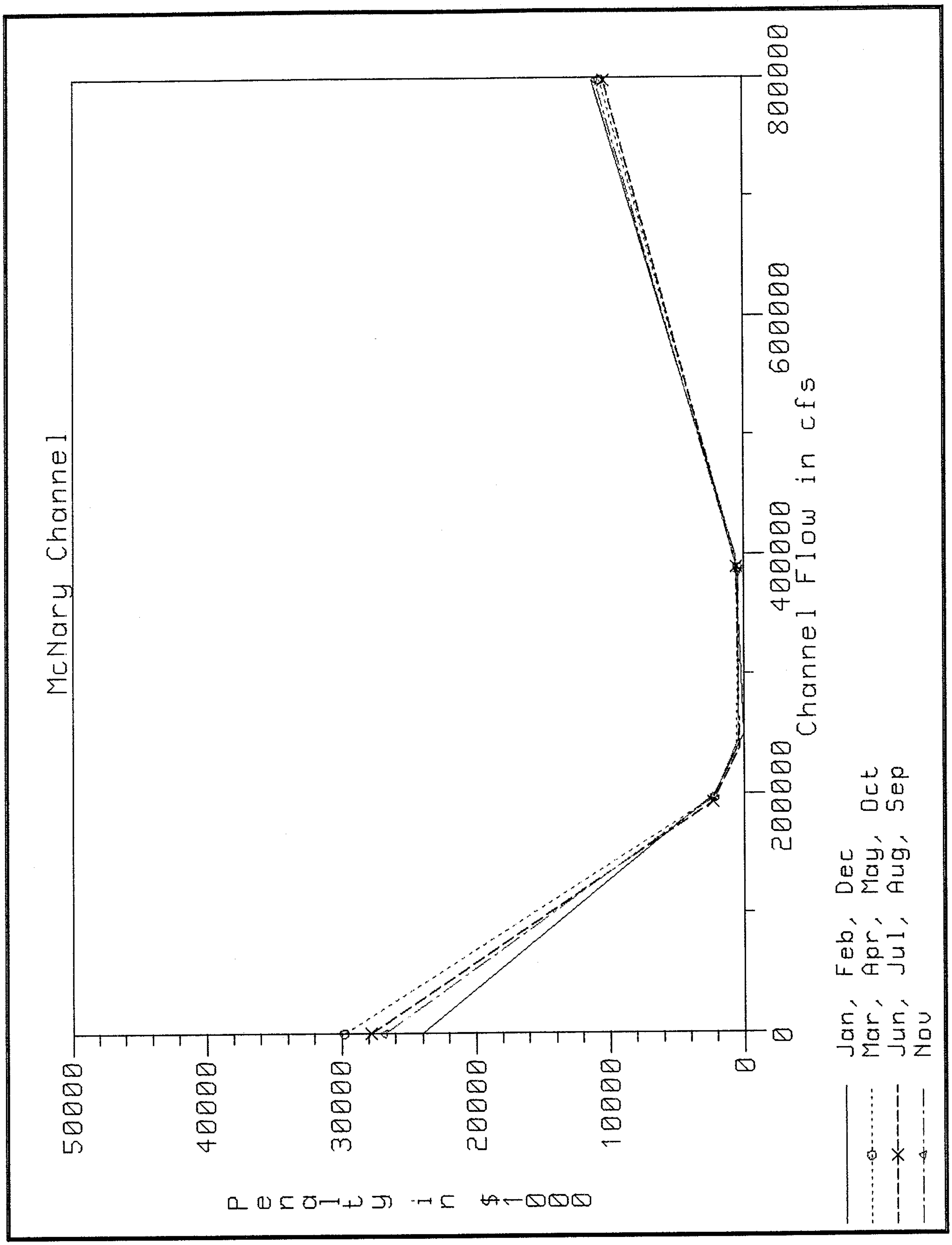

FIGURE E-26 McNary Channel

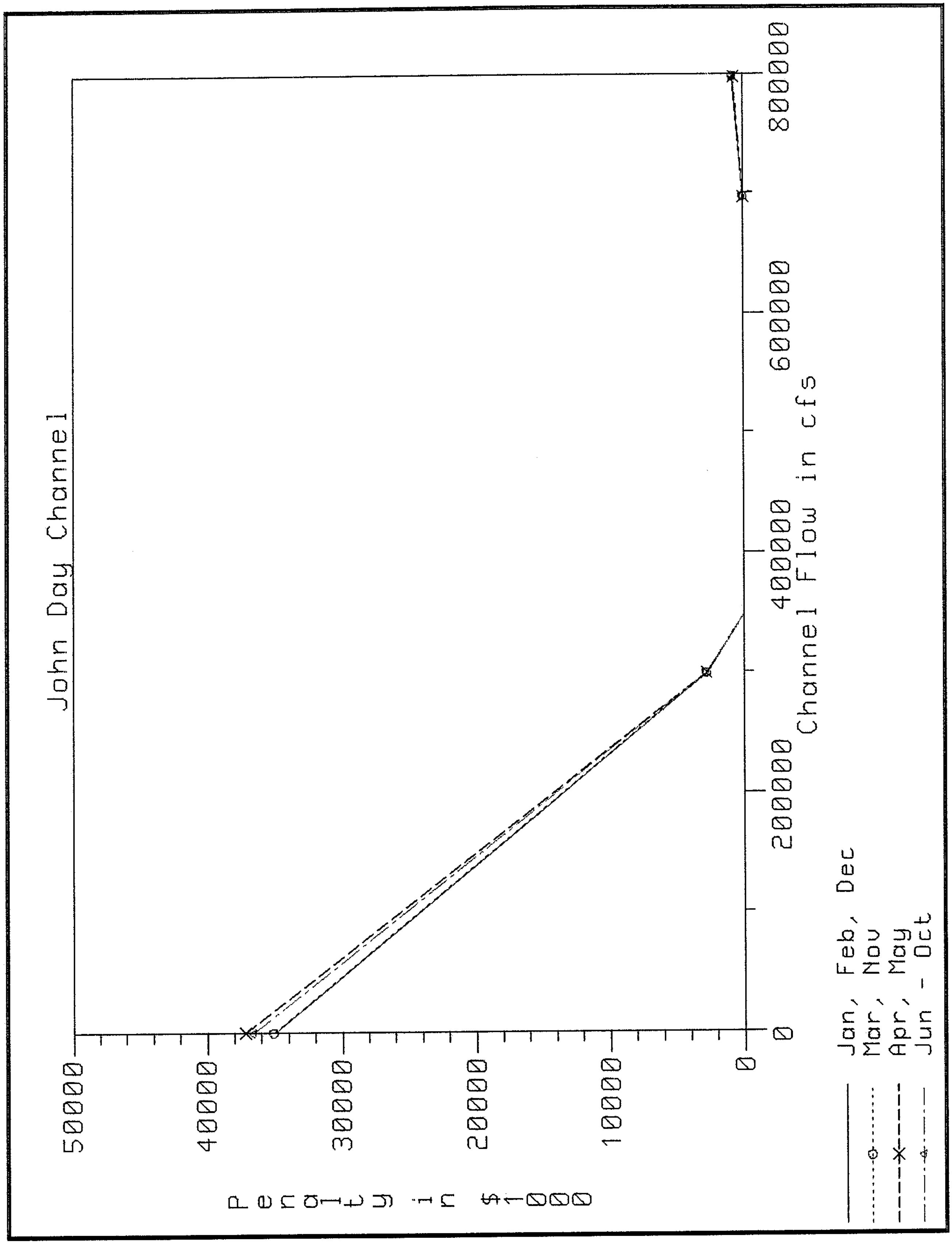

FIGURE E-27 John Day Channel

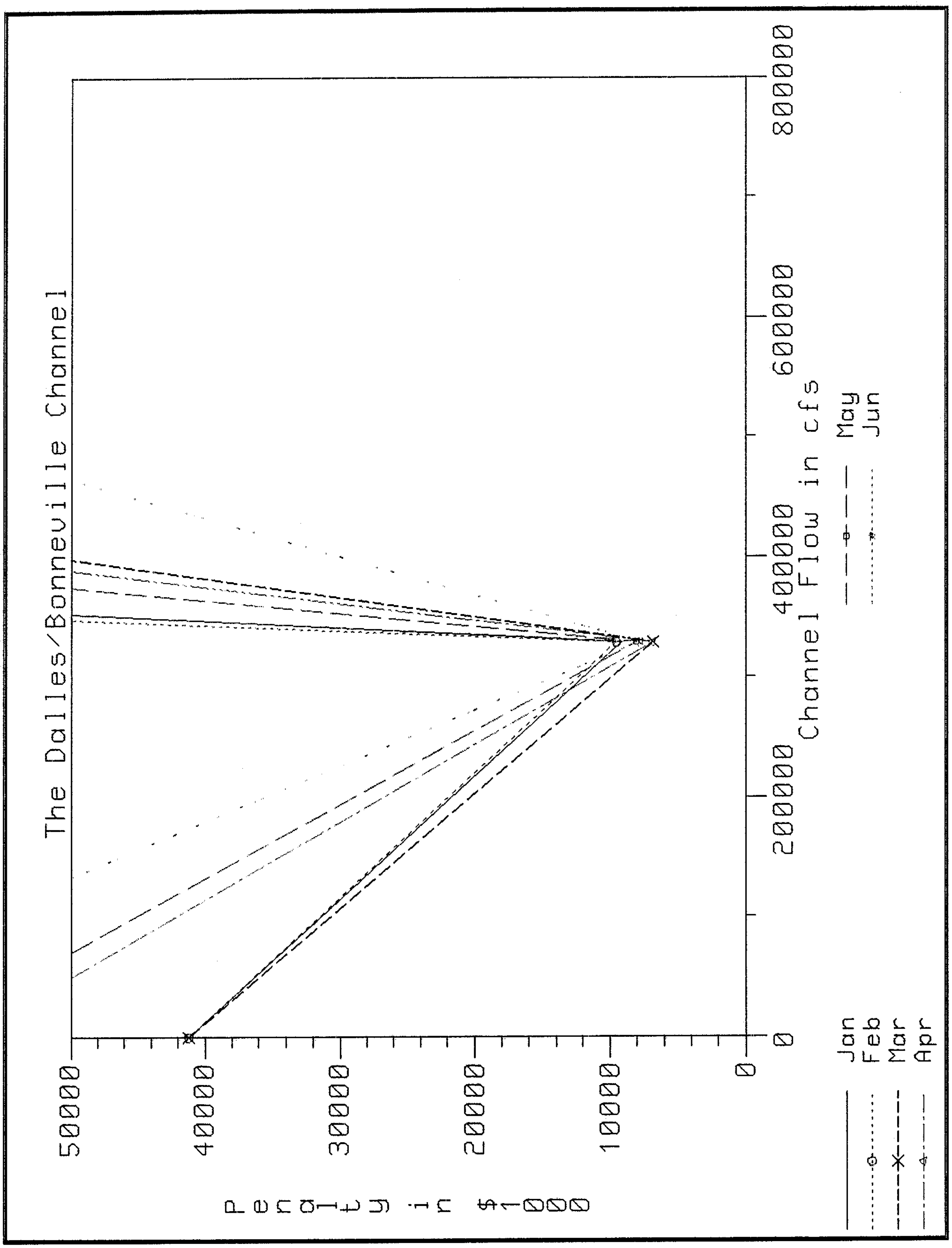

FIGURE E-28 The Dalles/Bonneville Channel

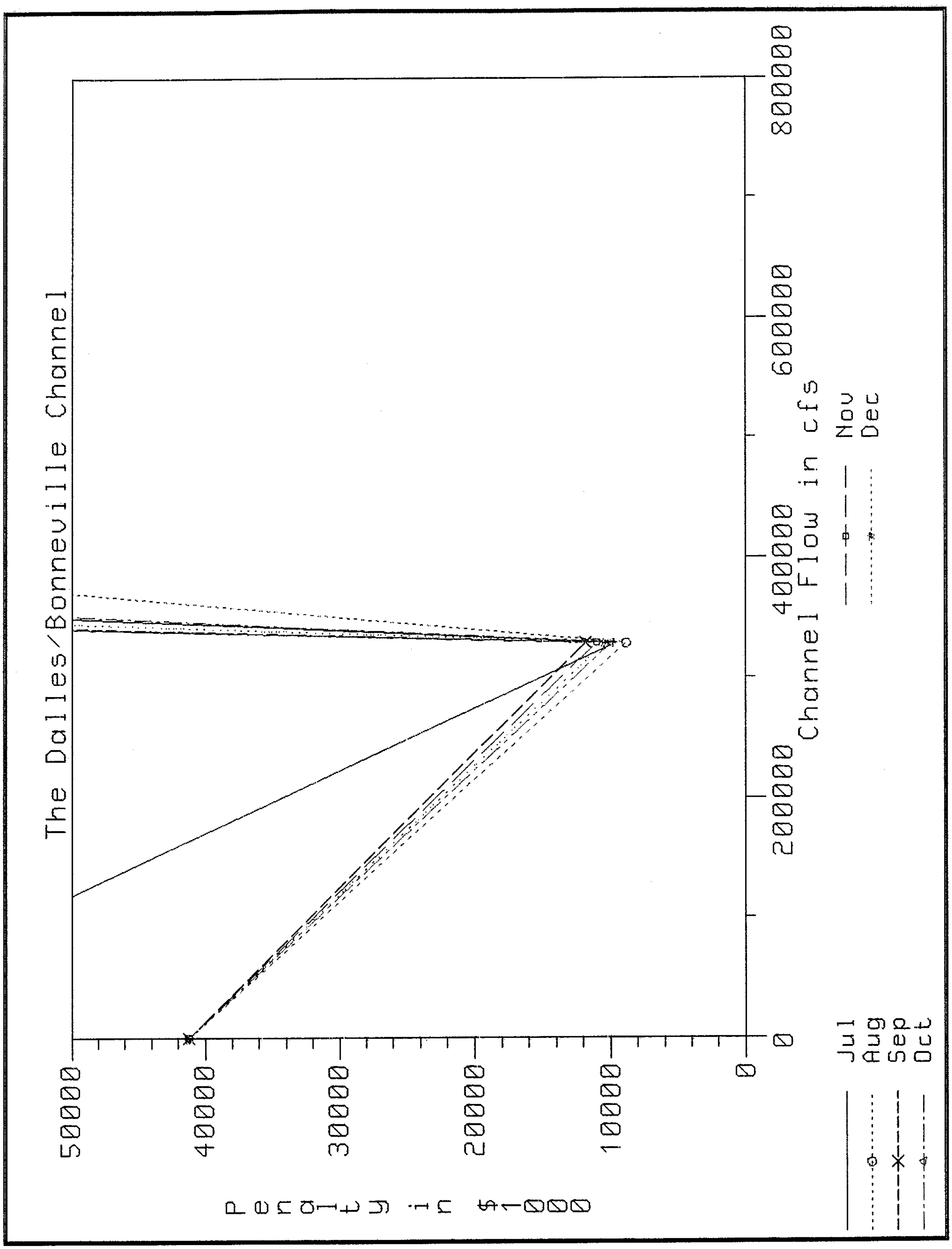

FIGURE E-28 The Dalles/Bonneville Channel (continued)