SPATIAL AND TEMPORAL WATER ALLOCATION IN THE KISSIMMEE RIVER BASIN*

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In many areas of the country, there is strong competition among agricultural, municipal, industrial and other users of water. Water managers are faced with the problem of allocating available water among alternative uses.

The study [11] upon which this paper is based was a cooperative effort with the Central and Southern Florida Control District which is typical of many water management districts making decisions regarding allocation of a limited amount of water among uses and users. When the District was formed, it was developed with emphasis on facilities to provide relief from flooding. Water management responsibilities such as water supply, recreation and the preservation and enhancement of fish and wildlife have become important to the public and consequently have received recognition by those responsible for managing the water. To fulfill these responsibilities, the Flood Control District operates a complex system of canals, levees, pumping stations, spillways, navigation locks and retention basins.

Operational procedures are based on fixed seasonal rule curves requiring a prescribed amount of flood storage space in each reservoir, each year, in the two or three month period preceding October 1. Operational decisions were predetermined for the provisions of flood protection and governed by calendar dates [15].

The Flood Control District recognized the operational rule curves based on flood control design criteria and previously existing demands can sometimes fall short of generating optimum benefits when the nature of land use, drainage, urbanization, pollution, industrialization and other things within the project area change. To improve the system of water management so it could better satisfy various users of the system, the Flood Control District undertook a research and development approach to adapt mathematical modeling techniques to its system [15]. Their goal has been to develop: (1) a physical systems model, (2) rainfall prediction model and (3) allocation model. The District's efforts in physical system modeling and rainfall prediction models have been reported elsewhere [12, 13, 14]. The study upon which this paper is based was directed toward the development of allocation models.

The purpose of this paper is to present a model for water allocation among alternative uses within a time period, and between uses in different time periods under certain physical and institutional constraints.

WATER MANAGEMENT MODELING

The process of making and implementing water management decisions involves physical, economic and institutional considerations. These three considerations should be evaluated and integrated into any water management decision or policy.

Physical considerations are concerned with what is physically possible. This involves specifying physical alternatives and determining limits of the water management system. Water management alternatives should also be evaluated in terms of what is economically desirable. Economic considerations involve economic evaluation of the physical possibilities of the system. Water management decisions concern how to meet the objectives most efficiently,

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given the physical system. In this case, development costs for the system are sunk costs. The economic evaluation now deals with net benefits of each management alternative within the given system.

Both physical and economic considerations are dependent upon what is institutionally permissable. Water management alternatives must be evaluated to determine if they are legally permissable and politically acceptable. The physical, economic and institutional considerations are all important components of any operational water management model. Figure 1 depicts the major components in the development and ultimate selection of an operational water management policy.

A long-term operational water management policy is developed in the following manner [11]:

(1) A proposed long-term regulation policy is specified. This is in the form of a gate regulation schedule (rule curve), water use regulation, land use change or any other modification.

(2) This policy affects the form of a surface water management model or the institutional constraint model.

(3) Hydrologic data are the primary inputs to a surface water management model, and the output is a set of lake surface elevations, the lake system states.

(4) The lake system states are inputs to the economic activities model, which given as output levels of the various water-use activities and net dollar benefits accruing to the various activities as a result of the regulation policy and subject to the institutional constraints.

(5) The lake states, benefit states and institutional constraints provide information on the reasonability of the proposed regulation policy. In the technical evaluation, if the proposed regulation policy is determined to be unacceptable, it is modified in light of the evaluation results and another run is made.

(6) If the policy is accepted, it is next evaluated by the governing board in light of considerations that have not been or cannot be quantified. If rejected, modifications and a new series of runs are made until the policy is acceptable to the governing board.

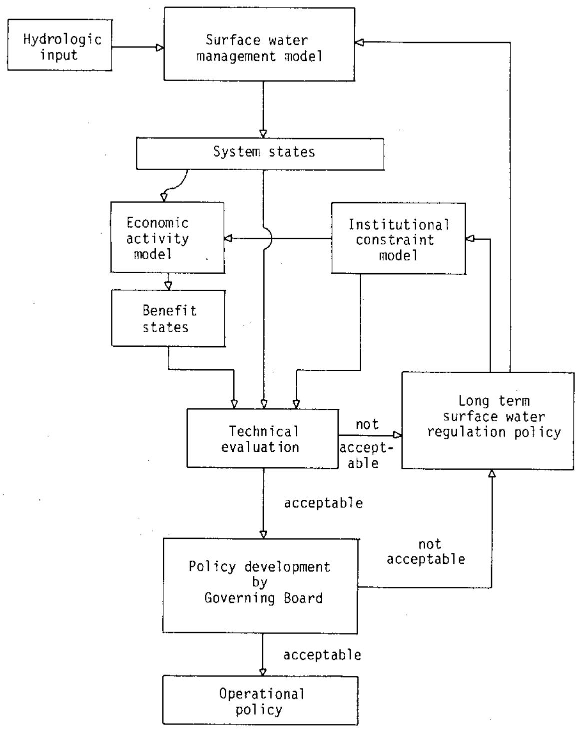

FIGURE 1. DEVELOPMENT OF OPERATIONAL WATER MANAGEMENT POLICY

When the long-term operational water management policy is satisfactorily developed, a short-term execution policy is formulated. This short-term execution policy is evaluated from rainfall input and the streamflow simulation, water surface elevation and gate operations models.[1]

Within this operational water management framework, the economic consequences of operational policy alternatives can be assessed. This paper presents a linear programming model that was used to assess the economic consequences of broad policy alternatives and the relative trade-offs based on economic returns from allocations of water among different users, locations and time periods.[2]

WATER ALLOCATION MODEL

The linear programming model[3] used in this study had as its objective the maximization of net

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[1] A more detailed explanation of the evaluation of short-term execution policy has been presented in [8, 11].

[2] In the same study a simulation model of the hydrologic-economic aspects of the system was also developed to assess short-term operational policies which are more specific, such as water level regulation schedules [8, 11].

[3] Several studies have used linear programming models in water resources research [1, 2, 6, 9, 10]. These studies have dealt with analyses concerning the planning and design of water resource systems (e.g., determining the optimum size and combination of structures). In this study the system was already constructed and we were concerned with determining the optimum allocation of water from alternative operating procedures within the given system.

economic benefits. The model can be represented algebraically by:

Maximize:

$$\text{Total Net Returns (TNR)} = \sum_{i} \sum_{k} [\sum_{j} a_{jki}\, C_{jki} + \sum_{n} a_{nki}\, S_{nki}] \quad (1)$$

Subject to:

$$C_{jki} \leq A_{jk}$$
$$S_{1ki} = ML_{ki}$$
$$S_{nki} \leq RLM_{nki}, \; n = 2, 3, \ldots$$
$$REL_{ki} \leq MXR_{ki}$$
$$MRL_{i} \leq \Sigma REL_{ki}, \; k = 3,4$$
$$Y_{ki} + \sum_{n} b_{nk(i-1)}\, S_{nk(i-1)} + REL_{(k-1)i} = \sum_{j} b_{jki}\, C_{jki} + \sum_{n} S_{nki} + REL_{ki}$$

Where

a_{jki} = per unit net returns from water consumptive activities

a_{nki} = per unit net returns from water used in non-consumptive activities

C_{jki} = level of activity (e.g., acres for citrus) of each of j water consumptive activities in each of k sub-basins, in each of i time periods (each time period being 2 to 4 months in length)

S_{nki} = amount of water stored, thus available for recreational and future consumptive uses, for each of n levels of storage, in each of k sub-basins, in each i time periods

Y_{ki} = water yield (net runoff water) available in each of k sub-basins and each of i time periods

b_{jki} = amount of water used for each water consumptive activity

b_{nki} = amount of water used (lost) in storage activities (e.g., evaporation)

A_{jk} = maximum number of units of each water consumption activity allowable in each sub-basin

ML_{ki} = minimum amount of water required to be stored for each sub-basin in each time period

RLM_{nki} = maximum allowable storage for each sub-basin in each time period

MRL_{i} = minimum amount of water required to be released from the system for each time period

MXR_{ki} = maximum amount of water allowed to be released from each sub-basin for each time period

REL_{ki} = amount of water released from each sub-basin for each time period (k-l denotes upstream sub-basin).

The model described above allocates available water over i time periods and k sub-basins such that total net returns (TNR) to society are maximized. TNR would consist of net returns (a_j, a_n) to water used in the various consumptive (C_j) and non-consumptive (S_n) uses. The per-unit net returns to water can be either positive (for uses beneficial to society), zero (for uses neither beneficial nor detrimental) or negative (for uses detrimental to society). The TNR is maximized subject to constraints on the water management system such as storage capacities within each sub-basin (RLM_k), minimum amounts of water required to be released from the system during each time period (MRL_i) and minimum amount of water required to be held in storage in each sub-basin (ML_k).

APPLICATION OF THE MODEL

The linear programming water allocation model was applied to the Kissimmee River Basin.[4] It was chosen as the study area because of availability of detailed hydrologic data. In addition, water in the Kissimmee River Basin can be controlled and allocated among alternative uses, watersheds and time periods. For study purposes the basin was divided into four sub-basins. Four time periods were established for use in the model: (1) June-September, (2) October-November, (3) December-January and (4) February-May, based on precipitation patterns in the area and on seasonal aspects of demands for water for crop irrigation and recreational purposes.

Minimum storage requirements (ML_k) for each sub-basin, maximum allowable storage level (RLM_k) for each sub-basin, alternative minimum release requirements (MRL_i) and water yields[5] (Y_{ki}) were estimated by the Flood Control District staff. Consumptive uses of water (C_j) in the basin were irrigated

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[4] The Kissimmee River Basin stretches from Orlando on the north to Lake Okeechobee on the south. It is a water management system of lakes, canals, control structures and the Kissimmee River.

[5] Water yield is determined by the distribution of rainfall and the resulting run-off or streamflow generated in the water management system in each time period.

crops. Six different crop-irrigation activities (C_{jki}) were specified and net returns per acre from each activity (a_{jki}), amount of water required by each activity (b_{jki}) and acreages of each crop (A_{jk}) were estimated by the authors and described in [11].

There were two non-consumptive uses of water or water related activities (S_{nki}) in the Kissimmee River Basin: recreational use of water in storage, and flood damages from excessive amounts of water in storage.[6] Net returns from recreation vary with amount of water in storage (Figure 2). Research in the Basin indicated decline in number of recreational visits per time period as the amount of water in storage fell below the mean storage level [3]. Based on this information, recreational benefits were assumed to be at a maximum between the mean storage level and maximum free storage; decrease by one-third as the water level fell from the mean to the minimum level; and decline when the storage level exceeded maximum free storage. Using this concept of the relationship between storage levels and value of water to recreational visitors, benefits in dollars per acre-foot of storage were determined as two linear functions [4, 5].

Net costs of flood damages per acre-foot of water above the regulated storage level for each basin were estimated by the Flood Control District Staff. To these were added losses in recreational benefits resulting from storage above specified levels (maximum free storage in Figure 2). Thus, the net cost of excessive quantities of water in storage was equal to flood damages plus losses in net returns to recreation.

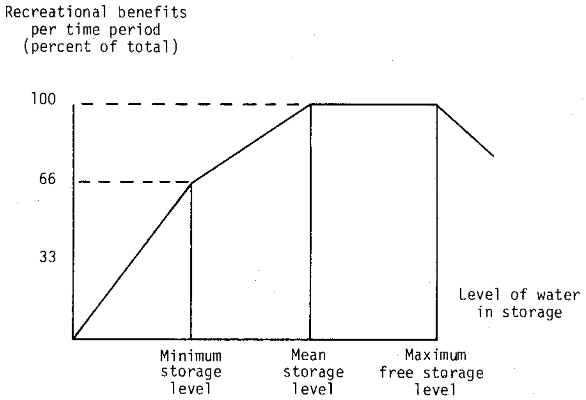

FIGURE 2. ACCUMULATION OF RECREATIONAL BENEFITS IN RELATION TO STORAGE LEVELS, KISSIMMEE RIVER BASIN, FLORIDA

Optimal allocations were obtained for the Kissimmee River Basin using three alternative minimum release requirements (MRL_i) and three levels of irrigated crop acreages (A_{jk}). These solutions were obtained using the 10-year average water yields (Y_{ki}) for each time period and sub-basin. The following information, which is useful in evaluating proposed changes in water regulation policy, was obtained for each sub-basin: 1) benefits from each type of irrigated activity; 2) benefits from recreation; 3) costs from flooding;[7] 4) total net benefits; 5) amount of water in storage at the end of each period; and 6) amount of water released. Except in the cases of benefits from irrigation and net benefits, this information was also generated by time period. Due to the way in which the irrigation activities were structured, benefits to irrigation were calculated only on an annual basis [11].

Amount of water released and total net benefits from optimal water allocation using alternative levels of release requirements and irrigated acreage are presented in Table 1. Total benefits decline by 15 percent if you change from a policy of "high irrigation-low release" to a policy of "low irrigation-high release." On the other hand, the difference in total benefits is only 0.1 percent between "low irrigation-low release" and "high irrigation-high release." These comparisons suggest that for the total basin, there exists possibilities for trade-offs between release requirements and acres of crops to be irrigated, while maintaining total benefits at a relatively constant rate. However, it is important to examine distribution of benefits among sub-basins and activities to evaluate which area or type of activity would gain or suffer from the proposed changes. For example, in comparing "low irrigation-low release" to "high irrigation-high release" alternatives, total benefits to the basin changed very little ($39,700) but irrigation benefits increased from $1.37 million to $4.05 million (Table 2). In moving from the "low irrigation-low release" to the "high irrigation-high release" alternative, downstream users of water (users outside the Basin) would benefit due to increased water releases as would irrigated agriculture.[8] Benefits to recreational users in the Basin, on the other

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[6] Flood damages to crops and real property in close proximity to the lakes and streams in the Kissimmee River Basin occur when water levels exceed certain specified elevations. Such flooding can be induced since the control structures were designed to effectively control water over a wide range of elevations.

[7] None of the optimal solutions obtained included storage levels sufficiently high to induce flood damages; therefore, costs from flooding were zero in all cases.

[8] Benefits from water released downstream of the Basin were not included in the benefits presented in Tables 1 and 2.

TABLE 1. WATER RELEASED AND TOTAL BENEFITS FROM THE OPTIMAL ALLOCATION OF WATER IN THE KISSIMMEE RIVER BASIN BY RELEASE REQUIREMENT AND LEVEL OF IRRIGATED ACREAGE

Irrigated acreage [a]	Release requirement[b]					
	Low		Medium		High	
	Benefits ($1000)	Releases (1000 ac. ft.)	Benefits ($1000)	Releases (1000 ac. ft.)	Benefits ($1000)	Releases (1000 ac. ft.)
Low	33,014.0	841.6	32,621.0	911.4	30,606.7	1,105.9
Medium	34,979.8	822.1	34,446.4	890.5	32,237.9	1,095.3
High	36,070.8	754.7	35,563.6	881.8	32,974.3	1,095.1

[a] Levels of irrigation were: Low = 1968 acreage irrigated from surface water (24,760); Medium = 1968 total irrigated acreage (55,816); and High = SCS projections of total irrigated acreage in 1980 (89,200).

[b] Alternative release requirements were: Low = average of the minimum releases over the last 10 years (231,000 acre feet); Medium = proposed regulation schedule (599,000 acre feet); and High = average discharges over the last 10 years (1,006,000 acre feet).

TABLE 2. BENEFITS FROM CROP IRRIGATION AND RECREATION OBTAINED FROM THE OPTIMAL ALLOCATION OF WATER IN THE KISSIMMEE RIVER BASIN BY LEVEL OF RELEASE REQUIREMENT AND IRRIGATED ACREAGE

Irrigated acreage	Release requirement					
	Low		Medium		High	
	Benefits $1,000	Percent of total	Benefits $1,000	Percent of total	Benefits $1,000	Percent of total
Low						
Crops	1,371.8	4.2	1,371.8	4.2	1,332.8	4.4
Recreation	31,642.2		31,249.2		29,273.9	
Medium						
Crops	3,337.7	9.5	3,337.7	9.7	3,143.2	9.8
Recreation	31,642.1		31,108.7		29.094.7	
High						
Crops	4,428.7	12.5	4,428.7	12.5	4,044.9	12.3
Recreation	31,642.1		31,134.9		28,929.4	

hand, would decrease by $2.7 million.

Increases in the release requirement caused reductions in total net benefits. By dividing the reduction in total net benefits by the additional acre-feet of water released, an indication of the cost (in terms of benefits foregone) per acre-foot of the water released can be obtained. Results of these calculations, presented in Table 3, indicate that average benefits foregone due to increasing the release requirement from "low" to "medium" range from $3.99 to $7.80 per acre-foot. Average benefits foregone from increasing the release requirement from "medium" to "high" range from $10.36 to $12.14 per acre-foot.

It should be noted that these estimates indicate that the benefits foregone from increasing the water

TABLE 3. BENEFITS FOREGONE DUE TO ADDITIONAL WATER RELEASES

Irrigated acreage	Release requirement change	
	Low to Medium	Medium to High
	---Dollars/acre-foot---	
Low	5.63	10.36
Medium	7.80	10.78
High	3.99[a]	12.14

[a] This estimate of the benefits foregone is much lower than expected and results from a substantially larger change in the amount of water released (denominator of ratio) than occurred at the low and medium levels of irrigated acreage. As water becomes more scarce at the medium and high release requirements there is less variation in the amount of water released.

release requirements from the Kissimmee River Basin tend to be quite sensitive to changes in the amount released. This relationship existed for both annual total releases and releases for each time period. Cost of water releases was also quite sensitive to the amount of water used for irrigation in the Basin.

SUMMARY AND CONCLUSIONS

A linear programming model of the hydrologic-economic system was used to determine the economic consequences of broad operational water management policy alternatives and the relative trade-offs based on economic returns from water allocations among different users, locations and time periods. Total net returns were maximized subject to constraints on the water management system such as storage capacities of each sub-basin, minimum quantity of water required to be released each time period and minimum quantity of water required in storage in each sub-basin.

Results obtained from application of the model to the Kissimmee River Basin provided the following conclusions concerning possible operating policy alternatives: 1) if mandatory release requirements are maintained at their minimum (low) levels, irrigated acreage can be expanded considerably for most years without decreasing recreational benefits; 2) benefits to society from use of water in the basin accrue mainly from its use as a recreational resource; and 3) cost (in terms of benefits foregone) for additional water released above the minimum required level is quite sensitive to the quantities of additional releases, the time period in which water is released, and the acres of each type of irrigated crops in the sub-basin.

This type of allocation model determines the optimum allocation (in terms of economic benefits) with respect to uses, time and location subject to hydrologic and institutional constraints. The input data requirements for this model were relatively simple. This model also provides a relatively easy comparison of changes in economic benefits due to changes in physical or institutional constraints, or changes in the level of water using activities. If the objective function is one of maximizing economic benefits, the costs of the trade-offs between water uses in time and space can be easily obtained.

One limitation of this type of model is inability to relate economic costs and returns of water-using activities to periods of time sufficiently small to reflect fluctuations in water yield and runoff. The length of time used in our model varied from two to four months. Shorter time periods can be used in this type of model (e.g., one month or two weeks), but the model is still unable to reflect the immediate fluctuation in water yield and runoff from a storm and any resulting flood damages. Another limitation is inability of the model to capture the incremental aspects of the decision-making process with respect to time. For example, the hydrologic yields for each time period are required as input data and these data are not available ahead of time.

This model can, however, provide both useful guidelines and initial indications for efficient spatial and temporal allocations of water managed by the system. More importantly, it can provide very useful indications of sensitivities of the various hydrologic and economic aspects of the system relative to proposed policy changes. Such information can be used to guide development of more detailed and specific information generating techniques for executing operational policies.

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