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14. ABSTRACT
This paper summarizes the interim findings of the second phase of the HEC-PRM Columbia River application. The HEC-PRM represents the Columbia system as a link-node network and uses network-flow programming to optimize, in time and space, flow and storage in the system. The representation of operation goals in HEC-PRM is accomplished through flow, storage, and energy economic penalty functions. Operation purposes represented by penalty functions included hydropower, water supply, flood control, navigation, recreation, and anadromous fish. The application was based on fifty year period-of-record with a monthly time interval. The HEC data storage system, HEC-DSS, was utilized extensively for data management and analysis of results.

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Application of the HEC Prescriptive Reservoir Model in the Columbia River System

Richard Hayes[1], Michael Burnham[1], and David Ford[2]

Abstract

The water resources of Columbia River system provide significant hydropower, water supply, flood control, recreation, fishery, and navigation benefits to the residents of the Pacific Northwest. Increasingly, the competition among the users of the Columbia system has been intensified by declining fishery resources. The Corps of Engineers (Corps), U.S. Bureau of Reclamation (Reclamation) and Bonneville Power Administration (BPA) are jointly conducting a review of fourteen federal projects within the Columbia basin. This effort has been termed the Columbia River System Operation Review (SOR). To provide the Corps SOR study team with a basis for more optimal allocation of system resources, the Hydrologic Engineering Center (HEC) has applied the recently developed Prescriptive Reservoir Model, HEC-PRM, to the major reservoirs of the Columbia River system upstream of Bonneville Dam.

The HEC-PRM represents the Columbia system as a link-node network and uses network-flow programming to optimize, in time and space, flow and storage in the system. The representation of operational goals in HEC-PRM is accomplished through flow, storage and energy economic penalty functions. Operational purposes represented by penalty functions included hydropower, water supply, flood control, navigation, recreation, and anadromous fish. The application was based on fifty year period-of-record with a monthly time interval. The HEC data storage system, HEC-DSS, was utilized extensively for data management and analysis of results.

This paper summarizes the interim findings of the second phase of this ongoing application.

System Description

The Columbia River basin embraces approximately 259,000 sq. mi. (670,000 sq. km.) of the Pacific Northwest from Canadian Province of British Columbia in the north to northern Nevada at its most southern point, and from the Pacific Ocean on the west to Wyoming on the east. Major storage and run-of-river reservoirs on the Columbia and its major tributaries (the Kootenai, Pend Oreille, Snake and Clearwater Rivers) are shown in Figure 1.

Average annual runoff is about 275,000 cfs (7,790 cms), of which 25 percent comes from Canada. Precipitation varies from an annual total of over 100 inches near Mica in British Columbia and along Cascade Range at the basins western boundary to about 6 inches in southern Idaho and central Washington. Runoff from the basin above Bonneville Dam has a strong seasonal pattern with most runoff resulting from snowmelt in April through July.

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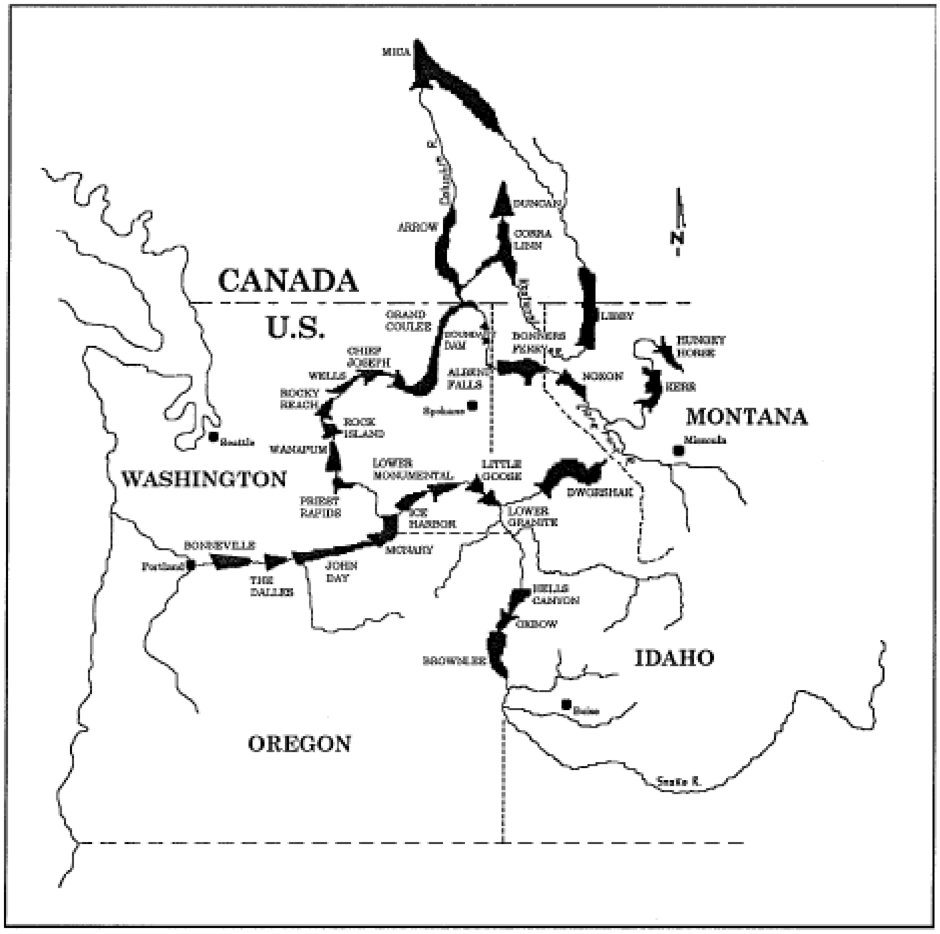

Figure 1 Columbia River System

Water Resources Development

Development of federal reservoirs along the main stem of the Columbia began in the 1930's primarily as consequence of nationwide unemployment during the Great Depression. Bonneville, a Corps navigation and hydropower project, was begun by the Works Progress Administration and was completed by the Corps in 1938. Grand Coulee, Reclamation's mainstem Columbia irrigation and hydropower project, went in service in 1941. Energy from both projects contributed significantly to the regions rapid industrial growth during World War II.

During the 1950's the Corps completed The Dalles, McNary, and Chief Joseph on the Columbia and Albeni Falls on the Pend Oreille River. Reclamation added Hungry Horse Reservoir on the Flathead River to the federal system in 1952. During the 1960's the Corps continued development of the Columbia-Snake River Waterway navigation system by finishing John Day on the Columbia and Ice Harbor and Lower Monumental on the lower Snake River. Corps development in the Snake River basin continued in the 1970's with Little Goose and Lower Granite on the Snake River and Dworshak on the North Fork of Clearwater River.

In January 1961, the United States and Canada became signatories to the Columbia River Treaty. The treaty provided for cooperative development of four storage projects to be operated for flood control and hydropower: Libby in Montana; and Mica, Arrow, and Duncan in British Columbia. Duncan, the first of the Canadian Treaty projects was completed in 1967; Arrow (Hugh Keenleyside) was completed in

1968; and, Mica was completed in 1973. In 1975, the Corps completed Libby Dam, the fourteenth federal reservoir included in the ongoing System Operation Review (SOR) investigations.

In addition to the major federal and treaty projects, numerous other reservoirs have been developed throughout the system principally for hydropower and irrigation. The Columbia River Basin Master Water Control Manual (USACE,1984) indicates that the Columbia Basin above its mouth includes 211 water control projects with a storage greater than 5,000 acre-feet or installed capacity of 5 mW or more.

The Problem

While reservoir projects within the Columbia Basin have provided significant flood control, irrigation, hydropower, recreation and navigation benefits for the region the cumulative effect of these works coupled with pollution, over harvesting, and other habitat changes have had an impact on the Columbia River fishery. According to the Master Water Control Manual, the 1911 harvest of Columbia River salmon and steelhead was about 50 million pounds. This figure has been estimated to be approximately the natural sustainable annual yield. The 1911 harvest stands in sharp contrast to the 10 million pound harvest in 1989 cited in The Columbia River System: The Inside Story (Interagency Team, 1991). The federal agencies and the fish and wildlife departments of Idaho, Oregon and Washington have invested heavily in physical facilities including fish hatcheries, ladders, screens and bypass facilities.

Operation modifications to aid the downstream migration of juvenile salmon and steelhead including provisions for increased springtime flows and spillway discharges are being utilized. Still other operation alternatives involving seasonal storage drawdowns, primarily on the navigation impoundments of the lower Snake River and increased flows from upstream storage reservoirs have been proposed. Operational or physical modifications to meet changing demands or enhance any of the uses at the various reservoirs and stream reaches of Columbia River will in all likelihood impact to some degree one or more of the other system uses.

The problems of operating the coordinated system of flood control and hydropower reservoirs by BPA, the Corps, and Reclamation are summarized in The Columbia River: A System Under Stress (BPA, USACE, BuRec, 1990) in which they state:

> *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-off must be considered ... in recent years, demands by the various users of the river have increased dramatically, resulting in increasing conflicts among uses*.

Consequently, in 1990 the North Pacific Division (NPD) of the Corps of Engineers proposed the interagency system operation review. To assist in the evaluation of the system and the analysis of potential trade-offs NPD requested the Hydrologic Engineering Center to provide technical assistance in the further development and application of the Center's reservoir system optimization model, HEC-PRM.

HEC-PRM

The HEC has recently developed a prescriptive reservoir model to assist in the analysis of Corps reservoir systems. This new model has been termed HEC-PRM (USACE, 1991a). The term "prescriptive" may be explained in part by comparison with the characteristics of another

HEC reservoir system model, the widely applied HEC-5 (USACE, 1982a). HEC-5 is classified as a "descriptive" reservoir model. Both types of models are similar in that they require a sequence of flows and link-node descriptions for continuity of flow. In a descriptive model, like HEC-5, operation policies are specified as storage rule curves, channel capacities, hydropower energy demands, diversions and flow requirements. The outcome of an HEC-5 simulation is typically a time series of flows, stages, and energy production which is obtained by following a specified operation policy. The evaluation of specified operation policies to select the "optimal" among those simulated is left to the model user.

HEC-PRM, on the other hand, uses as a formal objective function the minimization of total system cost. The model uses a network flow solver developed by Jensen and Bhaumik (1974) to determine the optimal distribution of flow, storage and energy production in space and time. The primary input to the HEC-PRM model are "penalty" functions, which relate the consequence (cost) of flow, storage and energy production in a system, and a network description to provide the basis for continuity as flow moves through a system of links and nodes. The penalty functions provide an economic basis for operation prioritization. The model automatically nominates alternative policies which it evaluates with a built-in simulation module. Feasible alternatives are evaluated until a minimum cost policy is determined.

For convenience, HEC-PRM input penalty functions and flow sequences, as well as optimized flows and storages, are handled with HEC-DSS (USACE, 1990). The HECDSS utility programs DSSMATH, DSSUTL and DSPLAY are used to develop, manage and plot time series data. Two HEC-PRM utility programs PENF (a graphical penalty function editor) and PRMPP (a post processor) are currently being developed and tested.

Columbia River HEC-PRM Application

HEC-PRM was demonstrated to be an appropriate tool for the analysis of reservoirs with its first application on the Missouri River system. This application for the Corps Missouri River Division (MRD) on the Corps' six mainstem reservoirs was completed in 1990 (USACE, 1991b). The Missouri River system, from the stand point of system optimization, is a relatively straight forward system with six large tandem reservoirs under the same management. The competing interests in the Missouri system included lake recreation, hydropower production, flood control, water supply and downstream navigation and environmental concerns.

The Corps North Pacific Division (NPD) in 1990 proposed an interagency review of the Columbia River system. The Columbia River, like the Missouri, has recently experienced a system wide water shortage that exacerbated the competition among the various system users. The two systems are similar in that they both have almost the same types of competing interests. The principle exception being in the Missouri system the major environmental concern is maintenance of steady flows for sand bar nesting birds; whereas, the major environmental concern of the Columbia system is the maintenance of seasonal flows to aid the downstream migration salmon and steelhead.

The NPD, as a part of the SOR requested HEC to test the applicability of HECPRM to the more complex and larger Columbia River system. This effort, termed Phase I, was initiated in and completed in 1991. It was anticipated that a second phase would follow with more economic detail if the Phase I application proved successful. The findings of the Phase I of the application are reported in Columbia River System Analysis Model - Phase I (USACE, 1991b). The results of the Phase I application verified the applicability of HEC-PRM to a complex system such as the Columbia. It was determined that the HEC would proceed with the second phase of the analysis.

It was agreed that this effort would include the following: expansion of the network to include more storage reservoirs; enhancements to the HEC-PRM hydropower analysis capability; analysis of several alternatives; and a workshop to transfer the technology the Corps SOR team.

HEC began the second phase of the application in fall of 1991. The Phase II network configuration is shown in Figure 2. The network includes fourteen storage reservoirs, five run-of-river (pondage) reservoirs and three non-reservoir locations.

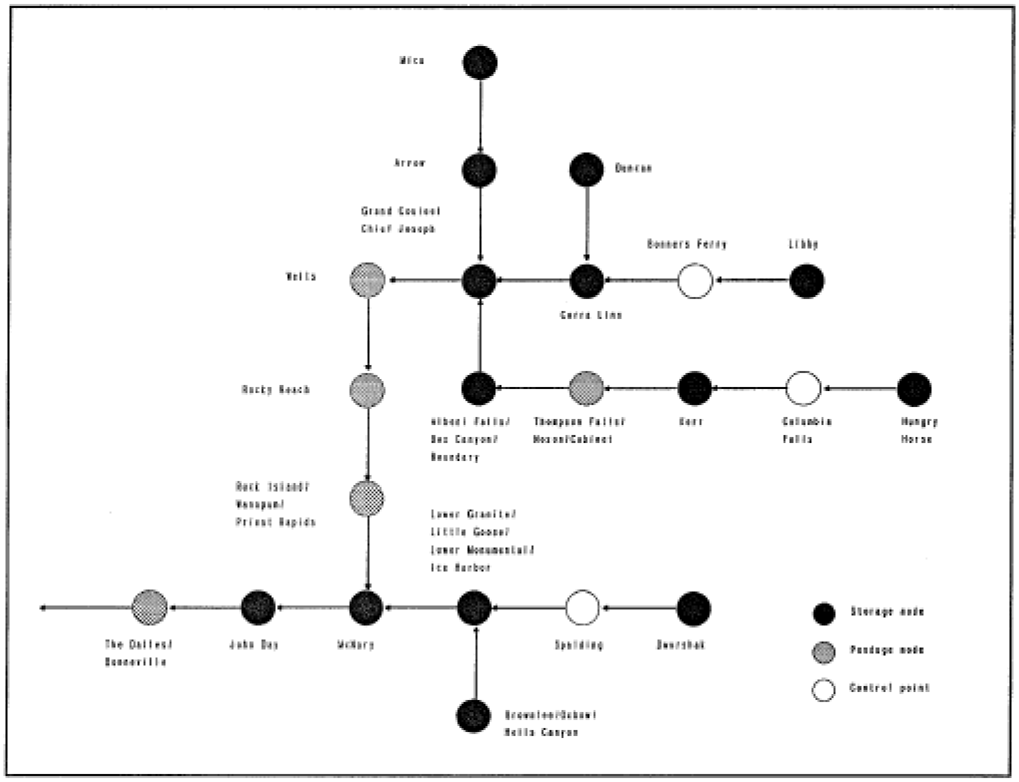

Figure 2 Single-period Network Model of Columbia River System

During the Phase I application it was noted that HEC-PRM storages for Corra Linn (Lake Kootenay), a Canadian hydropower project on the Kootenay River, did not correspond to the simulation results of NPD's HYSSR (USACE,1982b) simulation model to the degree deemed reasonable. Upon investigation it was determined that Corra Linn did not have sufficient outlet capacity to prevent storage from exceeding upper storage limit. It was further determined that two other reservoirs in the system could also exhibit the same characteristic. The other two are Kerr (Flathead Lake) and Albeni Falls (Lake Pend Oreille). All three are similar in that they are control structures located on a river reach some distance from a natural lake. In order to model these reservoirs, the nominal upper storage was raised to an arbitrarily high value and a restrictive maximum flow limit was specified. To discourage HEC-PRM from utilizing this zone in other than a flood condition, the reservoir storage penalties were modified to inflict a relatively high cost for storage above the nominal full pool. The results obtained have been determined to be appropriate for the current application. It is anticipated that polices determined with HEC-PRM will be modeled with a simulation model, in this case HYSSR, which can provide the additional operational details. Reservoir storage and flow limits are shown in Table 1.

Penalty functions are the "guiding light" with which HEC-PRM determines the optimal distribution of flow and storage in time and space. For the Columbia River application, penalty functions represented the following six types of system uses: hydropower; flood control; navigation; anadromous fish; water supply; and, recreation. The hydropower penalty function is expressed in terms of both flow and

Table 1
Columbia River System Storage and Release Limits

Reservoir	Storage Limits, 1000 Acre-Feet Minimum	Maximum	Release Limits - CFS Minimum	Maximum
Libby	889.9	5,869.4	3,000	-----
Corra Linn	144.0	9,999.0	-----	55,940
Duncan	30.0	1,398.6	100	-----
Hungry Horse	486.0	3,647.1	400	-----
Kerr	572.3	9,999.0	1,500	54,930
Albeni Falls	446.4	9,999.0	-----	129,800
Dworshak	1,452.2	3,468.0	1,000	-----
Brownlee	431.7	1,426.7	5,000	-----
Granite	144.0	1,825.0	-----	-----
Mica (Alts. 1 & 2)	13,075.0	20,075.0		
Mica (Alt. 3)	8,000.0	20,075.0		
Arrow	227.0	7,327.0	5,000	-----
Grand Coulee	3,879.0	9,107.4	-----	-----
McNary	1,170.0	1,350.0	-----	-----
John Day	1,989.0	2,523.0	-----	-----

variable storage. Each of the other uses were expressed in terms of a flow penalty in $/kaf (1,000's acre feet per month) or a storage penalty in $/kaf. Penalty functions are varied monthly to reflect the seasonal nature of the various purposes. At each location, the various penalty functions are combined to create a composite function for each month. HEC-PRM requires that all penalties must be piecewise linear convex functions. Figure 3 shows how penalty functions are combined and how an approximate edited function is determined to satisfy the convex requirement.

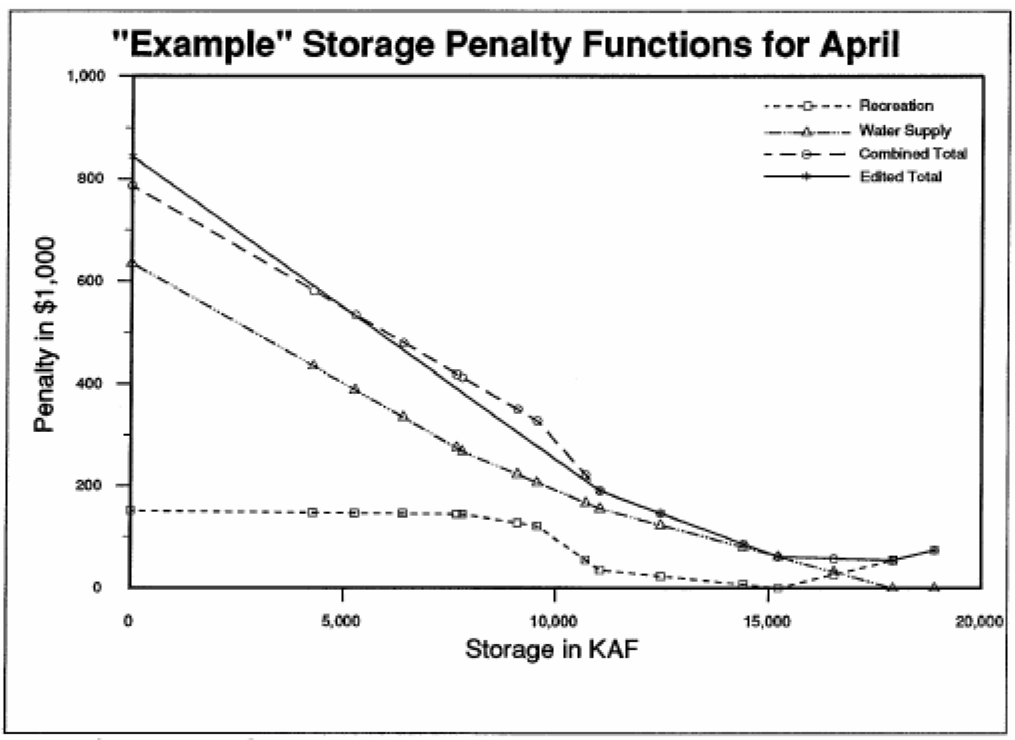

Figure 3 How Penalty Functions are Combined and Approximated

Economic data to create the necessary penalty functions was developed by Corps economists, planners, and engineers from NPD and the Division's Seattle, Portland and Walla Walla Districts under the direction of the Corps Institute for Water Resources (IWR). These data are documented in "Economic Value Functions for Columbia River System Analysis Model, Phase I (Draft)", (USACE, 1992). A graphical penalty function editor (PENF), which was developed during this phase, was used to develop the edited penalty functions. Economic data to develop penalty functions for the Canadian Treaty reservoirs (Mica, Arrow and Duncan) were not available for use in this phase. Table 2 indicates the purposes which were represented by economic penalty functions throughout the network.

Analysis Overview

The operation for the system was based on flows for the period of 1928 to 1978. Monthly flow data for this period, adjusted to a consistent level of development (1980) were provided by NPD (USACE, 1983). Irrigation depletions, returns and reservoir evaporation were accounted for in the flow data. Irrigation withdrawals from Grand Coulee to Bureau of Reclamation's Columbia Basin Project were treated as a fixed diversion (e.g. not optimized). Three system operation scenarios were selected for analysis, they were: Alternative 1, existing storage allocations with optimization for all operation purposes; Alternative 2, existing storage allocations without optimization for hydropower; and Alternative 3, five million acre-feet of additional storage in Mica, optimization for all operation purposes.

To evaluate system performance of all alternatives with a consistent frame of reference, which represented the present system with current rules and objectives, the results of NPD's continuous HYSSR simulation (SOR base case) were utilized. To provide a valid economic comparison, HYSSR flows and storages were applied to HECPRM storage, flow and hydropower penalty functions.

The analyses were performed on a 25 mHz 80486 MS-DOS personal computer with 16 mb memory. The current version of HEC-PRM utilizes allocatable arrays and virtual memory management, which make it extremely accommodating from a users point of view. Execution times for Alternatives 1 and 3 (about 150,000 simultaneous linear equations) for the 50 years of record were about fourteen hours each. For alternative 2, which did not optimize for hydropower, about three hours of execution time was required. Analyses for shorter time spans took significantly less execution time. It is worthwhile to note that for the Columbia system, which has a relatively small amount of storage compared to the annual flow, the presumed requirement to run the entire period of record in a single optimization run is not valid. The analyst has merely to start and end the optimization period at times when the system would be reliably full, which, in the case of the Columbia system, is frequently the case at the end of spring runoff.

To compare the analyses results, performance of all three alternatives and the HYSSR simulation have been computed with the following indices: total system penalty (as computed with HEC-PRM); reliability (the frequency of meeting monthly targets); resiliency (the frequency of recovery after a failure); and vulnerability (the average deviation from the target when a failure occurs).

Optimization results contrasting the three alternatives with HYSSR results at Dworshak Reservoir (storage) and The Dalles (flow) are shown in Figures 4 and 5 respectively, for the period of 1928-1938.

Study Status

A draft report, Columbia River Reservoir System Analysis: Interim Findings, (Draft), April 1993 has been transmitted to the North Pacific Division for review. It is anticipated that a workshop to transfer the HEC-PRM model and the input files that were developed in this study will be presented to Corps SOR

Table 2
Columbia River System Phase II Network Links and Operation Purposes Penalty Functions

Original Node[1] (1)	Terminal Node[1] (2)	Link Type[2] (3)	Operation purposes modeled[3]: FC (4)	Hydro (5)	Nav (6)	Irr/WS (7)	Fish (8)	Rec (9)
Libby	Libby	S						✓
Libby	Bonners Ferry	H		✓				✓
Bonners Ferry	Corra Linn	C	✓					
Duncan	Duncan	S						
Duncan	Corra Linn	R	✓					
Corra Linn	Corra Linn	S	✓					
Corra Linn	Coulee	R						
Hungry Horse	Hungry Horse	S						✓
Hungry Horse	Columbia Falls	H		✓				
Columbia Falls	Kerr	C	✓					
Kerr	Kerr	S	✓					
Kerr	Thompson	H	✓	✓				
Thompson	Thompson	S						
Thompson	Albeni	H		✓				
Albeni	Albeni	S	✓					✓
Albeni	Coluee	H	✓	✓				
Dworshak	Dworshak	S			✓			✓
Dworshak	Spalding	H		✓				
Spalding	Granite	C	✓					
Brownlee	Brownlee	S						
Brownlee	Granite	H		✓				
Granite	Granite	S			✓	✓		✓
Granite	McNary	H		✓			✓	
Mica	Mica	S						
Mica	Arrow							
Arrow	Arrow	S						
Arrow	Coulee	R						
Coulee	Coulee	S				✓		✓
Coulee	Wells	H		✓				
Wells	Wells	S						
Wells	Rocky Reach	H		✓				
Rocky Reach	Rocky Reach	S						
Rocky Reach	Rock Island	H		✓				
Rock Island	Rock Island	S						
Rock Island	McNary	H		✓				
McNary	McNary	S			✓	✓		✓
McNary	John Day	H		✓				
John Day	John Day	S			✓	✓		
John Day	Dalles	H		✓				
Dalles	Dalles	S						
Dalles	Sink	H	✓	✓			✓	

[1] Refer to Figure 2 for relative location of nodes.
[2] R = simple reservoir-release link; S = storage (period to period) link; H = hydropower reservoir-release link; C = channel-flow link; D = diversion link.
[3] FC = flood control; Hydro = hydroelectric-power generation; Nav = navigation; Irr/WS = irrigation and/or water supply; Fish = fish protection; Rec = recreation.

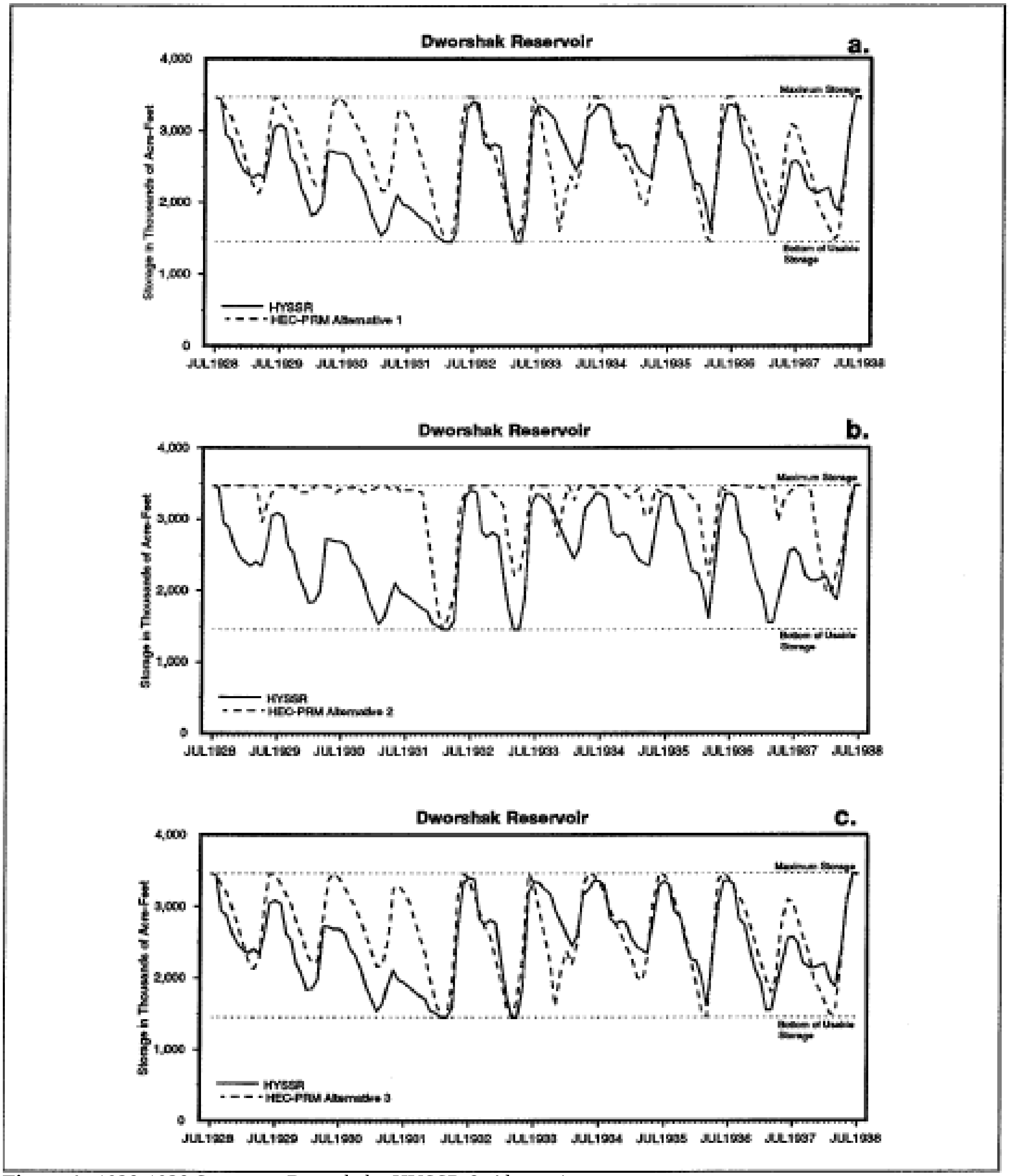

Figure 4 1928-1938 Storage at Dworshak: HYSSR & Alternatives

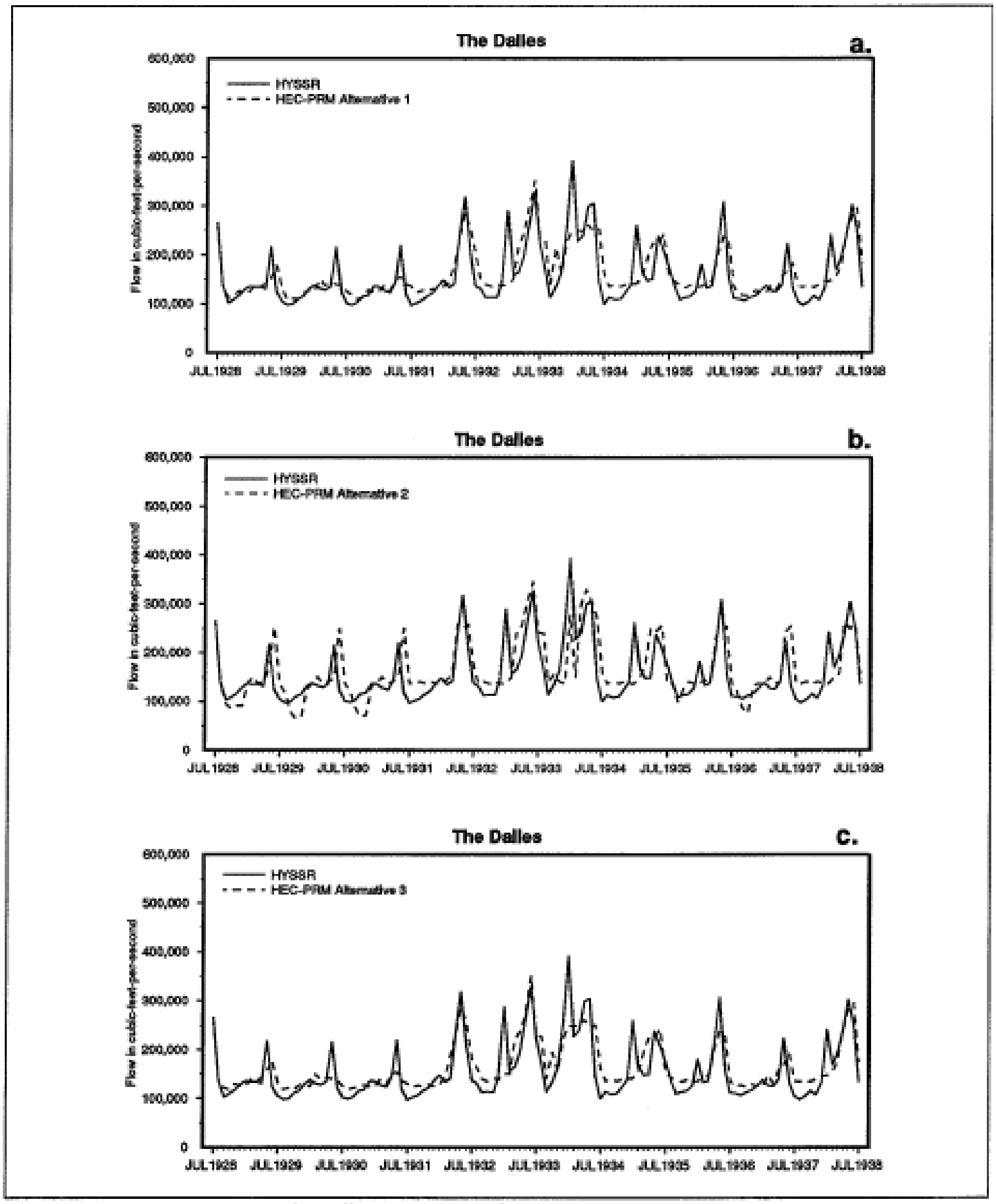

Figure 5 1928-1938 Storage at The Dalles: HYSSR & Alternatives

team members in July 1993. At the time of the workshop, it is expected that economic data to develop penalty functions for the Canadian treaty reservoirs may become available. Additional work will be required to develop reservoir operating rules which closely follow the optimal time series of storage and flow; HEC hopes to assist NPD in this effort. The HEC will publish a Phase II report at the conclusion of the study. HEC plans to make a version of HEC-PRM available to the public by the middle of 1993.

Conclusion and Observations

1. HEC-PRM has been demonstrated to be capable of period-of-record optimization of complex systems of reservoirs with commonly available computer systems.

2. The partially updated Phase I economic data which was the basis for this study should be revisited.

3. Penalty data for the Canadian Treaty reservoirs should be developed.

Acknowledgements

This project was supported by the U.S. Army Corps of Engineers, North Pacific Division and Corps research funds. Dr. David Moser of the Institute for Water Resources guided the development of the economic penalty functions. Dr. Quentin Martin, of the Lower Colorado River Authority, played a key role in the implementation and testing of the HEC-PRM hydropower algorithm. Vladamir Plesa, of the University of California, Davis, developed the PENF and PRMPP programs during the study. Robert Carl, of the Hydrologic Engineering Center (HEC), developed the HEC-PRM computer software, contributed to overall analysis and generated the post processing results. Marilyn Hurst, of HEC, performed data preparation, and analysis of results. Loshan Law, of HEC, typed and assembled the report. Darryl Davis, HEC Director, provided general supervision and guidance for the project.

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