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A SCREENING MODEL FOR WATER RESOURCES PLANNING[1]

Warren Viessman, Jr., Gary L. Lewis,
Isaac Yomtovian and Norma J. Viessman[2]

ABSTRACT: Techniques of optimization and simulation are merged to select the most efficient arrangement of components for regional water resources development and management. Application is made to the Elkhorn River Basin in Nebraska. The Basin extends over 7,000 square miles and includes 184 proposed reservoirs. Structure sizes, locations and operating policies are selected for optimal plans based on economic efficiency and regional development. Results indicate that substantial savings in time and costs over conventional planning techniques are effected. Agreement between model output and agency design values was noted.
(KEY TERMS: systems analysis; water resources planning; optimization; linear programming.)

INTRODUCTION

Screening models are digital "optimization" models and are designed to select a best plan from many alternatives for a specified planning objective. Simulation models, in contrast, are better suited for detailed analyses of specific alternatives and yield reliable information on which to base final designs or operating policies. Used together, these tools become a powerful adjunct to traditional planning technologies. They can provide detailed information about more planning alternatives for less cost than other approaches.

Other examples of optimization and simulation model versatility include the ability to quickly and inexpensively assess the impact of uncertainties in cost and benefit coefficients, anticipated annual or seasonal requirements, stream flows, land-use practices, environmental issues and other factors of interest. By adding this quantitative dimension, traditional approaches to planning are strengthened and extended.

ELKHORN RIVER BASIN

The Elkhorn River is a tributary of the Platte and drains an area of about 7,000 square miles in northeastern Nebraska. The western edge of the Basin extends into the Sandhills and the lowermost reach is within the Platte River Valley. The eastern part is one of Nebraska's most productive agricultural areas.

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[2] Director of the Nebraska Water Resources Research Institute, Assistant Professor of Civil Engineering, Research Associate and Systems Analyst, University of Nebraska 68503.

About seven percent of the Basin area is irrigable by gravity-distribution systems. Throughout the dryland section, the natural potential for evaporation usually exceeds the available moisture supply. Average annual precipitation ranges from 21 inches at the upper end to 29 inches at the lower end. Little runoff occurs in the western part of the Basin because of sandy soils while silts and clays in the eastern section reverse this tendency.

MODEL STRUCTURE

General

Many variables must be considered in investment and management decisions for water resources systems. Some of the most important, determined by the model are:

(1) Active over-year and within-year reservoir storage capacities (capacities required for allocation of various downstream firm and secondary yields).

(2) Flood control storage capacities to allow temporary storage of flood flows throughout the year.

(3) Total storage capacities (the sums of active capacity, dead storage and flood control storage).

(4) Annual and seasonal firm and secondary yields or allocations to uses such as reservoir storage, domestic supplies, commercial and industrial supplies, irrigation, hydroelectric energy production, flow augmentation for water quality, fish and wildlife enhancement, diversions and reservoir-based recreation.

(5) Annual and within-year reservoir drawdowns or releases (if any) in excess of releases of firm and secondary yields.

(6) Reservoir storage volumes at the beginning of each year and within-year season.

(7) Annual and seasonal firm and secondary target, deficit and surplus allocations to each consumptive and nonconsumptive use if values are not preassigned.

Input to the model consists of an historical or simulated sequence of unregulated annual and within-year period streamflows at each water use or management site. When economic efficiency is a planning objective, input includes derived benefit, loss and cost criteria in the form of functional relationships between costs and long- and short-run benefits as functions of various levels of decision variables. For this objective, the model maximizes total expected benefits from all water uses, less the amortized costs, OMR costs and the sum of losses due to deficit or surplus allocations.

Benefits and losses associated with various developments, allocations and uses of water are defined as the lesser of either the least costly alternative means of achieving the same allocation from outside the system (opportunity cost) or the willingness of consumers to pay for the allocation. For water uses having no economic loss or benefit data, constraints specifying minimum acceptable annual or seasonal allocations are used. Surface water uses include irrigation, recreation, fish and wildlife enhancement and flood control. Municipal and industrial water supplies are principally met from groundwater and were not incorporated as allocations.

Techniques for evaluating surface water investment and management alternatives include various optimization and simulation models. The proposed model, patterned after a design by Loucks (1973), is intended as a preliminary screening tool. It is easy to apply, has minimal data requirements and has a sound physical base. Manageability is obtained, however, at the expense of detailed approximation of reality. The model also includes aspects of river basin management (over-year storage capacity requirements and estimates of mean probabilities that each flow, yield or allocation will be exceeded) ommitted from most others.

Elkhorn Screening Model

Nineteen U. S. Army Corps of Engineers projects, three U. S. Bureau of Reclamation projects and 161 Soil Conservation Service floodwater retarding structures were included as potential plan elements in the analysis. This is the first known example wherein a mixture of small and large multi-purpose projects were studied concurrently.

The model is based on a linear programming formulation. Functions used were, in general, non-linear and had to be linearized before a solution could be effected. For each site, a set of equations representing average annual costs and benefits to be gained from various activities was formulated. A constraint set assures that pertinent physical, institutional or legal restrictions are included. The model is designed to accomodate sequences of years as well as any number of desired seasons.

Objectives used in evaluating alternatives included:

(1) Maximize net annual benefits using 1970 flood damages for interest rates of 6-7/8 and 5-5/8 percent;

(2) Maximize net annual benefits based on 2020 flood damages, 6-7/8 percent interest rate; and

(3) Minimize annual cost for 30 and 60 percent flood damage reduction on a site-by-site basis and on a basin-wide basis.

Other configurations included weighting of recreation benefits at selected sites and sensitivity studies of expected flood damages. The model can be structured to handle multiple objectives through use of special weightings or constraints and once formulated, modifications in objectives or constraints are easily incorporated.

Objective Function Components (Costs and Benefits)

Recreation benefits were assigned all major reservoirs (Corps, USBR) and some SCS projects depending on size and/or public accessibility. It was considered that there would be 70 visits per acre at a maximum of $2.25 per visit. This rule was used where specific information on recreation benefits was not available.

Fish and wildlife benefits and associated mitigation costs were provided by those responsible for the project or the Bureau of Sport Fisheries and Wildlife.

Benefits for structural or nonstructural flood control measures were defined as the difference between expected damages for unregulated conditions and expected damages after measures were implemented. Flood damages prior to implementation of control were determined by examining flood plain property values and assigning monetary units to damages for temporary or sustained flooding. Post-implementation flood damages were determined in a similar fashion with proper recognition given to either the reduction in property value if nonstructural alternatives were implemented, or to the physical changes in flood-frequency relationships if structural measures were adopted, and in this case, reductions in peak flows constituted the measure of flood control.

Flood damages in a particular reach of a stream were assumed to be concentrated at a single point called a "flood damage site." One-hundred and fifty-three of these were identified. Damages for various flood events were summarized in the form of stage-damage or discharge-damage curves. These allowed a graphical determination of expected damages for any flood control plan.

A flood control plan would accumulate benefits for flood control at one or more downstream damage sites for each flood that occurs after implementation of the plan. Repeated flooding for a succession of years would result in a value of accumulated damages in every reach. Because conventional analyses of costs and benefits compare annual values, average annual damages rather than accumulated values were determined.

Cost functions were based on site-specific information or generalized cost vs. storage capacity curves. Both 5-5/8 and 6-7/8 percent interest rates were used. OMR costs were added to annual costs. These were calculated as 0.5 percent of capital costs. Most cost and benefit functions were non-linear but were approximated with a small number of linear segments.

Constraints

The constraint set related decision variables to proposed water uses and system hydrology. A typical set of statements is:

(1) *Reservoir-Based Recreation Constraints*
Target Storage – Deficit from Target + Excess from Target = Average Over-Year Storage + Dead Storage + Average Within-Year Storage.

(2) *Within-Year Storage Constraints*
Within-Year Storage at End of Season 1 + Seasonal Inflow – Seasonal Firm Yield – Seasonal Excess Release = Storage at End of Season 2.

(3) *Over-Year Storage Constraints*
Storage in Reservoir – Evaporation and Seepage in Year 1 + Inflow – Firm Yield – Excess Release = Over-Year Storage at End of Year 2.

(4) *Total Reservoir Capacity Constraints*
Total Reservoir Capacity ≥ Dead Storage + Maximum Over-Year Storage + Maximum Within-Year Storage + Flood Control Capacity.

(5) *Flood Control Constraints*
Flood Control at Each Flood Damage Site = Function of Upstream Capacities.

(6) *Irrigation Constraints*
Reservoir Yield – Irrigation Target – Recreation Target + Dead Storage ≥ 0.
Irrigation Target ≤ Maximum Potential Allocation at an Irrigation Site.

Recreation and irrigation targets were imposed where seasonal considerations were important. A penalty was charged if water, supplied for a use, exceeded or fell short of the objective. Targets then became decision variables.

Model solutions indicated whether a project should be constructed, and if so, how storage capacity should be distributed and how storage volumes should be allocated.

FLOOD CONTROL

One alternative for achieving flood control in a river system involves the construction of reservoir capacity for temporary storage of flood flows. Net economic benefits are computed as the difference between annual flood damage reduction and development costs. Three techniques for screening structural flood control alternatives were used (Viessman, et al., 1974), and each required the intermediate use of a flood-event simulation model.

Flood magnitudes are influenced by many factors such as antecedent wetness, snowmelt, channel condition and ice-affected stages. Simulation of floods and reservoir capacities for the detention and release of flood flows depend on these. Since computational limitations of opimization models do not allow incorporation of details normally included in simulation models, assumptions must be made to reduce complexity. These include:

(1) Reservoir storage capacity for flood control would be available prior to a major storm.

(2) Flood control reservoirs would be designed with the water level at sediment pool elevation.

(3) Each SCS floodwater retarding structure has a principal spillway that would release 10 cfs per square mile of drainage area. Each Corps and USBR principal spillway would release an average of 5 cfs per square mile.

(4) Principal spillway inlets are at sediment pool elevation.

(5) Each structure could be designed for flood or sediment control purposes only.

(6) A reservoir causing reductions in flood peaks for a severe storm would cause the same percent reduction for all damaging storms.

(7) Flood peaks originating in different tributaries to a damage site arrive at about the same time.

The simulation model used to generate constraint functions for the optimization model uses actual or critical storm rainfall to synthesize direct runoff hydrographs (Yomtovian, 1973). These were combined and routed along stream channels and through reservoirs.

Input consisted of (1) control parameters defining channel segments and sub-watershed linkages; (2) sub-watershed characteristics of slope, area, length and loss characteristics; (3) channel segment slopes, lengths, roughness coefficients and base flows; (4) reservoir characteristics including storage-elevation and area-elevation curves, principal and emergency spillway parameters and maximum feasible capacities; (5) points of interest at which hydrographs are to be output; (6) parameters describing storm distribution, intensity and duration; and (7) hydrograph data at interest points where data were available and comparisons of measured and synthesized hydrographs were desired.

Output depends on user-specified parameters and can range from all generated values to single hydrographs or hydrograph peaks at single points. Options were available for various output forms, including line-printed values, calcomp plots or punched cards to be used as input to other programs.

Flood peak reduction functions for various values of flood capacity at a reservoir are illustrated in Figure 1.

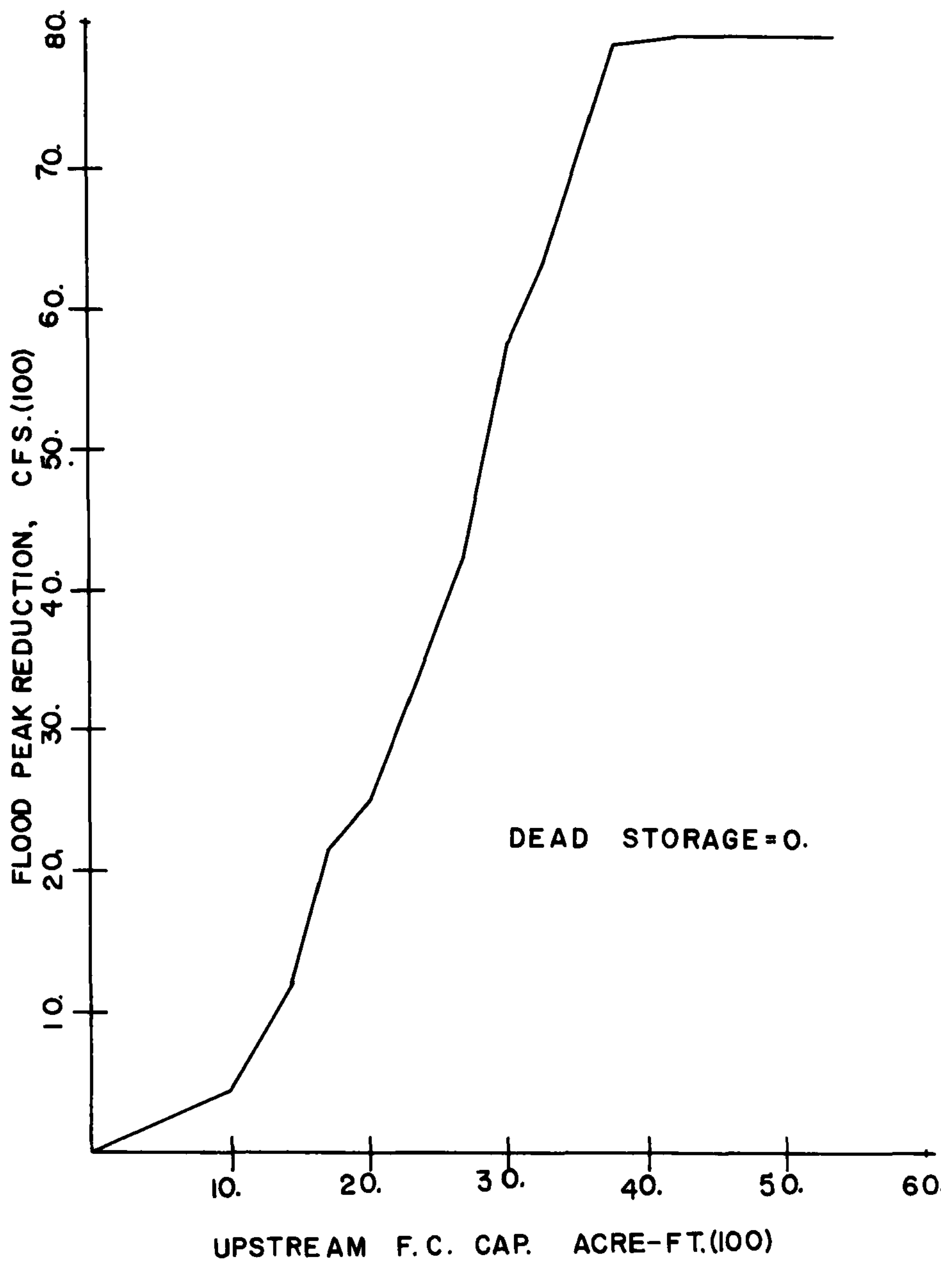

Figure 1. Computer-generated Graph of Flood Peak Reduction at Site 30 for Various Flood Capacities in Reservoir 1, Maple Creek Watershed.

DESCRIPTION OF MODEL RUNS

The Basin was divided into seven independent watersheds. One of these, the Mainstem, draining about 4,300 square miles (Figure 2) will be discussed. Potential development

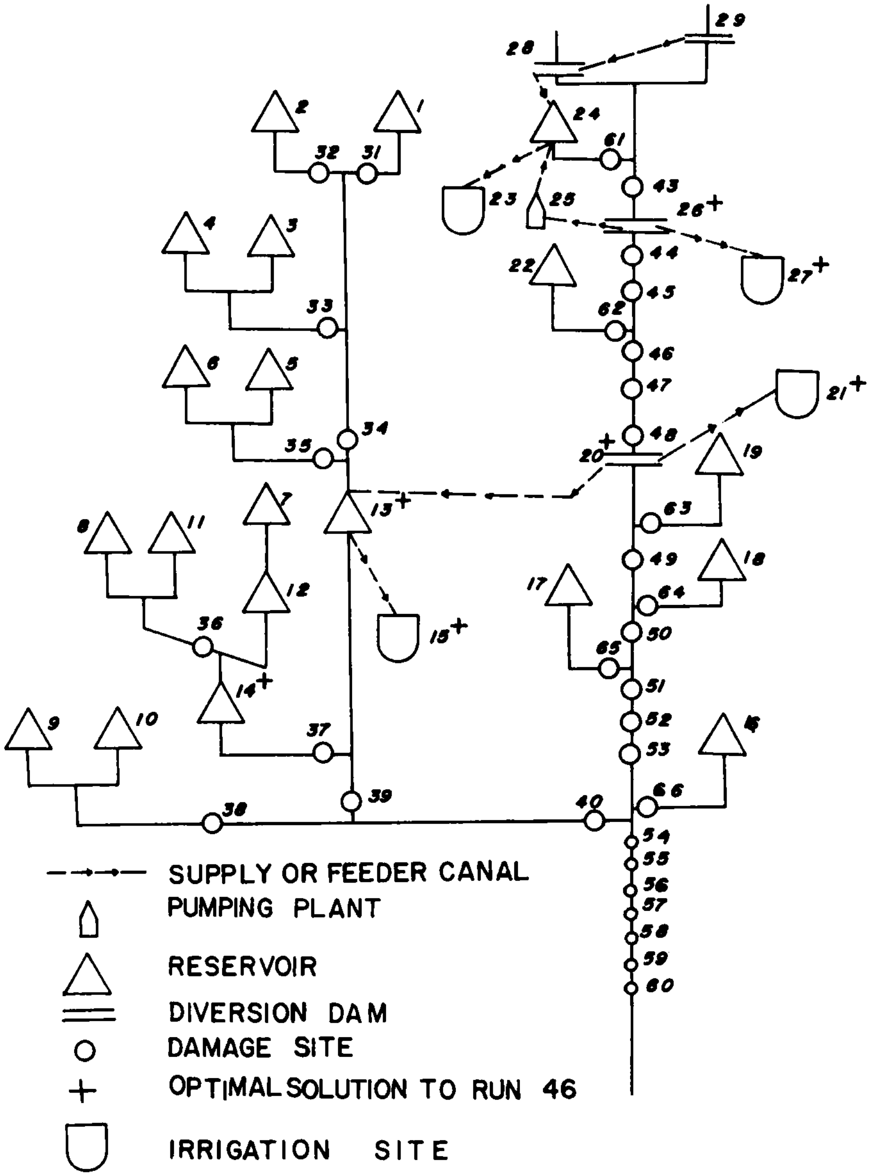

Figure 2. Screening Model Schematic of Projects on Elkhorn Mainstem Watershed.

includes two Bureau of Reclamation projects, seven Corps projects and ten SCS projects. This watershed was the most complex due to the physical character of irrigation works. Benefits included irrigation, recreation, fish and wildlife enhancement and flood control. The model was operated to maximize net annual benefits over two seasons and a five-year hydrologic trace. Runs 46, 48 and ALL were based on 1970 damages while run 47 was based on damages estimated at the year 2020. All calculations were based on 5-5/8 percent interest except those in run 48 where 6-7/8 percent was used. Run ALL includes a constraint to provide 15 percent flood damage reduction for the entire Basin.

Optimization results for the Mainstem Watershed are presented in Figure 2 and Tables 1-3. Figure 2 displays optimal results for a National Economic Development (NED) objective using 5-5/8 percent interest (Run 46). The Monterey Reservoir (13) was assigned a capacity of 37,670 acre-feet. This represents within-year storage at the end of season 1 (September through May) and is released in the Ridgeley Canal to irrigation site 15 during season 2 (June through August). Because of inadequate inflows to site 13, Monterey Feeder Canal diverts 71,724 acre-feet during season 2 from the Elkhorn River at Warnerville (20). The optimal recreation target at site 13 is 18,835 acre-feet; providing $108,000 in recreation benefits.

Norfolk Canal is to supply irrigation site 21 by diverting flows from the Elkhorn River at the Warnerville Diversion (site 20). The irrigation target at site 21 for run 46 is at the specified upper limit of 22,500 acre-feet.

Reservoir 14 appears as a recreation site in NED runs with a dead storage of 2,200 acre-feet and has an additional flood detention capacity of 10,020 acre-feet for run ALL.

The St. Clair Reservoir (24) appeared in NED runs 46-48 with zero capacity. Annual costs and irrigation benefits in Table 1 for site 24 were associated with an optimal annual diversion of 22,500 acre-feet at Tilden to irrigate site 27 which did not require storage in or releases from St. Clair Reservoir. The model suggested that Tilden Diversion Dam (26) and Tilden Canal were the only efficient components of the Highland Unit when NED objectives were considered. The optimal target of 22,500 acre-feet (3.00 acre-feet per acre) was a specified upper limit. This suggested that additional benefits would be provided if a reevaluation of potential acreage resulted in increased crop yields or availability of more than 7,500 irrigable acres.

TABLE 1. Optimal Reservoir Capacities
Run 47 – Mainstem Watershed
Maximize Net Benefits, 2020 Flood Damages, 5-5/8 Percent, No Minimum Reduction

Reservoir Site No.	Optimal Sed. Cap. Acre-Ft.	Optimal F. C. Cap. Acre-Ft.	Optimal Over-Yr. Cap. Acre-Ft.	Optimal Total Cap. Acre-Ft.	Total Annual Cost $	F. D. $	Rec. $	Irrig. $	Total $	B/C Ratio Each Res.
13	0	0	0	37670	1120960	0	104032	1645133	1749164	1.6
14	2200	0	0	2200	39962	0	53160	0	53160	1.3
22	13800	0	0	13800	218459	77525	182250	0	259775	1.2
24	0	0	0	0	564750	0	0	895500	895500	1.6

In run 47 (Table 1) when 2020 flood damages were used, reservoirs 13, 14 and 24 appeared with capacities and components identical to run 46. An additional Corps reservoir (22) on Battle Creek appeared with high recreation benefits and flood control potential at damage site 62. Table 2 suggests that 14,800 acre-feet of dead storage in reservoir 22 also produced small flood damage reductions at sites 46 and 47.

When the interest rate was increased to 6-7/8 percent in run 48, the optimal plans at site 14 and the Highland Unit were the same; however, at that percentage, reservoir 13 would not be constructed. The annual cost and irrigation benefits for site 13 apply to an optimal season 2 diversion of 22,500 acre-feet at Warnerville to irrigate site 21 via the Norfolk Canal which did not require diversions to or storages in Monterey Reservoir. An optimal target of 22,500 acre-feet was a specified limit, indicating a need for additional analysis of the irrigation potential along the river downstream from Norfolk (site 20).

Initial attempts to generate a regional development plan which would provide 60 percent reduction in 1970 damages along the Mainstem were infeasible, which means this level of reduction could not be achieved. Annual damages at sites for the Mainstem Watershed total $818,600. By repeatedly reducing the requirement for reduction in damages, a feasible solution was obtained when total flood control benefits were reduced to $125,000 or about 15 percent of the unregulated value.

TABLE 2. Model Results at Flood Damage Sites
Run 47 – Mainstem Watershed
Maximize Net Benefits, 2020 Flood Damages, 5-5/8 Percent, No Minimum Reduction.

Flood Damage Site No.	Unregulated Average Annual Damages, $	Upstream Reservoirs With Influence	Damage Reduction $, Due to Each Resv.	Reduction Percent of Unregulated Damages	Total F. C. Benefits at DMG. Site, $	Total Percent Reduction in Unregulated Damages
39	14789	13	0	0.0		
		14	0	0.0	0	0.0
40	133230	13	0	0.0		
		14	0	0.0	0	0.0
37	106477	14	0	0.0	0	0.0
62	220875	22	76421	34.6	76421	34.6
46	19785	22	611	3.1		
		24	0	0.0	611	3.1
47	16244	22	491	3.0	491	3.0
48	39880	22	2	0.0	2	0.0
61	20000	24	0	0.0	0	0.0
43	1802	24	0	0.0	0	0.0
44	4205	24	0	0.0	0	0.0
45	9290	24	0	0.0	0	0.0

Appearing in the regional development (RD) run were Monterey (13) and St. Clair (24) Reservoirs with all potential components, all Corps reservoirs and eight SCS reservoirs on Pebble Creek and its tributaries. SCS sites 1, 2 and 3 were exclued due to relatively small unregulated flood damages at sites 31 and 32. All other damage sites were influenced in various amounts. On a percentage basis, the smallest reductions occurred at damage sites along the Mainstem. In terms of dollar amounts, the distribution of flood control benefits were concentrated below Corps sites in tributaries to the Elkhorn including Pebble Creek.

The USBR sites 13 and 24 appeared in the RD run with total capacities of 80,700 and 157,800 acre-feet, respectively, compared to preliminary agency values of 211,100 and 310,000 acre-feet. Irrigation deliveries were allocated as follows:

Irrigation Site	Canal	Season 2 Supply Acre-Feet	Irrigable Acres	Annual Irrigation Benefits
21 Norfolk Unit	Norfolk	22,500	5,100	895,500
15 Norfolk Unit	Ridgeley	16,855	25,000	335,417
27 Highland Unit	Tilden	22,500	7,500	895,500
23 Highland Unit	Humphrey	20,815	48,000	414,217
	Totals	82,670	85,600	2,540,632

Based on the five-year record of streamflows, over-year storage was not required at sites 13 and 24. However, within-year storages of 16,855 and 20,815 acre-feet at the end of the first season (September through May) were required to meet season-two allocations. Optimal recreation targets at sites 13 and 24 were 30,928 and 32,907 acre-feet, respectively.

Within-year storage in the St. Clair Reservoir was obtained from natural runoff combined with a season-two diversion of 32,378 acre-feet at Inman (29) and an additional season-two diversion of 6,370 acre-feet from the South Fork at the Holt Diversion Dam (28). In a similar fashion, 52,594 acre-feet were to be diverted during season two at the Warnerville Diversion Dam (20) with 22,500 acre-feet allocated to site 21 and the remaining 30,094 acre-feet were supplied by the Monterey Feeder Canal to site 13.

Table 3 summarizes all runs for the Mainstem Watershed. The first NED runs showed favorable benefit-cost ratios but incorporated only a few of the potential sites. The single RD plan called for 17 reservoirs but was not economically efficient on a national scale. Only two of the four plans produced flood control benefits.

CONCLUSIONS

By *comparing* screening model results with plans formulated by the various agencies,

TABLE 3. Summary of Results For All Model Runs For Mainstem Watershed.

Run No.	No. of Iters. to Solve	No. of Eqns. in Model	No. of Col. in Model	Cost of Run, $	Run Time, Min.	No. of Resvrs. in Sol.	Total Dead St. Acre-Ft.	Total F.C. Cap. Acre-Ft.	Total Active Acre-Ft.	Total Capcty. Acre-Ft.
46	304	332	717	23.15	4.1	3	2200	0	0	39870
47	305	332	717	22.95	6.7	4	16000	0	0	53670
48	300	332	717	23.13	3.7	3	2200	0	0	2200
ALL	584	333	717	38.35	31.1	17	204964	138023	0	380657

Run No.	Net Annual Benefits,$	Annual Costs, $ Capital & OMR	Canal Cost	Total Cost	Annual Benefits, $ F. C. Ben.	Rec. Ben.	Irrig. Ben.	Total Ben.	Basin B/C Ratio
46	972153	554534	1171137	1725671	0	157192	2540633	2697824	1.6
47	1013468	772995	1171137	1944131	77525	339442	2540633	2957599	1.5
48	625201	48734	1170224	1218959	0	53160	1791000	1844160	1.5
ALL	-1794482	4492582	949259	5441840	124999	981733	2540632	3647358	0.7

agreement on most significant issues was apparent. The modeling approach permits development and evaluation of preliminary plans in a more rapid time-frame than conventional techniques. Expenditures would also be reduced. Data requirements for this level of planning are not excessive and could be met for most river basins in the United States where some rainfall and streamflow records exist and where topography is available. Cost and benefit data can be estimated with sufficient reliability for screening from current agency sources. Once formulated, the planning models are extremely versatile and offer the opportunity to evaluate sensitivity of a proposed plan to any of its elements. They are easily modified to accommodate revisions and greater detail if desired.

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