OPTIMAL MANAGEMENT OF ARTIFICIAL RECHARGE FACILITIES

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الخلاصة :

يمكن ملاحظة بعض التشابه في مكامن المياه الصخرية ، والمكامن السطحية من حيث إدارتها وتشغيلها . وهناك كثير من الميزات نتيجة لإدارة المكامن الصخرية المائية بحيث تحتوي على صرف اصطناعي ، وقابلية لتخزين المياه لمدة طويلة .

وفضلاً عن زيادة مياه المشروع وفوائدة في التقليل من الآثار السلبية على البيئة . وهوما يحتم علينا التوسع في بناء السدود ، والاهتمام بالبيئة .

نعرض في هذا البحث محاكاة لإدارة مشروع المكامن الصخرية المائية على نحو أفضل . وتتكوّن هذه المحاكاة من نموذج (HEC-3) للمحاكاة ، ونموذج القيمة العظمي الملائمة .

وتجدر الإشارة إلى الإفادة من تجربة مشروع مماثل في ولاية كاليفورنيا ، يمكن أن يُحتذىٰ في الحالات المشابهة في الشرق الأوسط .

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ABSTRACT

Aquifers may be considered as underground reservoirs and managed or operated similarly to surface reservoirs. There are numerous advantages to altering aquifer management to include artificial recharge and long term storage of excess water. Among these are increased net benefits to the total water supply system and decreased negative environmental impacts. This study illustrates how to optimally manage aquifer storage similarly to a surface reservoir by the combined use of a simulation model (HEC-3) and optimization model (the out-of-kilter algorithm). The simulation model shows how the system reacts to the management scheme resulting from running the optimization model. If the simulation results are infeasible, the constraints of the optimization model are modified and the cycle repeated. The method is illustrated by applying it to several basins in California. Similar situations exist in the Middle East, to which this approach may be applied. The results of the study showed that the water production of a stream–aquifer system might be significantly increased by operating them together, using artificial recharge and optimally timed ground water withdrawals.

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1. INTRODUCTION

The California Department of Water Resources (DWR) has initiated a conjunctive use program whereby excess Delta water is recharged into three selected groundwater basins: San Fernando, Chino, and Kern River Fan Area. These basins are, in effect, reservoirs from which water is drawn when needed. DWR is interested in optimal operation of the system and calculating the additional water it might produce. This study utilizes a simulation model, HEC-3, in conjunction with an optimization model, out-of-kilter network flow programming algorithm, to calculate (at the General Appraisal planning stage) the additional "firm yield" available by optimally operating the State Water Project (SWP) conjunctively. The study also indicates which basins cause the greatest change in total net benefits and which constraints are binding (*i.e.*, prevent greater "firm yield").

The level of detail adopted for this study is "general appraisal" or "level B" [1]. Before initiating an implementation study which would require substantial data collection and modeling costs, DWR would like to know the probability of success, *i.e.* what are the probable benefits to be derived from the costs. Consequently, the quantitative results of this study are meant to answer this question.

The area of study is the California State Water Project (SWP); it mainly concentrates on the three SWP groundwater basins for artificial recharge [2–6]. The locations of these three groundwater basins are shown in Figure 1. Detailed descriptions of these groundwater basins are given by Prasad [7].

This study uses the DWR definitions of "firm yield" and "critical period." That is, for input into the simulation, the critical period used to design much of the SWP is utilized (*e.g.*, the seven-year dry period between 1928 and 1934). The inflows ranging over this dry period are the lowest in the sequences over the fifty-seven year period of historical record. Firm yield is defined as the maximum amount of water the system can deliver without failure each year with optimal operation, assuming the inflows (precipitation) of the critical period. Non-firm yield is additional water available beyond the firm yield volume.

Any area with some surface runoff and corresponding aquifer storage may utilize this method of large-scale planning and operation. Certainly, regions of the arid Middle East need to utilize the available water even more carefully than California. Hopefully, the California application will better explain the methodology.

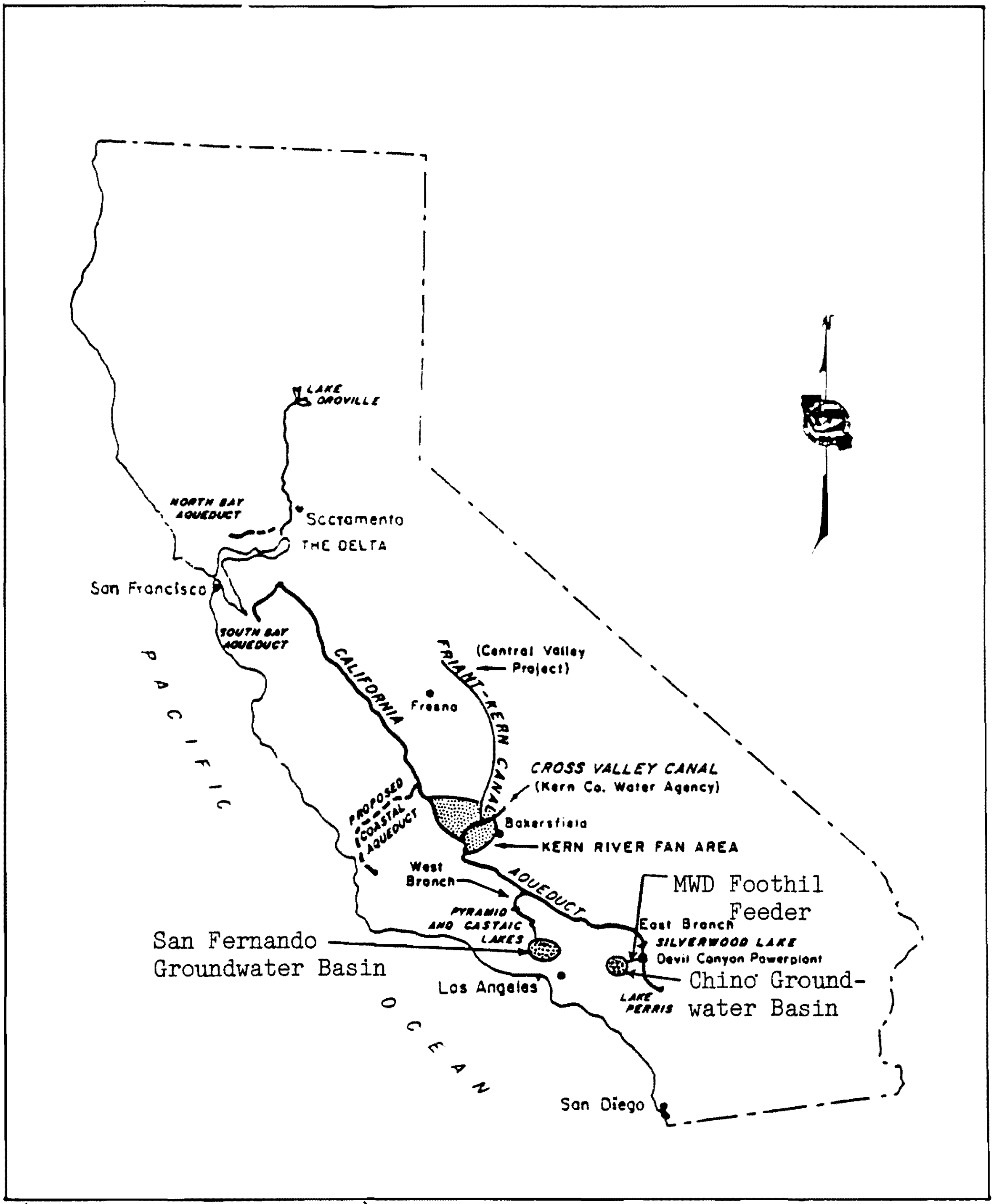
2. DEFINITION OF THE PROBLEM

Water demand in California is increasing day by day. If this trend continues, a time will come when the present yield of 3452 million cubic meters (MCM) from the State Water Project will be insufficient to meet all these demands. When this happens, it will be necessary either to expand the present surface water system or to operate it more efficiently. Three major problems that discourage expanding the surface water system are cost, environmental concerns, and necessary lead time. Because of this, improving the operation of the SWP utilizing conjunctive use may be one of the feasible alternatives.

There are five main constraints that limit the magnitude of the firm yield of the conjunctive use systems: the size of the available aquifer storage, the recharge rate, the pumping rate, the capacity of the SWP delivery system, and the amount of available excess water from the Delta pumping plant. Whichever of these constraints proves to be binding will dictate whether it will be feasible to increase the firm yield of the system either economically or physically.

Because the firm yield at a common point obtained through conjunctive operation of the surface water and groundwater will be a function of the constraints, it is helpful to examine the sensitivity of the firm yield of the conjunctively operated system to the tight constraints in order to evaluate possible measures to "relax" them.

The main objectives of this study are to make a preliminary determination of the maximum firm yield of the system; to examine the sensitivity of the firm yield to recharge rate, aquifer size, and pumping capacity; and to



(Source: DWR, California)

Figure 1 Area of Study

Figure 1. Area of Study.

demonstrate the utility of the combined models approach to complete the above determinations. Though not explicitly dealt with in this paper, the modeling effort also determined the optimal size of the conveyance system between the California Aqueduct and recharge points in the basins as well as the required capacities of the pumping plants that would be used in extracting the water from the basins. Although water quality was not a factor in this paper, it could be added as a constraint to the optimization model and may be included in future studies.

3. DESCRIPTION OF SIMULATION AND OPTIMIZATION MODELS

3.1. Simulation Model

The California Department of Water Resources, DWR, has constructed a simulation model, using HEC-3, developed at the Hydrologic Engineering Center, Corps of Engineers, U.S. Army, Davis, California [8, 9]. This program can be used to simulate the operation of reservoir systems for the following purposes:

(*a*) Water Supply
(*b*) Navigation
(*c*) Recreation
(*d*) Low flow augmentation, and
(*e*) Hydro-electric power.

There are six groups of input parameters that are required in the operation of HEC-3. These describe the system (*i*) hydrology, (*ii*) reservoirs, (*iii*) control points, (*iv*) power plants, (*v*) diversions, and (*vi*) economic benefits. A schematic diagram of input and output information for HEC-3 is given in Figure 2.

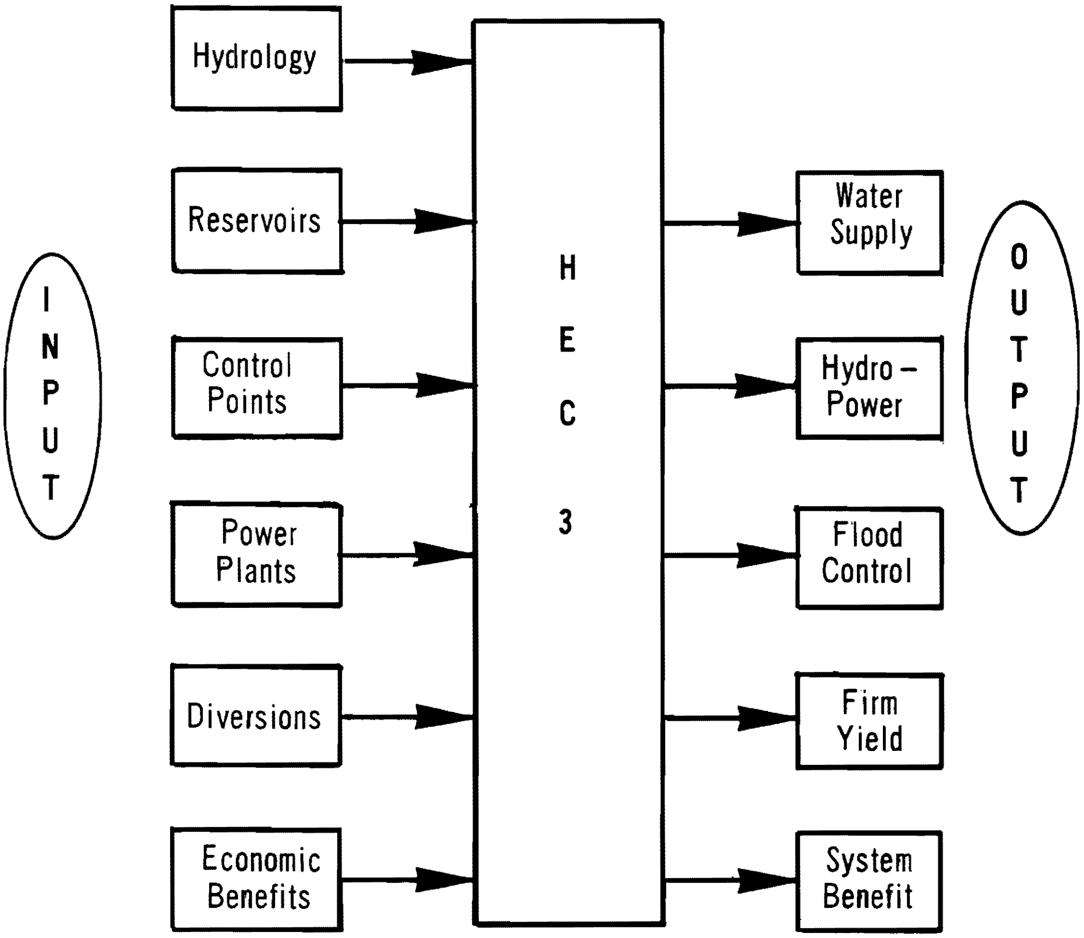


Figure 2. Schematic Diagram of Input an Output Information for HEC-3.

HEC-3 simulates a sequential operation of a system of reservoirs and connecting rivers or canals. Each reservoir must have a starting storage and storage values for each target level that are connected to each purpose, *i.e.*, hydropower, recreation, *etc.* Each reservoir operates for itself and designated downstream control points. The control points are usually channel capacities but may be minimum flow requirements that are constant or vary over time.

A number of stream routing methods may be selected for the reaches as well as different routing methods through the reservoirs. The whole simulation is broken up into time periods which may be days, weeks, or months, depending on the length of the simulation time. Diversions and other system parameters are also flexible in their form.

The simulation model starts with an initial condition and meets the upstream reservoir requirements. It then proceeds downstream, operating the reservoirs in accordance with the input rules until the whole system is operating feasibly, or optimally, as the case may be. The final flows, storage, and operation policies are outputted; and, in the case of this paper, the output data is then utilized as input data for the optimization model.

3.2. Optimization Model

Water resources systems are composed of a number of interconnected physical components, each of which usually serves a different purpose, such as irrigation, water supply, recreation, navigation, or hydropower. The objective of a system is normally to minimize overall costs given a demand or maximize overall net benefits. The structure of a water resources system with linearized costs or constraints suggests using network flow theory, which is a modified branch of linear algorithm which can be used for static as well as dynamic system operation studies [9, 10]. This is done by transforming the problem so that the node–link configuration for each time period is repeated; one then interconnects them to make a single system.

The reservoirs (represented by triangles) and non-storage junctions (represented by circles) in a flow network are graphically represented by nodes, and river reaches and canals are described by links. River reaches are represented by dashed lines and canal or closed conduits are represented by solid lines. For numbering purposes, the nodes representing the reservoirs are numbered first, followed by the nodes representing the non-storage junctions. Similarly, the links representing the canals and conduits are numbered after the links representing the river reaches are numbered.

In formulating the problem, it is assumed that the water can enter and leave the system only at the node points. The network representing a real water resource system includes demand nodes, spill nodes, a balance node, and consumptive loss links. Demand nodes are points in the system from which water is diverted to meet individual demands. Spill nodes are nodes in the system where any excess volume of water beyond the capacity of that node is transferred to any other node. The balance node is incorporated in the system to maintain the conservation of mass. This is the one common node to which all demands and supplies are routed.

The consumptive loss links represent the actual consumptive loss in the system. The consumptive losses are assumed to be proportional to water use and are usually assumed to be a certain percentage of the actual consumption. In this study, consumptive losses in the system are excluded in the formulation of the optimization model. These losses are incorporated in the simulation model and will be explained later. All links in the network have lower and upper bounds representing the actual minimum and maximum capacities respectively of the physical elements of the real system.

In the network each unit of flow is associated with some cost which is to be minimized. Description of the unit costs of flow in different types of links are given in Table 1. Unit costs of flow in each demand link and each storage link are considered as negative costs, *i.e.*, benefits, while the unit costs of flow in physical system components (river reach, pipeline, canal) and spill links are assumed to be positive costs.

The "out-of-kilter" algorithm is mainly based on duality theory and may be briefly described as follows. For a detailed treatment of this theory as well as an explanation of the terms, "primal," "dual," *etc.*, see references [11, 12]. Suppose in a network that X_{ij} is the flow in any link (i,j) from node i to node j and C_{ij} is the cost of a unit flow moving from node i to node j in the link (i,j). To minimize the total cost of flow, the objective function may be stated as

$$\text{Minimize} \sum_{(i,j)\varepsilon N} C_{ij} X_{ij} \tag{1}$$

where N is the set of all links in the network.

The objective function given by Equation (1) is subjected to the following conditions:

(*a*) each node should obey the rule of conservation of flow, *i.e.*, flow out of the node equals the flow into the node;

$$X_{i,j} = X_{i+1,j+1} \; \forall i, j \, . \tag{2a}$$

(*b*) the flow in each link must be within the range between the established lower and upper bounds for the link.

Now if the lower and upper limits on the flow in link (i,j) are L_{ij} and U_{ij} respectively, then the constraints may be written as

$$X_{ij} \geq L_{ij}, (i,j) \in N \tag{2b}$$

$$X_{ij} \leq U_{ij}, (i,j) \in N \, . \tag{2c}$$

If Y_i, Y'_{ij}, and Y''_{ij} are the dual variables associated with constraints Equation (2) of the above primal problem, then dual of this problem may be given by

$$\text{Maximize} \sum_{(i,j) \in N} [Y_{ij} L_{ij} - Y_{ij} U_{ij}] \, . \tag{3a}$$

Subject to

$$(Y_i - Y_j) + (Y_{ij} - Y_{ij}) \leq C_{ij}, \qquad (i,j) \in N \tag{3b}$$

$$Y_{ij} \geq 0, \qquad (i,j) \in N \tag{3c}$$

$$Y''_{ij} \geq 0, \qquad (i,j) \in N \tag{3d}$$

Table 1. Unit Cost of Flow in a Link.

Type of Link	Cost
Surface water reservoir inflow	None
Surface water reservoir outflow	Transportation and treatment costs
Ground water reservoir inflow	
1. Natural recharge	None
2. Artificial recharge	Transportation and operation costs
Ground water outflow (pumping)	Pumping and capital costs
Initial storage	
1. Surface water reservoir	None
2. Ground water reservoir	None
Carryover from previous period	
1. Surface water reservoir	None
2. Ground water reservoir	None
Final storage	
1. Surface water reservoir	None
2. Ground water reservoir	None

Y_i is unrestricted for $i = 1, 2, \ldots n$, and represents the price of unit flow at node i, similarly Y_j is the node price at node j.

The sum of unit cost of flow from node i to node j and the difference of unit flow price at node i and node j is called the relative cost. It is also known as "marginal cost" or "net cost." Mathematically it can be stated as

$$\overline{C_{ij}} \equiv C_{ij} + Y_i - Y_j \tag{4}$$

where C_{ij} is the marginal cost and represents the total cost to the system of transporting one unit of flow from node i to node j. If C_{ij} is negative, meaning negative cost, then there would be a profit to the system. Hence flow in link (k,j) may be increased up to its maximum capacity U_{kj}. Conversely, if C_{ij} is positive, then there will be a positive cost to the system for each additional unit of flow in the link (i,j). In this case, it would be beneficial to keep the flow as low as possible. But the flow cannot be decreased below the lower bound of the link. Hence the flow should be equated to the lower bound of the link, L_{ij}. If C_{ij} is equal to zero, then flow may take on any value between the lower and upper bounds for the link (i,j).

4. METHOD OF SOLUTION

The two-part solution procedure consists of simulation followed by optimization. The simulation model generates input data for the optimization model, and then the optimization model is run several times to conduct a sensitivity analysis. The output obtained from the simulation model is scaled to an integer to fulfill the requirements of the "out-of-kilter" algorithm (optimization model).

In order to simulate the operation of the State Water Project (SWP) and the Central Valley Project in the State of California, the SWP–CVP system is represented by 85 control points, as shown in Figures 3*a* to 3*c* [8, 14, 15]. All surface and groundwater reservoirs are represented by triangles, and other control points are denoted by circles. Note that the export from node 39 in Figure 3*a* is the input to node 39 in Figure 3*b* and node 85, the surplus delta outflow, links Figures 3*b* and 3*c*.

The input data, *i.e.*, local flow, unregulated flow, total inflow, initial storage, storage capacity, required diversions, minimum desired flow and minimum required flow for each control point of the system for the critical period 1928–34, were obtained from the Department of Water Resources, State of California. When running the simulation model HEC-3, it is assumed that there are no groundwater reservoirs in the system. This assumption is made only to determine the net quantity of surplus Delta outflow (control point 85, Figure 3*b*) after meeting all the demands and commitments of both the SWP and the CVP.

The surplus Delta outflow would be the only water available during seven consecutive years of a dry period such as 1928 to 1934. The water available from rainfall is assumed to be negligible because the precipitation during the critical seven-year period did not produce significant runoff. This surplus Delta water can be used for recharging the Kern River Fan Area, the San Fernando, and/or the Chino groundwater basins.

The seven-year period from 1983 to 1989 was selected for the optimization modeling period with the demand and other estimates corresponding to this same period. However, the hydrologic inputs to the optimization model were produced by the simulation model, HEC-3, and the hydrology from the seven-year period, 1928-34 which, as mentioned, is a design critical period.

4.1. Formation of Network

The State Water Project System from Delta Pumping Plant to the end of the East and West branches of the California Aqueduct can be represented by a node–link configuration, as shown in Figure 4.

Nodes 1, 2, and 3 represent the Kern River Area Groundwater Basin, the San Fernando Groundwater Basin and the Chino Groundwater Basin respectively. Node 4 represents the Buena Vista Pumping Plant and Node 5 represents the junction point of the East and West branches of the California Aqueduct and Devil Canyon Power Plant along the East branch of the California Aqueduct, respectively. Node 8 represents the common demand point of the three groundwater basins under study.

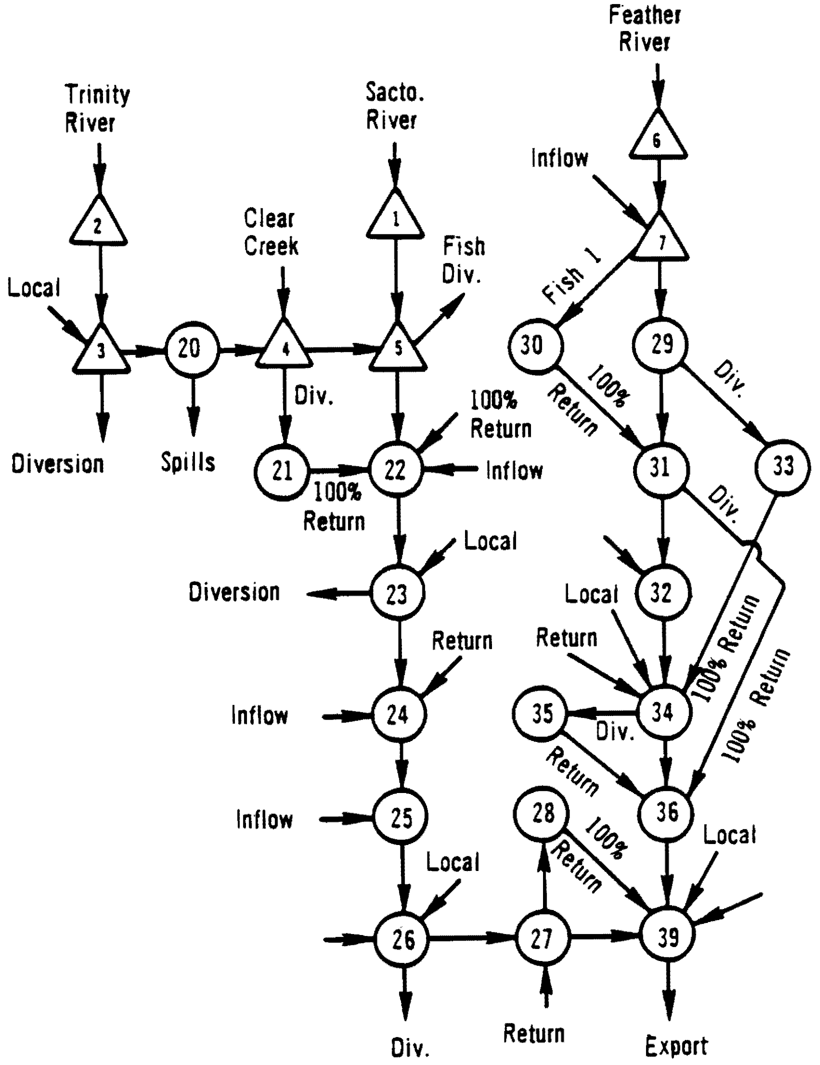


Figure 3a. CVP–SWP Water Resources System.

In practice, there will be a number of delivery points along the California Aqueduct for sending the water to recharge the groundwater basins. If all these delivery points are represented by different nodes, then the node–link configuration will be quite large, but not conceptually different. To keep the configuration simple, it is assumed that only one point represents the water delivery points for recharging each groundwater basin. In this network Buena Vista Pumping Plant, Castaic Reservoir, and Devil Canyon Power Plant are considered as turnout points for recharge water to the Kern River Fan Area, San Fernando, and Chino respectively. Similarly, with no loss of generality, it is also assumed that all pumped water from each basin enters the Aqueduct at a single point as shown in Figure 4. The total yield from the system including the three groundwater reservoirs is measured at Node 8.

The nodes are connected by different links as shown in Figure 5 (see Period 1). Links 1 and 2 represent the California Aqueduct from SWP Delta Pumping Plant to the Buena Vista Pumping Plant and from Buena Vista Pumping Plant to the junction of the East and West branches of the California Aqueduct respectively. Link 3 represents the West branch of the California Aqueduct from the junction point to Castaic Reservoir, and Link 4 represents the East branch of the California Aqueduct from the junction point to Devil Canyon Power Plant. The initial storages of Kern River Fan Area, San Fernando, and Chino are represented by Links 14, 15, and 16 respectively. The pumping from the Kern River Fan Area is represented by Link 6. Similarly the pumping from San Fernando and Chino basins are shown by Links 8 and 10 respectively. Links 5, 7, and 9 represent the recharge to the Kern River Fan Area, San Fernando, and Chino Groundwater Basins respectively. Link 13 represents the total annual yield from the system.

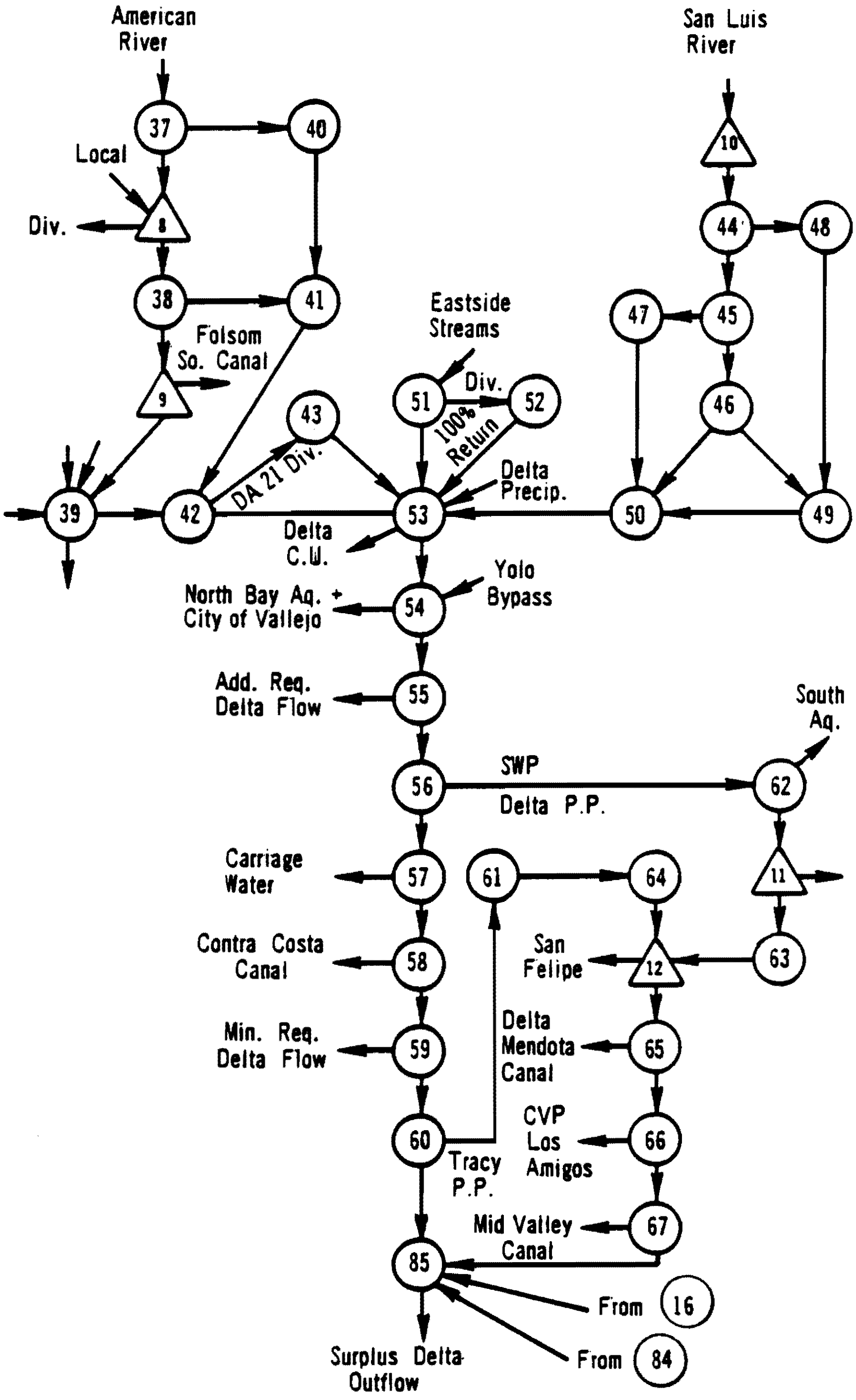


Figure 3b. CVP–SWP Water Resources System (cont.).

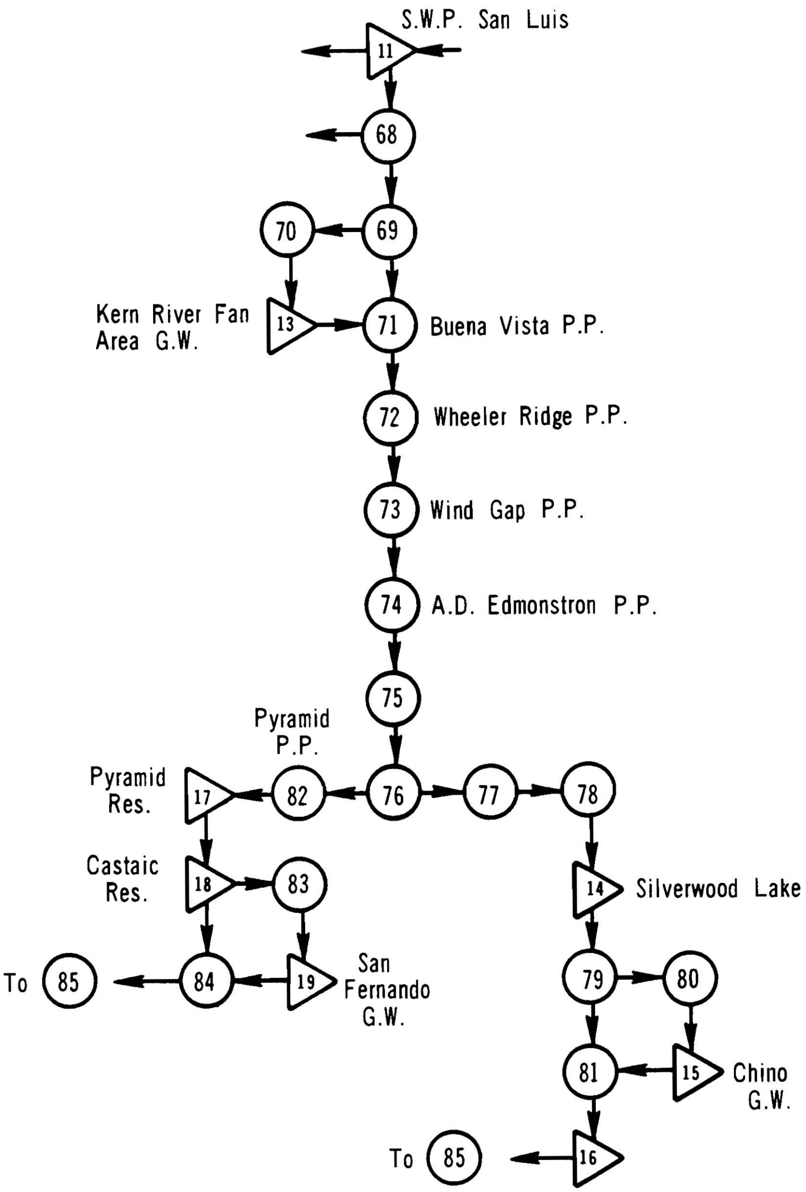


Figure 3c. CVP–SWP Water Resources System (cont.).

The Node–Link configuration described in Figure 4 only represents one single year of the study period. To make it suitable for the seven-year study period (1983–1989), this configuration must be extended to represent a seven-year system, the first four years of which are shown in Figure 5. For each year the configuration is the same, but the numbering of nodes and links is done in ascending order starting from 1 in the first year (1983). Each year's configuration is connected with links representing carryover storage in the groundwater basins from the previous period. The links representing carry over storage of the last year are connected to Node 57. The configuration, when completed for the seven year period, consists of 57 nodes and 115 arcs.

An artificial Node 57 is also introduced in the network, but this is not shown in Figure 5. This node represents the network source and sink, as explained further now. It is assumed that all inflows start from and all outflows return to the same source–sink node. This assumption is made to make the configuration a circulation network to fit the requirements of the out-of-kilter algorithm, which minimizes the total cost of flow only in a circulating network.

4.2. Constraints

Flow in each link in the network has lower and upper bounds. The lower bound is the minimum required flow in that link of the physical system and the upper bound describes the maximum capacity or maximum demand of the physical system. In most cases the lower bound is zero except in cases where a minimum flow is required in the link for low-flow augmentation to meet water quality criteria or carryover storage.

In this network model, the simulation model results are used to calculate inflow which is the minimum of (*i*) the remaining capacity of SWP Delta Pumping Plant, (*ii*) the remaining capacity of the aqueduct, and (*iii*) the surplus Delta outflow. The simulation was conducted using a monthly time step, but the optimization used an annual time step, in order to limit the size of the problem. The annual inflow constraint is fixed in the optimization model by setting the lower bound equal to the upper bound.

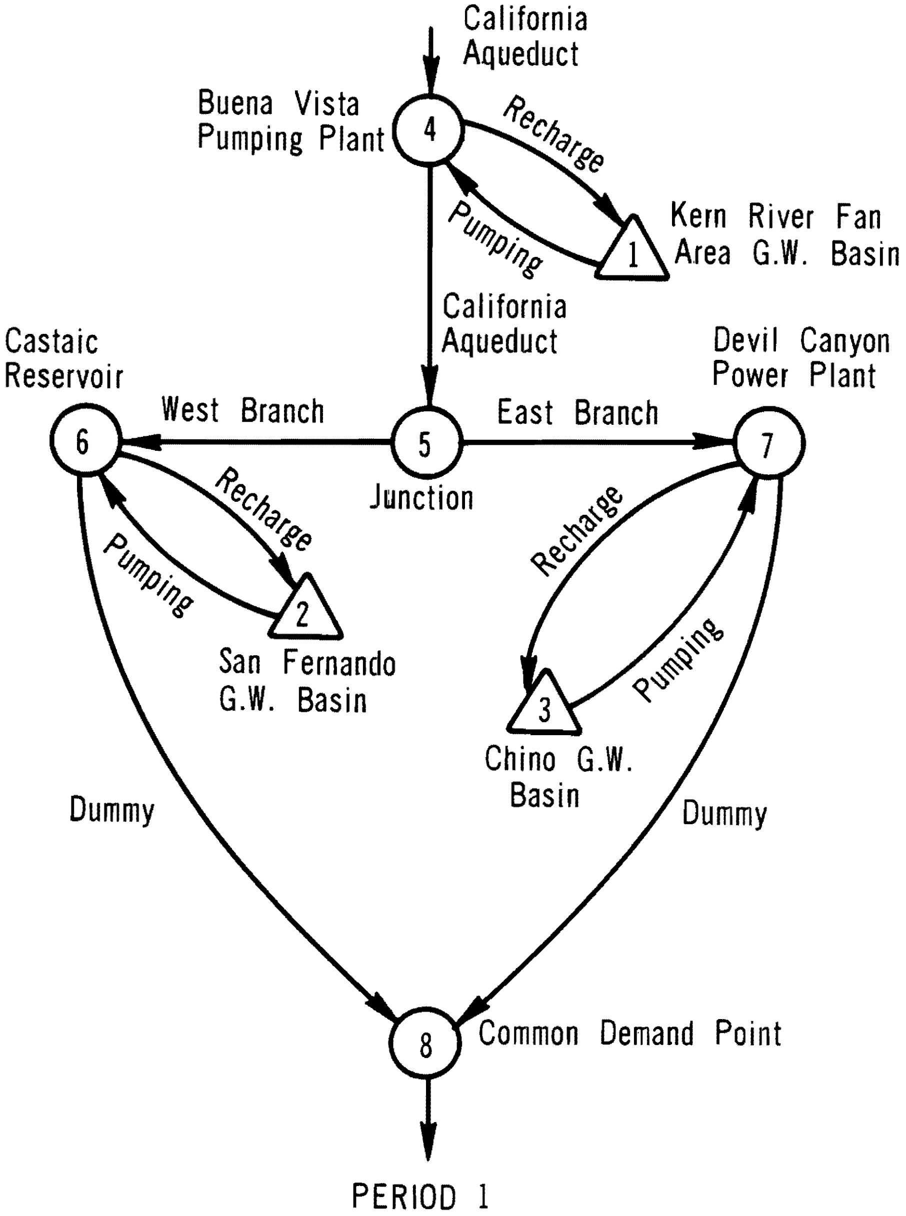


Figure 4. Node-Link Configuration for Single Period.

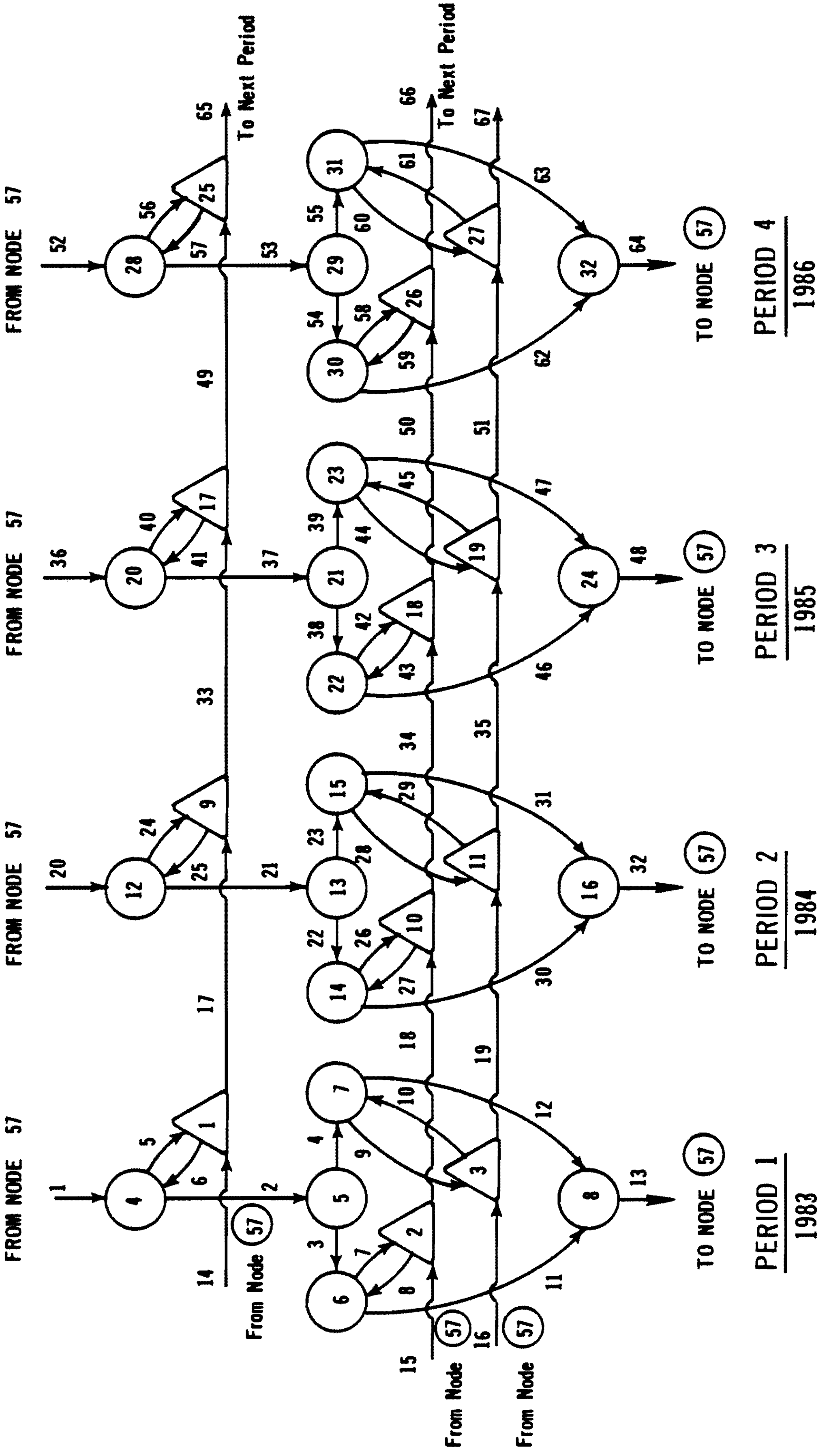


Figure 5. Node-Link Configuration for Several Periods.

In the California Aqueduct from Buena Vista Pumping Plant to the junction of the East and West branches of the Aqueduct, the lower bound is taken as zero and the upper bound as the remaining capacity (unused capacity) of the Aqueduct. The lower bound and upper bound for the East and West branches of the Aqueduct were computed in the same manner. The lower and upper bounds of the arcs representing the initial storages in the ground water basins were equally set to the initial storage values to fulfill the requirement of the model.

The carryover storage from one period to another period and the final storages in the basins at the end of the study period have upper bounds equal to the estimated capacity of the basins. The lower bounds at the end of each year were taken as half of the initial storages. In accordance with DWR policy, this prevented the operation of the system from pumping more than half of the initial storages within a year.

The recharge to the basins has lower bounds of zero and upper bounds equal to the maximum recharge rate of the potential recharge facilities. Similarly, for pumping the lower bounds are zero and upper bounds are chosen to be the capacities of the pumping facilities.

The dummy links have lower bounds equal to zero and the upper bounds equal to a very large arbitrary number so that there is no practical upper bound on the flow in these links.

The upper bounds on the system's yield links have been taken to be the maximum flow which can be achieved uniformly for the seven continuous years of the study period. The lower bounds are zero for these links. This forces the model to meet these demands if possible.

4.3. Calculation of Unit Cost of Flow

The information for calculating the unit cost of flow is taken from DWR, California. The unit costs of flow in the links representing initial storage in the basin, carryover storage from one period to another, final storage in the basin and in the dummy links have been taken to be zero since there is no expenditure for the flows in these links. The unit cost of flows in the other links is calculated as follows:

(*a*) *Inflow Links.* The costs of these links are transportation cost of water from the Delta Pumping Plant to Buena Vista Pumping Plant and cost of Delta water. In transporting water through the California Aqueduct only the cost of pumping the water is considered. Construction costs and the operation and maintenance cost of the Aqueduct are not considered because the flow is using only the unused space of the Aqueduct.

(*b*) *Recharge Links.* The costs for recharge have two parts: one is the construction cost of the recharge facilities including the transportation of water from the California Aqueduct to different spreading grounds, the development of existing spreading grounds, and/or construction of new spreading grounds; the other is the operation and maintenance of the recharge facilities.

(*c*) *Pumping Links.* The unit cost of flow in these links is the sum of the unit cost of the construction of pumping facilities including construction of new wells, installation of pumps, and the unit cost of the annual operation and maintenance of the pumping facilities.

(*d*) *Yield Links.* In these links, an arbitrary negative cost is assumed. These negative costs force the model to meet the maximum flows in these links (demands), if possible.

5. RESULTS AND ANALYSIS

Table 2 gives the optimal annual yield corresponding to various sets of annual demands. The annual recharge and pumping for each groundwater basin to achieve a firm annual yield of 1406 MCM are given in Table 3.

The maximum yield from the conjunctive operation of surplus Delta water and three groundwater basins (Kern River Fan Area, San Fernando, and Chino) is 11 008 MCM over the seven-year period. But the annual distribution of yield during the seven-year period is irregular and varies from 2176 MCM to 963 MCM (see col. 2, Table 2). The maximum uniform annual (firm) yield is 1406 MCM, as is evident from Table 2. The trade-off between operating for an annual demand of 2466 MCM and an annual demand of 1406 MCM is that the total amount of water delivered over the seven-year period decreases from 11 009 MCM to 9842 MCM; however, operating for the lower demands assures a higher minimum annual delivery (*i.e.*, 1406 MCM instead of 963 MCM).

Table 2. Optimal Yield at Various Demands (MCM/Year).

Year	Demand = 2466	Demand = 1541	Demand = 1418	Demand = 1406	Demand = 1393
1983	2176	1541	1418	1406	1393
1984	1543	1541	1418	1406	1393
1985	1936	1541	1418	1406	1393
1986	1406	1406	1406	1406	1393
1987	1979	1541	1418	1406	1393
1988	1006	1406	1406	1406	1393
1989	963	1541	1418	1406	1393
Total	11 009	10 517	9902	9842	9751

Table 3. Pumping in MCM at Uniform Optimal Yield of 1406 MCM/Year.

	1983	1984	1985	1986	1987	1988	1989
Kern River Fan	0	479	86	616	210	616	616
San Fernando	173	173	173	173	173	173	173
Chino	292	616	616	617	280	617	443
Total	465	1268	875	1406	663	1406	1232
Surplus Delta Outflow	941	138	531	0	743	0	174
Total Yield	1406	1406	1406	1406	1406	1406	1406

The modeling results showed that any excess delta water during the critical seven-year dry period should be used directly instead of being recharged into the ground water basins. During wet years, the surplus delta water exceeds the demand of the system, this excess delta outflow should be used to recharge the ground water basins. One aspect that should be included in a more detailed study is in-stream use and the need for some occasional flushing of the delta with fresh water to maintain the ecological balance of the delta.

A detailed sensitivity analysis was conducted to see what effect varying the pumping capacities of the ground water basins would have on the net benefits of the project. These showed that as the maximum pumping capacity of these basins were approached, the net benefits became less sensitive to which basin was pumped. The actual economic values from the analysis are available in the full report [7].

6. SUMMARY AND CONCLUSIONS

It appears that the methodology presented can be a useful tool in managing stream–aquifer systems. Correspondingly, it appears that utilizing aquifers as dynamic storage reservoirs can produce significant increases in firm yields and total available water during critical dry periods. The major constraint to invoking such a management is, as usual, political. To implement the suggested strategy, the agency (in this case, the California Department of Water Resources) would have to have considerable control over the aquifers, which may be politically infeasible. This disadvantage would be minimized in, for example, Saudi Arabia, where the central government is able to control ground water withdrawal and aquifer management.

The following conclusions were drawn from the analysis of recharge and pumping in conjunctive operation of surface and groundwater. Most of these have not been established in this paper, but were demonstrated in the full report of the study [7].

(*i*) In the dry period, when the surplus Delta water is less than the demands of the system, the excess Delta outflow should directly be utilized to meet demands instead of used to recharge the groundwater basins.

(*ii*) In a flood flow year, when the surplus Delta water exceeds the demands of the system, the excess Delta outflow should be used for recharging the groundwater basins.

(*iii*) With the existing capacity of State Water Project delivery system and existing Delta pumping plant, the maximum annual uniform (firm) yield in a dry period, such as 1928 to 1934, that could be achieved from optimal system operation is 1406 MCM above what is presently realized. This rather dramatic increase may prove to be optimistic if the monthly and annual time steps mask system capacity limitations. More detailed studies are required to verify these conclusions.

(*iv*) The capacities of the East and West branches of the California Aqueduct also create important constraints in this model. They limit the rates of recharge to Chino basin and San Fernando basin in wet months and delivery from the Kern River Fan Area in dry months.

(*v*) From this example, areas in Western Saudi Arabia and parts of the Middle East may have similar opportunities for conjunctive use and thereby increasing water use efficiency even though surface water resources are severely limited. Water quality constraints were not a part of this study, but could be easily added to the optimization model in terms of augmenting the low-flows of rivers during drought conditions, *etc.*

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