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14. ABSTRACT

Paper summarizing the development of the HEC Prescriptive Reservoir Model (HEC-PRM) and its application to the Missouri River System. The model represents the reservoir/river system as a network and uses network-flow programming to allocate optimally, the system water. Applications for a validation period (5 years) and drought period (13 years) are documented. Comments regarding model use in climate change impact studies are offered.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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PRESCRIPTIVE RESERVOIR SYSTEM ANALYSIS MODEL MISSOURI RIVER SYSTEM APPLICATION[1]

by

Darryl W. Davis and Michael W. Burnham[2]

Abstract

A reservoir system analysis model has been developed that is based on determining prescriptive operations for use by water managers in the Corps of Engineers. The model, coined HEC-PRM, represents the reservoir system as a network and uses network-flow programming to allocate optimally the system water. The goals of and constraints on system operation are represented with system penalty functions. The objective function of the network problem is the sum of convex, piece-wise linear approximations of these penalty functions. The solution is the optimal allocation of water in space and time for the system based on minimizing the total system penalty. The results are processed to display time series of reservoir releases, reservoir storage volumes, channel flows, and other pertinent information. The model has been successfully tested on the Missouri River system. Operation purposes include hydroelectric power, in-stream and reservoir recreation, navigation, flood control, in-stream and reservoir water supply, and environmental goals and constraints. Analyses are performed for period-of-record monthly flow sequences. In climate change studies, it is proposed that the model be applied for hydrologic time series representing present conditions, then successively applied for hydrologic time series representing changed future conditions. Value (penalty) functions could also be altered to reflect future preferences.

PROBLEM DESCRIPTION

The Missouri River main-stem reservoir system consists of six reservoirs: Ft. Peck, Garrison, Oahe, Big Bend, Ft. Randall, and Gavins Point. According to the reservoir regulation master manual (USACE, 1979), the main-stem system is operated "...for flood control, navigation, irrigation, power, water supply, water quality control, recreation, and fish and wildlife." Current operation priorities in operating the reservoirs to meet these objectives are described as follows in the regulation manual (pg. IX-1, IX-2):

> *First, flood control will be provided by insuring vacant space at the beginning of each year's flood season; second, all irrigation, and other upstream water uses will be allowed for; third, downstream M&I water supply and water quality requirements will be provided for; fourth, the remaining water supply will be regulated for equitable service to navigation and power; fifth,...the efficient generation of power; and sixth, the reservoirs will be operated for maximum benefit to recreation, fish and wildlife.*

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[1]Presented at the First National Conference on Climate Change and Water Resources Management, 5-7 November 1991, Albuquerque, New Mexico.

[2]Director, Hydrologic Engineering Center and Chief, Planning Analysis Division, respectively, Hydrologic Engineering Center, Davis, California.

A review of these priorities was prompted by the following (USACE, 1990a):

> *(1) It has been 10 years since the last [manual] update, (2) the current (3 year) drought has pointed out that parts of the existing Master Water Control Manual may require change, (3) recreation on the reservoirs and the river downstream is becoming an increasingly important industry, (4) the current drought has demonstrated the importance of Missouri River water to commercial navigation, and (5) the Master Water Control Manual needs to be updated to include regulation criteria for endangered and threatened species, new data collection methods, and flood history which has occurred since the last update.*

To review the priorities in a systematic fashion, an analysis tool is required. This tool must evaluate system operation for all purposes in terms of hydrologic, economic, and environmental efficiency.

Analysis tools appropriate for the Missouri River reservoir main-stem study may be classified broadly as descriptive tools or prescriptive tools. Descriptive tools typically simulate operation with a specified operation policy. The alternative policies considered are proposed by a user, or an alternative-generating scheme. A prescriptive tool, on the other hand, relies on a formal definition of the goals of and constraints on system operation to define best system operation. It nominates automatically the alternative policies to be considered. It evaluates the feasibility of each with a built-in simulation model. With a formal definition of operation goals and objectives, it quantifies the efficiency of each feasible alternative. Finally, after considering all alternatives, it identifies the best policy. Examples of prescriptive tools are linear-programming models, nonlinear-programming models, and dynamic-programming models.

PROPOSED SOLUTION

The 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 is 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. 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 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.

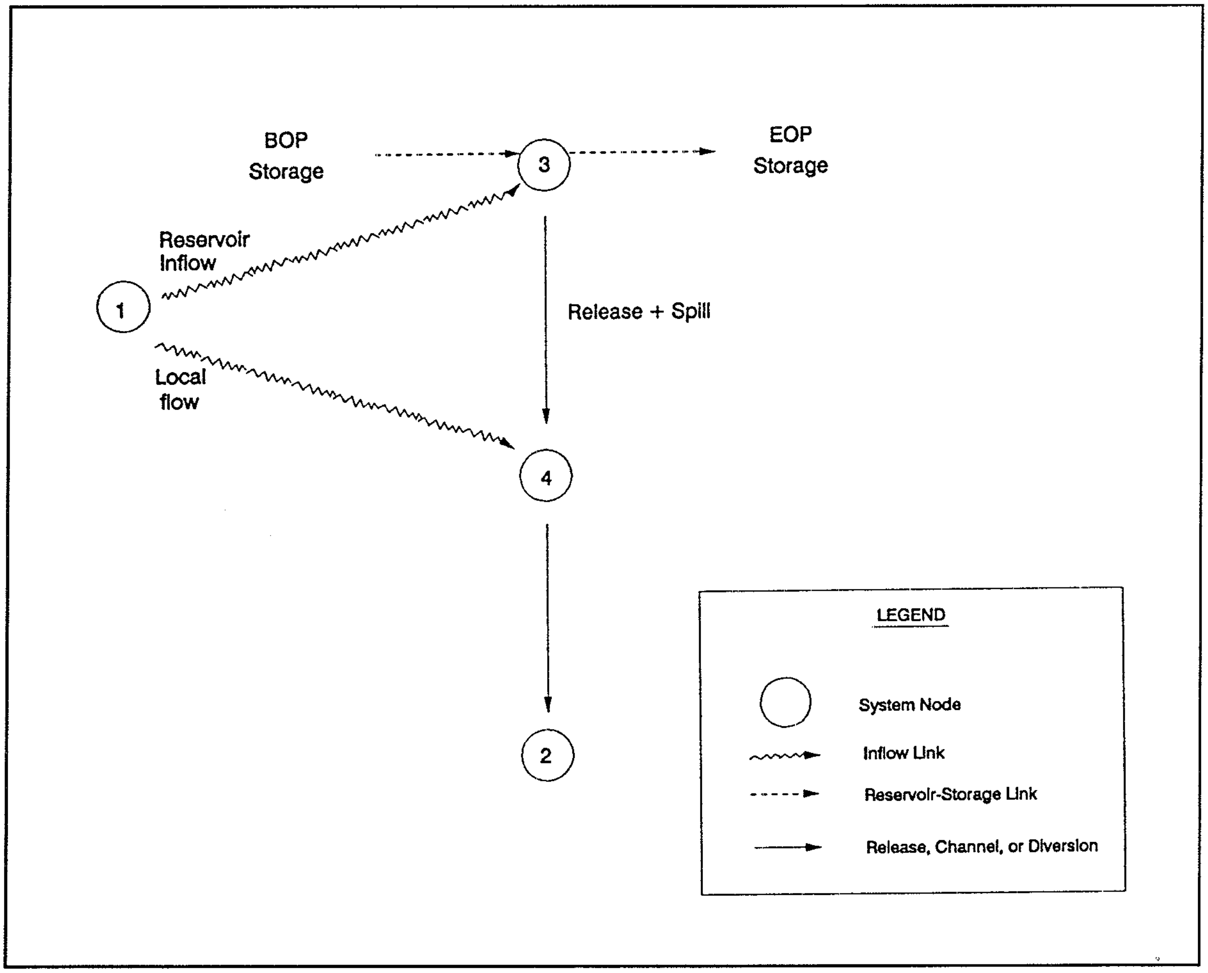

FIGURE 1 Simplified Single-period Network

To analyze multiple-period system operation, a layered network is 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. The duplicate networks are connected by arcs that represent reservoir storage.

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. 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 a 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. It may be positive or negative. The total cost for flow along the arc represented is the product of flow and the unit cost. The simplest linear function is too simple to represent adequately many of the goals of reservoir operation. Instead, a nonlinear function, such as that shown in Figure 2, may be required.

Convex cost functions can be approximated in a piecewise linear fashion for the proposed network model. Figure 2 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, but increase the complexity and time for solution of the resulting network-flow programming problem. Thus, as the approximation improves, the time for solution increases. Jensen and Barnes discuss this approximation in detail (1980, pgs. 355-357).

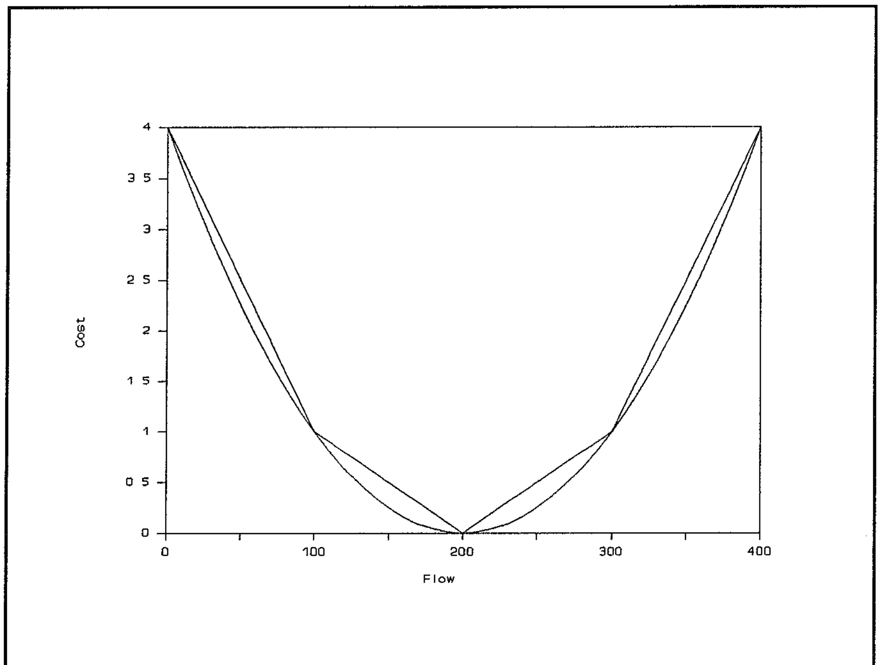

FIGURE 2 Piecewise Linear Approximation of Nonlinear Penalty Function

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.

Develop Objective Function Representing Desirable Operation

While desireable, it is unlikely that all goals of system operation can 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 strictly 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. Thus, even if failure to meet, for example, an environmental operation goal has no measurable economic cost, the penalty may be great.

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. 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.

Penalty functions are developed for various purposes for stream reaches and reservoirs as needed. 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 3 illustrates this.

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

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

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

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

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

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.

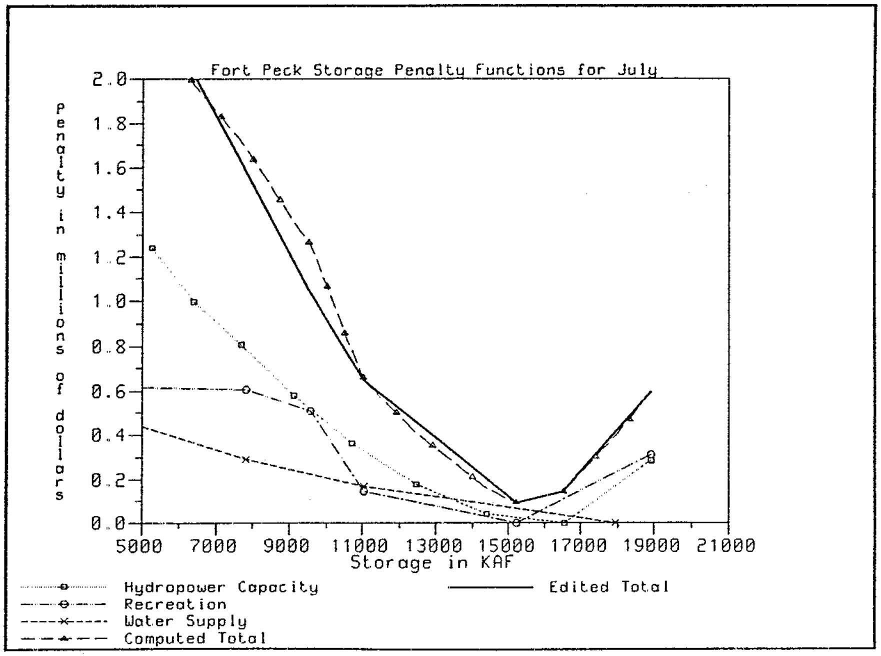

FIGURE 3 Penalty Functions Combined

The optimal allocation of water in the layered network is determined with a network solver. The solver used at present implements an algorithm developed by Jensen and Bhaumik (1974), and documented and applied by Martin (1982). 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 are translated into reservoir releases, hydropower generation, storage volumes, diversion rates, and channel flows and presented in reports and displays. For convenience, the results after translation are stored with the HEC data storage system, HECDSS (USACE, 1990b). The results can be displayed or processed further as needed to provide information required for decision making.

MODEL-BUILDING SOFTWARE

The software to implement the network model is general purpose and is referred to herein as the Hydrologic Engineering Center Prescriptive Reservoir Model, or HEC-PRM. With HEC-PRM, an analyst can define the layout of any existing or proposed reservoir system. Further, the analyst can describe the physical features of the system reservoirs and channels and the goals of and constraints on their operation. The operation goals can be defined by penalty functions associated with flow, storage, or both.

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

(1) Inflow link;
(2) Diversion link;
(3) Channel-flow link;
(4) Simple reservoir-release link;
(5) Hydropower reservoir-release link;
(6) Reservoir-storage link;
(7) Initial-storage link;
(8) Final-storage link; and
(9) Nodes at which links are connected.

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.

MISSOURI RIVER SYSTEM APPLICATION

The Missouri River System model development and application is documented in a report published by HEC (USACE, 1991). The network representation of the Missouri River Main Stem System includes six reservoir and six non-reservoir nodes, as shown by Figure 4. The reservoir nodes represent Ft. Peck, Garrison, Oahe, Big Bend, Ft. Randall, and Gavins Point. The non-reservoir nodes represent Sioux City, Omaha, Nebraska City, Kansas City, Boonville, and Hermann.

An inflow link terminates each period at the Ft. Peck, Garrison, Oahe, Ft. Randall, and Gavins Point reservoir nodes. There is no local inflow into Big Bend Reservoir and therefore there is no inflow link to that node. An inflow link terminates each period at all non-reservoir nodes. An initial-storage link terminates at each reservoir node in the first period of analysis. The network ends with a diversion link at Hermann each period. A final storage link originates at each reservoir node in the final period of analysis. Channel-flow links connect the six non-reservoir nodes each period. A reservoir-release link connects each reservoir node with the next downstream node each period. Storage in each reservoir each period is represented with a reservoir-storage link.

Goals of and constraints on Missouri River reservoir system operation are represented with system penalty functions. Procedures for developing these functions are documented (USACE, 1990c). Penalty functions are of two types: cost-based or non-cost-based. The cost-based functions, "...show the loss in economic value as the flow in each model link deviates from the optimum flow" (USACE, 1990c). For the Missouri River application, individual economic cost-based penalty functions were developed for the following outputs: urban and agricultural flooding; water supply; recreation; hydropower; and navigation. These functions vary by month if appropriate. Non-cost-based penalty functions represent goals of system operation that cannot be quantified in economic terms. For example, a flow requirement for fish and wildlife protections may be represented with a penalty function in which the penalty arbitrarily is set to force the desired operation. Only cost based functions have thus far been used in the Missouri Studies.

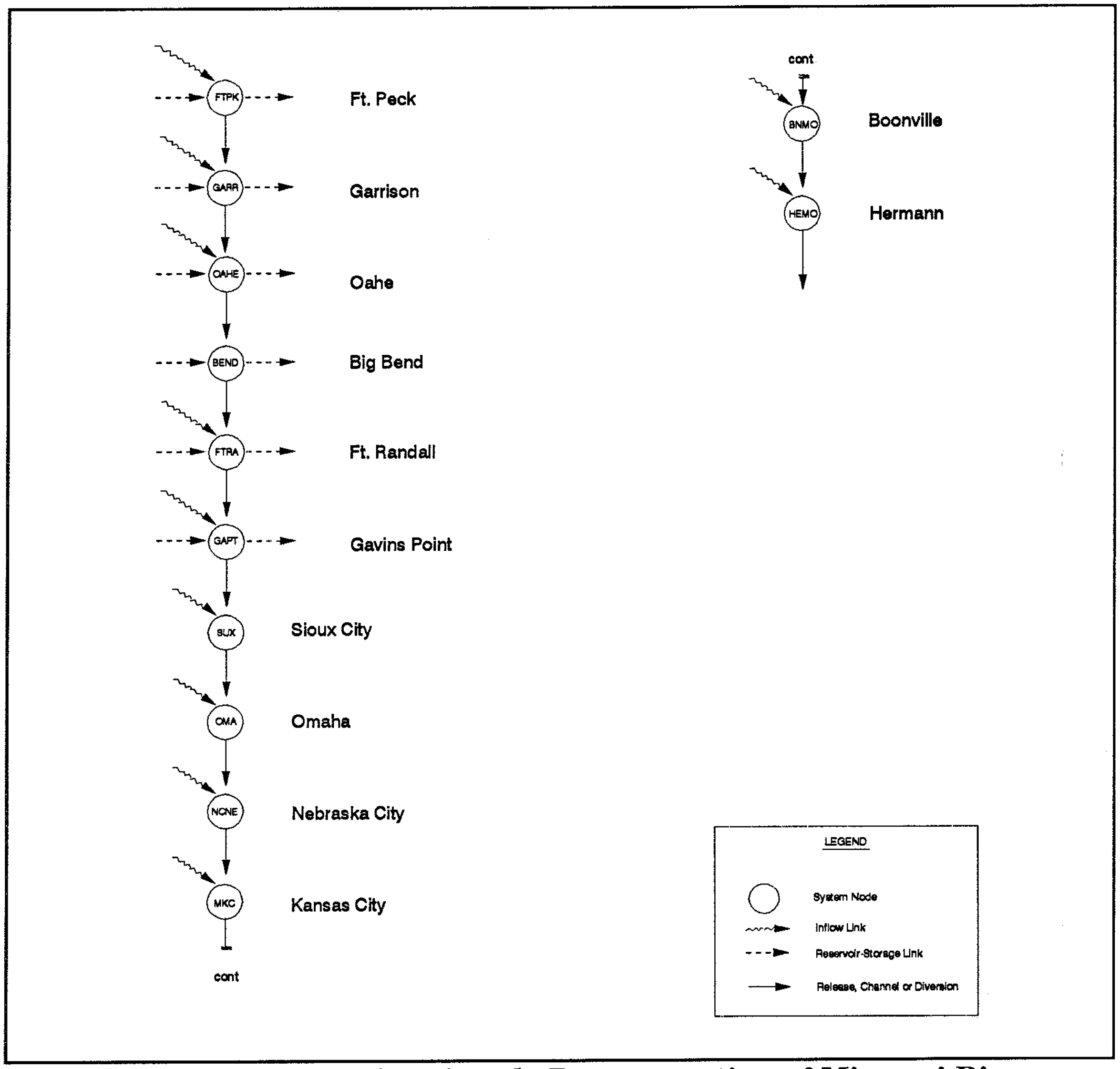

FIGURE 4 Single-period Link-node Representation of Missouri River System

PHYSICAL SYSTEM AND HYDROLOGIC DATA

The Missouri River basin is 530,000 square miles with mean annual runoff of about 24 million acre feet. Historically, annual runoff has varied from a low of 11 million acre-feet, to a high of 40 million acre-feet. Monthly volumes for the inflow links shown in Figure 4 for the 92 year historic record were compiled. These data are adjusted for upstream and local depletions to reflect 1975 conditions. Selected periods of this record are used in analyses as described later. Table 1 summarizes data on the main-stem reservoirs.

TABLE 1
Reservoir Storage Information

Reservoir	Top Inactive Storage, in 1000 Acre-ft	Top Carry-over, Multiple-use Storage, in 1000 Acre-ft	Top Flood-Control & Multiple-use Storage, in 1000 Acre-ft	Top Exclusive Flood-control Storage, in 1000 Acre-ft
(1)	(2)	(3)	(4)	(5)
Ft. Peck	4,211	14,996	17,714	18,688
Garrison	4,990	18,210	22,430	23,924
Oahe	5,451	19,054	22,240	23,337
Big Bend	1,696	-	1,813	1,873
Ft. Randall	1,568	3,267	4,589	5,574
Gavins Point	340	-	432	492

MODEL VALIDATION

Unlike a descriptive model, a prescriptive model 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. Model logic, input data, and solution algorithms can be scrutinized. This was done. In addition, model validity was explored by applying HEC-PRM to analysis of a meaningful period, comparing the results to operation with current rules, and assessing critically the differences.

MRD system operation was analyzed with HEC-PRM for a five-year average flow period, March 1965 to March 1970. Hydrologic data include monthly reservoir inflows and local flows, depletions, and lake evaporation rates. Initial and final storage values for the main-stem reservoirs are identical to those used with the reservoir simulation model in use by the Corps Missouri River Division (MRD), applied to the same period.

Composite, piecewise-linear penalty functions were developed for all purposes at all locations. Only economic (cost based) penalty functions are used. Maximum reservoir storage was limited to the top of annual flood-control and multiple-use zone. Minimum storage was limited to the top of inactive pool.

To test the reasonableness of the results, HEC-PRM results were compared with those of the MRD 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. The MRD model follows existing operation rules, and HEC-PRM operates to minimize total system penalty for the period.

As a consequence of the validation test, HEC-PRM was accepted for subsequent analyses. It is clear from the test results that the model does what it is supposed to do: It defines a minimum-penalty allocation of system water. The test also reveals the sensitivity of the model to the penalty functions used, an expected result.

MODEL APPLICATION

Two applications of HEC-PRM have been completed and published to date: (1) analysis of the critical period for the system with the best-currently-available estimates of system penalty functions; and (2) analysis of the same critical period with a hypothetical substantially increased navigation penalty function for Sioux City flow. The reservoir storage levels, reservoir releases, and downstream flows were computed and compared. Figure 5 is a plot of reservoir storage for the critical period. Other plots of reservoir releases, downstream flows, stream reach and penalty values were developed and compared, but, are omitted here to conserve space. The results of the analysis of the critical period for the system with the best-currently-available estimates of the system penalty functions are shown solid. The results of the analysis with inclusion of the hypothetical navigation penalty function is shown dashed for all plots.

The critical period for the system was identified as March 1930 - March 1949. This includes the 12 year (1930 - 1941) drought of record and the period required for refilling of reservoirs when following current operation policy. These data include reservoir inflows and local flows, depletions, and lake evaporation rates. As a rule, energy generation dominates the operation. HEC-PRM proposes release of water to drive the energy penalty to zero if sufficient water is available. Otherwise, it proposes making no release and storing water for subsequent use. This is again a case of long-term verses short-term operation decision making. The model must choose between making minimum releases for hydropower now or storing water for later use. It chooses the latter based on total system penalty, as defined by the penalty functions. Although a skilled operator might choose a less drastic operation, the penalty functions used in this application do not indicate that another policy is better, although it may be as good.

In the second application of HEC-PRM, operation was analyzed for the same period described in the previous section. A hypothetical navigation penalty function was added to demonstrate the impact of system operation for high-penalty downstream requirements. The hypothetical navigation penalty function causes the flow pattern at Sioux City to be smoother, as the range of flows there is reduced and this draws on more storage. Often the system has operated to provide exactly the minimum penalty flow during April-November. For December-March, the system has reduced releases to a bare minimum to conserve water to meet subsequent April-November demands. Even so, to satisfy the minimum at Sioux City, the system must draw down Ft. Peck, Garrison, and Oahe, starting in 1939. Earlier and later in the critical period, the Ft. Peck storages are approximately the same with and without the function. Then sufficient water is available to meet the demand without drawing on upstream storage.

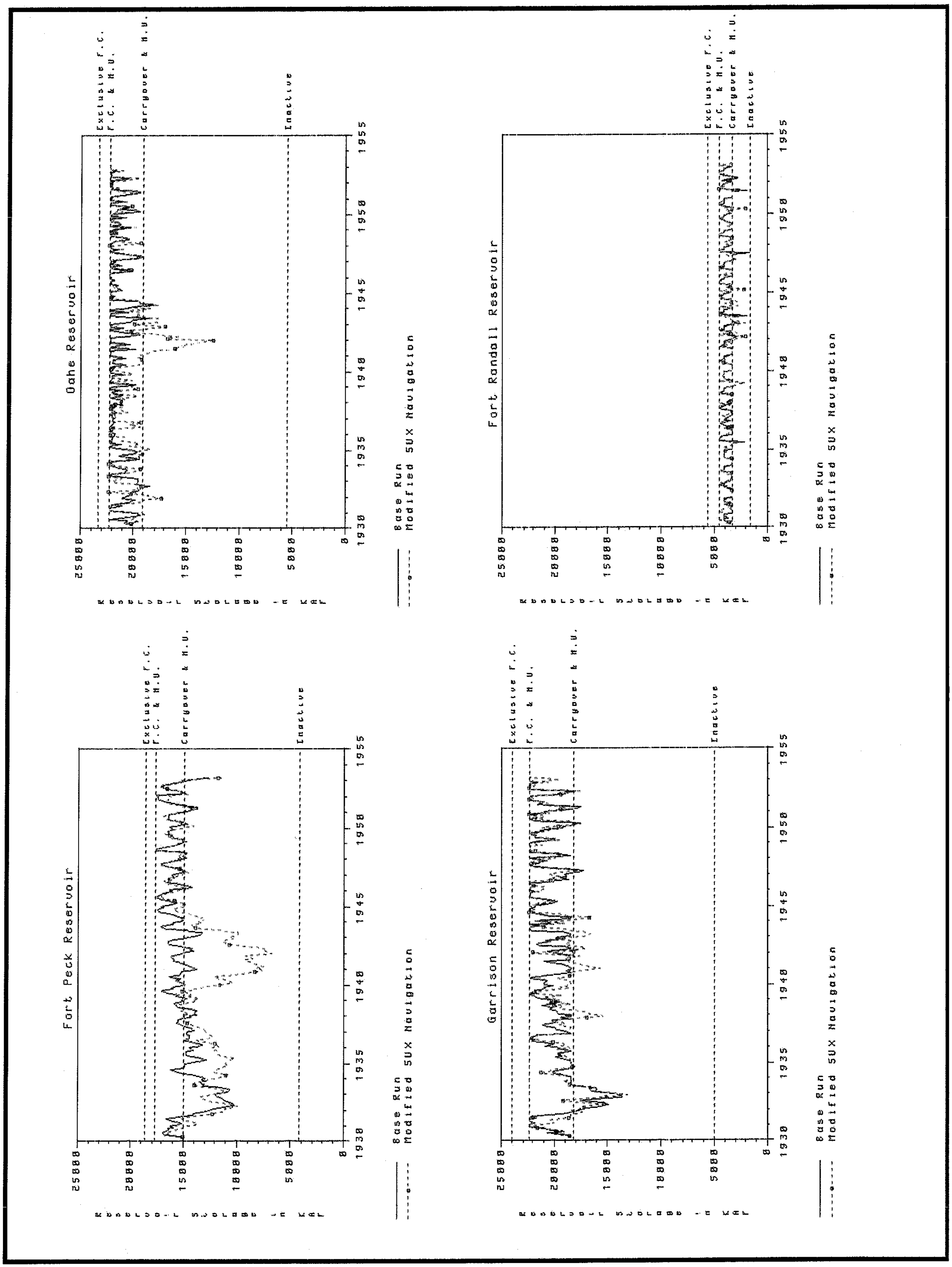

FIGURE 5 Reservoir Storages for Critical Period Analysis

MODEL STATUS, FUTURE DEVELOPMENT

HEC-PRM will be delivered to MRD in working version form in a workshop in December 1991. The model is now usable with assistance by HEC. Preliminary user documentation is also available. MRD will be applying the model early in 1992, in studies contributing to update of the Missouri River Main Stem Master Water Control Manual. The model is intended to be used to provide insight into trade-offs between water storage and release allocation alternatives. Together with complimentary studies underway using the MRD simulation model, updated system-wide operation rules will be derived to guide reservoir operation decisions in the coming years.

A similar application commenced in January of 1991, to the Columbia River System. Additional model development is occurring that will improve the hydropower representation (include non-linearity in head, flow, power functions), update the solver to state-of-the-art capabilities, implement a user shell to facilitate ease of data entry and display, and implement general-purpose post-processor reporting and display capabilities. The Columbia River System application will conclude in the fall of 1992.

Current plans are that a fully capable, tested, and documented, HEC-PRM program will be ready for general public release in early 1993. The program would at that time, meet HEC's high standards for publicly releasable programs, such as represented by the well known HEC-1 and HEC-2 programs. Other applications and refinements are anticipated between now and general release in 1993.

CLIMATE CHANGE APPLICATIONS

In the context used here, climate change refers to the long-term, fundamental shift in climate induced by permanent changes in contributing atmospheric and hydrometerological factors. Short-term or transient deviations from historic weather patterns that are explainable by usual random fluctuations are not considered. Climate change, should it occur, will therefore effect both the available water through changes to streamflow and societies requirements for water by altering use patterns. Studies of the water management impacts of climate change must address both these issues.

Should it be possible to represent anticipated climate change effects with quantified, altered, expected streamflow and water demands, application of prescriptive models, such as HEC-PRM, could contribute insight into trade-offs in water management policies. Alternative hydrologic monthly streamflow sequences would be prepared by adjusting historic period-of-record (or stochastic) streamflow for postulated climate change effects, penalty functions would be altered to reflect postulated demand/value changes, and HEC-PRM executed. Results would then be compared for a wide-array of hydrologic, water use, and value parameters, and conclusions drawn. If the results indicated that improved operation rules and policies would be desirable, further studies would be conducted to refine rule curves to reflect the postulated changes.

At present, climate change studies are not part of the Missouri River Main Stem Master Manual Update studies. Current studies are based on evaluating alternative operation policies on the adjusted (to present) 92 year historic streamflow sequence. The potential for climate change and possible streamflow impact thereof, continues to be debated be scientists. Far more definitive characterization of climate change than has been possible to date, is required before system operation studies would be meaningful. At present, significant changes in use patterns and society preferences are the issues being addressed in studies to update operation policies. Nonetheless, operation policies and rules are revisited at regular intervals, often about 10 years , so that ample opportunity will exist to consider desired policy changes at such a future time as results of climate change possibilities become more certain and quantified.

CONCLUSIONS

From the activities of Phase I, HEC staff conclude the following:

- Network flow programming is an appropriate tool for analysis of long-term system operation. It is simple enough to understand in theory, yet sophisticated enough to account for most critical system characteristics and operation requirements.

- A usable model (HEC-PRM) has been implemented.

- The success of a prescriptive model such as HEC-PRM depends on the capability of the penalty functions to capture the essence of operation goals and constraints.

- Additional development is required before the model and results will be available for distribution. The work underway will yield a model and penalty functions that will provide useful information for making decisions regarding long-term operation rules for the MRD system.

- There is a role for prescriptive models, such as HEC-PRM, in study of water management impacts of possible climate change.

ACKNOWLEDGEMENTS

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