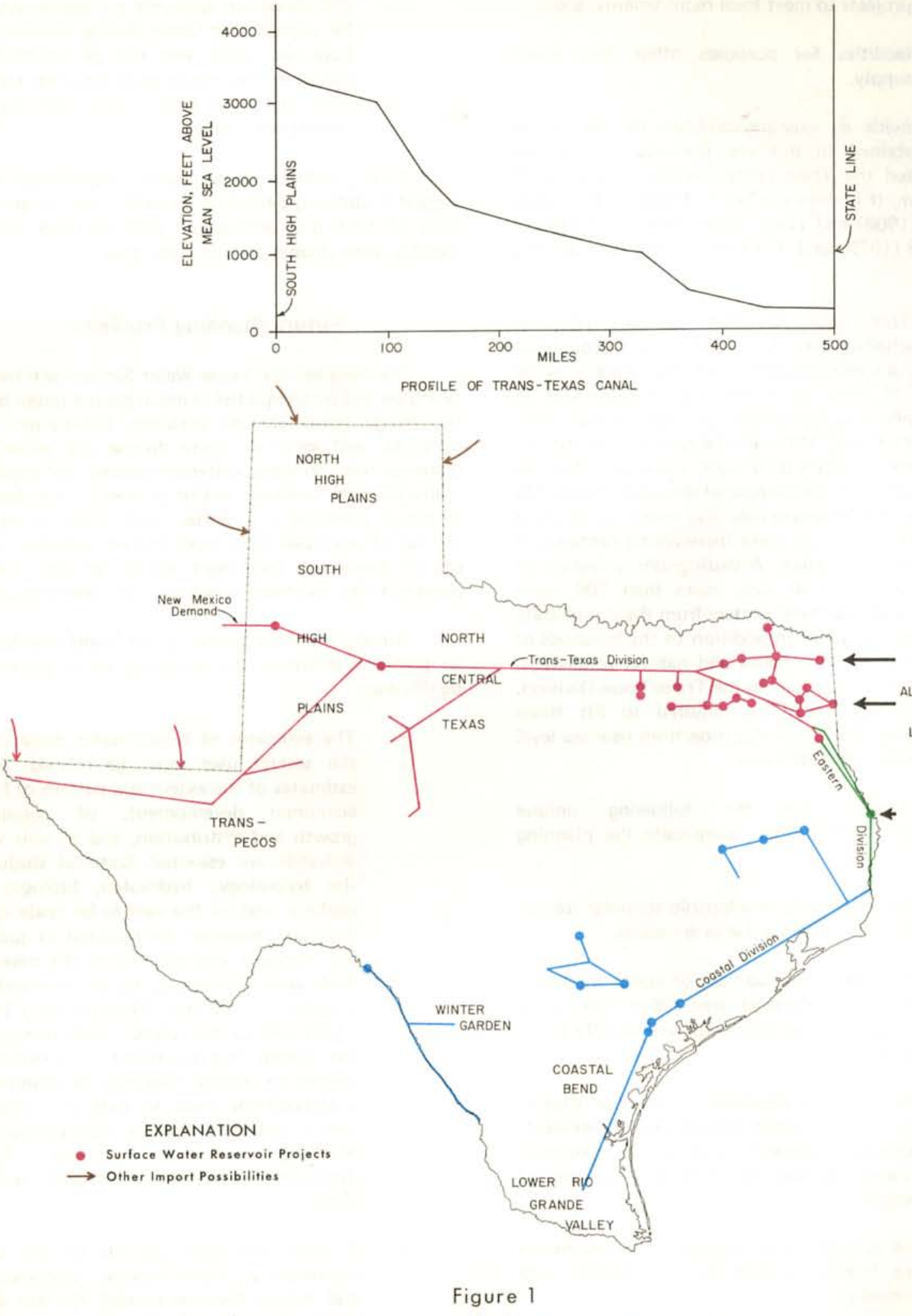


Figure 1

Schematic Diagram of the Texas Water System

(Includes major conveyance facilities and related reservoirs)

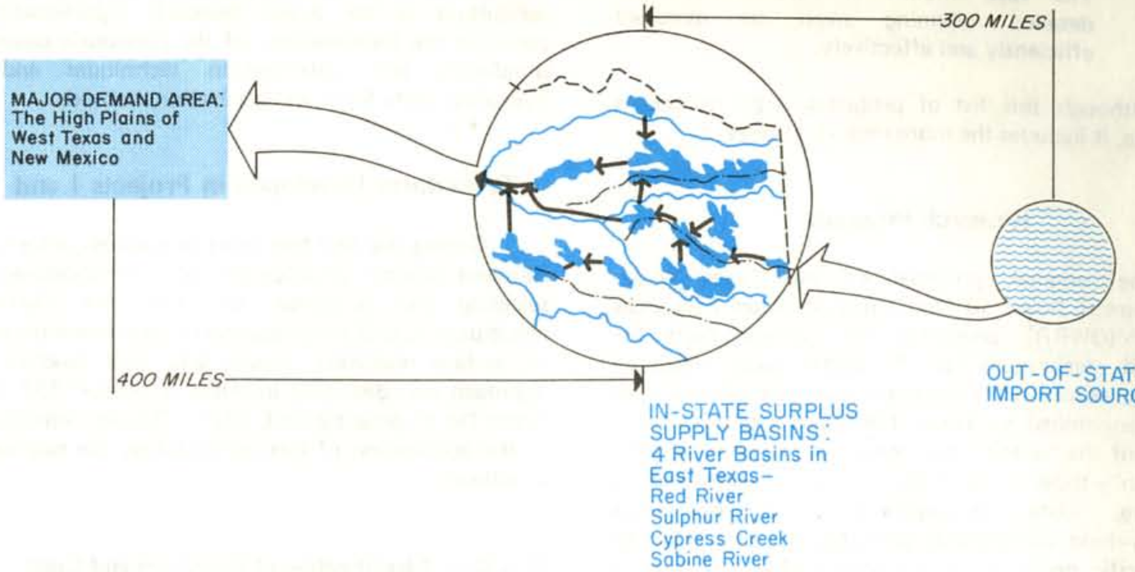


Figure 2. Major Supply and Demand Areas for the Trans-Texas Division of the Texas Water System

basin basis, but also on combinations of river basins with different hydrologic characteristics.

- The impact of recent developments in wastewater treatment technology and discharge water quality criteria on water availability must be analyzed. Increased waste treatment requirements and costs will likely have a considerable effect on wastewater reuse and thus on return flow availability. Wastewater reuse must also be considered as an alternative to transfers of surface and ground waters.

- Desalting of saline and/or brackish waters, both surface and ground, must also be considered as alternative water supplies where such saline water supplies are available. Technological advances may make desalting and wastewater reuse competitive with interbasin transfers of water in some areas.

- The quality of the water delivered by any water resource system must be suitable for each intended use. The quality of water required for domestic uses is not necessarily suitable for the organisms in an aquatic ecosystem. For example, salt content has a direct effect on the suitability of water for irrigation of certain crops. It is important for the planner to consider the economic impact of precluding certain crops from an irrigated area because of water quality considerations. Similarly, the hardness of water supplied for municipal and industrial uses has a bearing on treatment and consumer costs. The list of water quality considerations is long, and the planner must, if possible and if the information is available, evaluate all potential impacts.

- The environmental effects of any water resources plan and each of its elements must be carefully analyzed. Both beneficial and detrimental effects on ecosystems must be identified, and, if possible, quantified.

- The market and non-market benefits and costs of water resources projects must be evaluated. In particular, the secondary and tertiary effects of water supply projects on regional and national economies should be considered.

- Conjunctive use of underground water resources, particularly the Ogallala Formation underlying the High Plains of West Texas, with the surface water to be supplied must be investigated.

- The configuration, sizing, sequencing, and staging of the physical facilities required to supply water from the resources available must take into account the probabilities of occurrence of both resources and demands.

- Operational criteria for water resources projects must be developed on a systematic basis to maximize yield and minimize costs.

- Institutional arrangements for the operation of completed water resource systems must also be made.

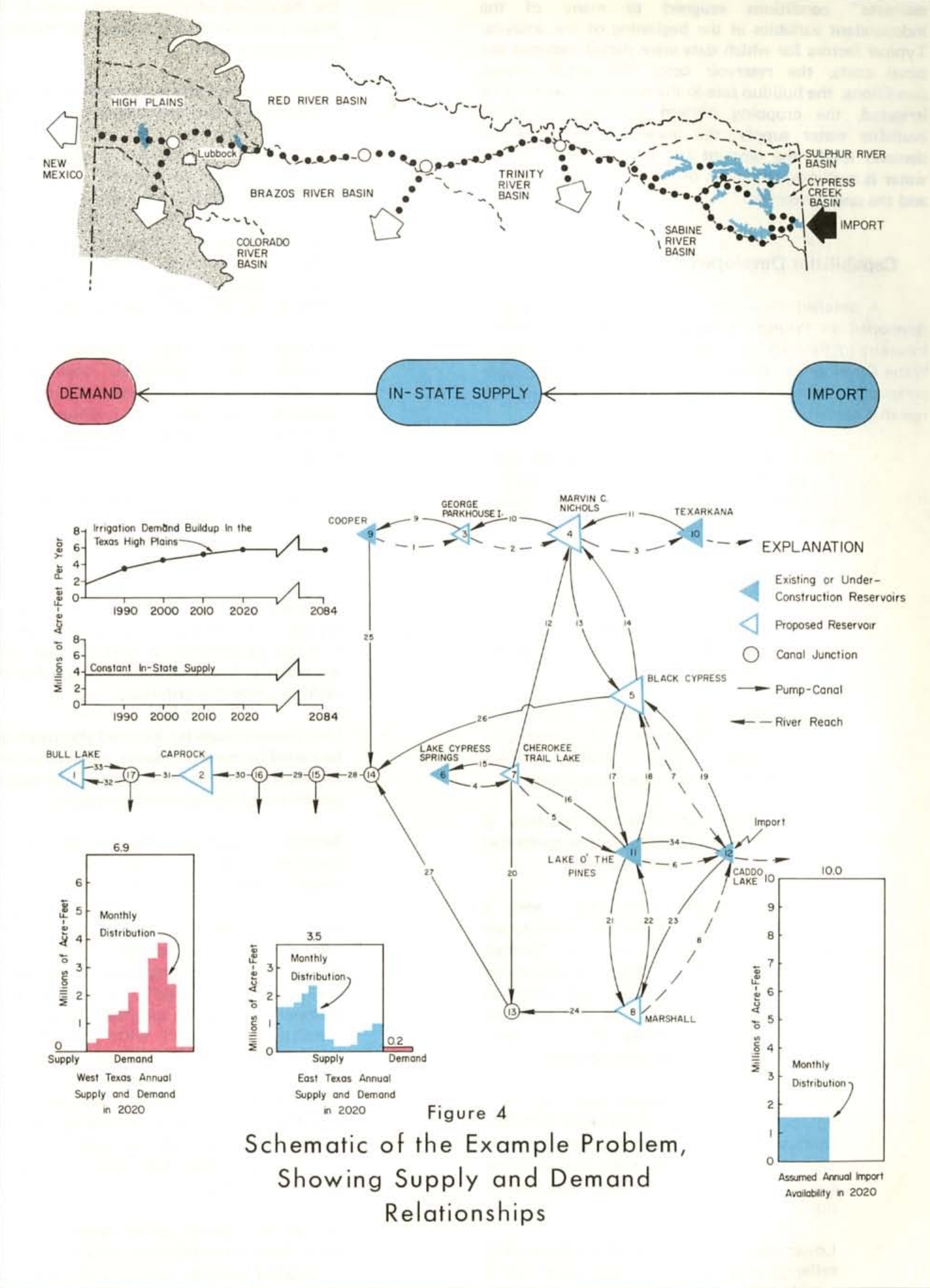


Figure 4
Schematic of the Example Problem, Showing Supply and Demand Relationships

Step Two - Develop Storage Plots

Step Two involves the use of the results from the first step to develop envelopes of storage plots for years in which surplus waters were spilled from the system and for years in which shortages were incurred. Figure 7 illustrates example envelopes of this type of reservoir storage plot. If the reservoir storage could be maintained along the envelope of *maximum* storage levels that occurred during years of shortages, demands would have a high probability of being satisfied. In other words, this envelope describes a reservoir operational pattern that would minimize water shortages. The envelope of *minimum* storage levels that occurred during years of system spillage describes the highest levels at which a reservoir can be maintained without risking the chance of spilling surplus inflows. This envelope represents an operational pattern that would minimize system water spillage.

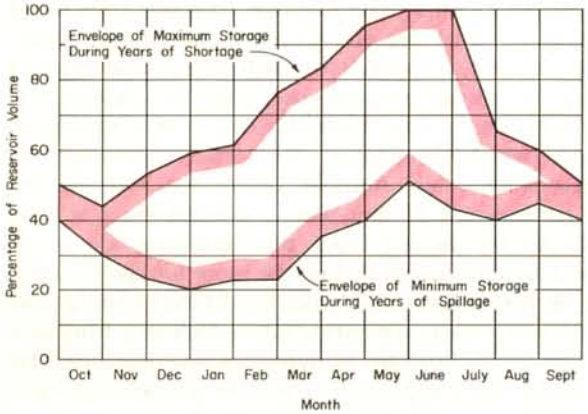


Figure 7. Typical Storage Plots

Where the storage targets are set between these two envelopes depends upon the inflows to and the demands from the reservoir since (1) the closer the targets are to the upper envelope the greater the risk of spillage, and (2) the closer they are to the lower envelope the greater the probability of shortages being incurred. It must be reiterated at this point that the technique being described is designed to provide operating rules which minimize system cost while minimizing water shortages. The benefits accruing to various storage levels are derived from the capability of the system to meet demands and not from any other criteria. The goal, of course, is to find storage targets that, when used in SIM-IV, will predict the same shortages and spills that were predicted by the allocation model. (It is possible that shortages would be reduced because SIM-IV predicts evaporation losses more accurately than AL-III.)

In addition to providing information for setting storage targets, these plots indicate some general operational characteristics of the reservoirs. If the two envelopes are very far apart, this indicates the reservoir is probably not too important in reducing either spills or deficits and the targets should be set primarily to minimize storage fluctuations. A careful analysis may in fact indicate that the reservoir is not necessary for proper functioning of the system. On the other hand, when the two envelopes are close to one another the reservoir is probably critical to the performance of the system and the storage targets should be set very carefully. If the condition occurs where the minimum storage envelope for spillage exceeds the maximum storage envelope for shortages, this means the reservoir is critical but that targets can be set anywhere within the range. The logic behind this analysis is as follows: if the system is experiencing a year in which some demands for water cannot be met (shortages), it follows that to minimize the shortages the reservoir storages throughout the year should be maximized, implying a maximum availability of water to meet demands. Conversely, in wet periods in which water must be spilled from the system it is desirable to maintain the reservoirs at the lowest possible levels to maximize the quantity of water captured. A wide gap between the two envelopes simply indicates an insensitivity of system demands and system spills to the storage in the particular reservoir. A narrow gap or reversal of position of the two curves indicates a progressively more sensitive relationship.

At the conclusion of this step the reservoirs should be characterized by their envelopes of minimum and maximum storage, their local demand-inflow ratio, and their relative importance to the system operation. This analysis provides the basis for setting "benefits" for maintaining storage in selected reservoirs based on a system minimum-cost criterion considering meeting system demands as the most beneficial use of water.

Step Three - Establish Initial Rules

From the two envelopes shown on the storage plots, initial storage target levels are determined using the reservoir's demand-inflow ratio as a guide. If this ratio is high, targets are set initially along the envelope of maximum storage to minimize shortages. For reservoirs with a low ratio of demands to inflows, the initial targets are set along the minimum storage envelope to minimize spills. In the case of reservoirs whose inflows are about the same as their demands, initial targets are set midway between the two envelopes with a smooth seasonal pattern.

Next, benefit values for storage in each reservoir must be set to complete the data requirements of the rules. The two possible bases for such costs are (1) evaluate the economic value of water in the reservoir for future uses, and (2) set the values based upon the priorities of reservoirs to meet the demands in the system. The first alternative requires a detailed economic procedure is complete and the reservoir operating rules are established.

An Example Problem

The Trans-Texas Division of the Texas Water System as illustrated in Figure 8 was used as an example problem to test the procedure. The reservoir and canal capabilities were designed to meet the expected 1990 levels of demand. The historical hydrologic sequence described in Report 131 (Texas Water Development Board, 1971) was also used in this example.

Step One - Simulate System With Allocation Model

Table 1 summarizes the cost results at five-year intervals for a 35-year simulation using the allocation model with three-year forecasting capability. Three-year forecasts were used to reduce analysis costs and, since the length of the most critical droughts in the historical sequence was three years, no additional advantage could be obtained by use of four-year forecasting.

These results represent the costs derived from operating the system with essentially perfect foresight of water supplies and demands. For the purposes of this example only reservoirs 1, 2, and 4 were analyzed although all 12 reservoirs should be similarly treated in an actual planning analysis.

Step Two - Develop Storage Plots

Figure 9 shows the storage plots derived by plotting the envelopes of storage levels in years of shortage and years of spillage for reservoirs 1, 2, and 4.

Step Three - Establish Initial Rules

Reservoirs 1 and 2 have very high demands with virtually no local inflow and therefore the maximum storage envelopes based upon years of shortage were used to set inital targets. Reservoir 4 is in an area where most of the system inflow occurs with very small demands and thus the minimum storage envelope in years of system spilling was used to set initial target storage levels. Table 2 shows the reservoir target storage levels and fraction-full for each month as derived from the storage plots.

A cursory analysis of the initial target storage values indicates that it may, after further analysis, be possible to reduce the sizes of reservoirs 1 and 4 by 31 percent and 10 percent, respectively.

Based upon their location in the system the reservoirs were assigned benefit values for storage. Reservoirs 1 and 2 are the prime supply locations, and consequently were assigned the highest storage benefit values. No benefits were assigned to storage for meeting any uses other than system demands. For the three

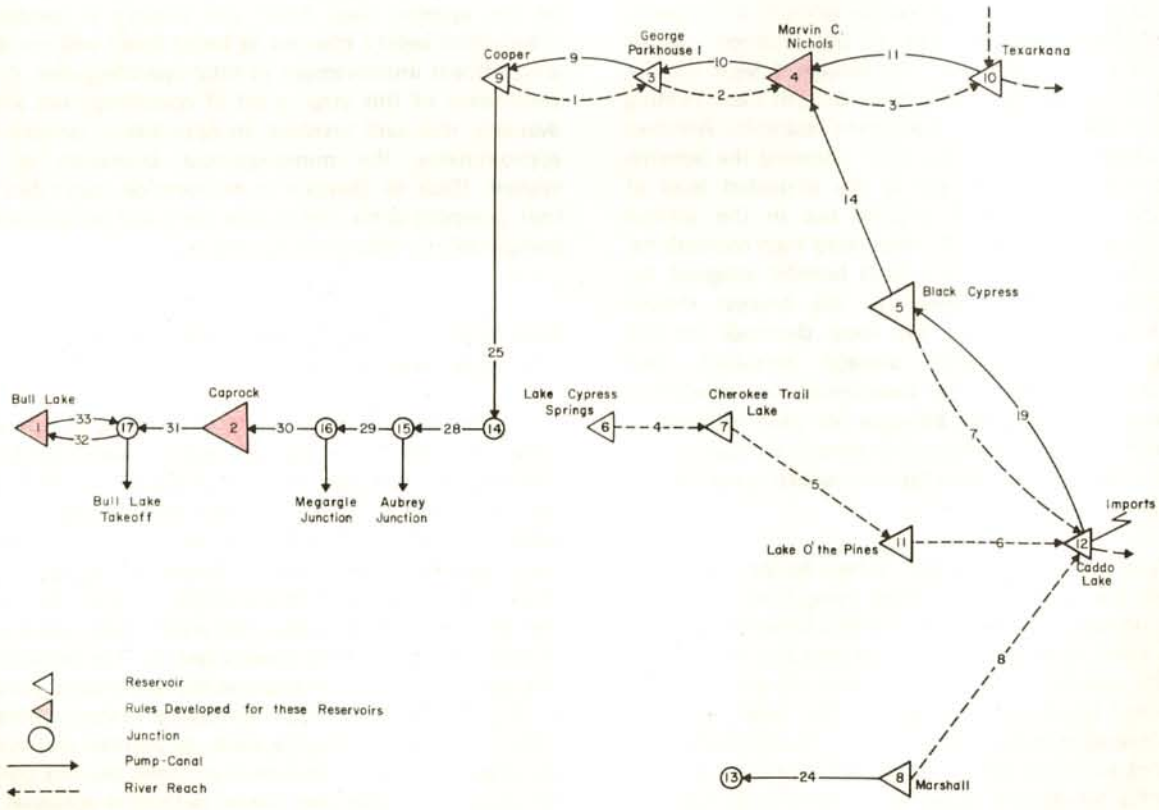
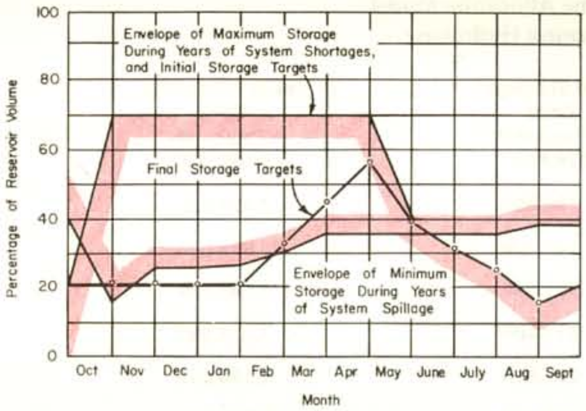
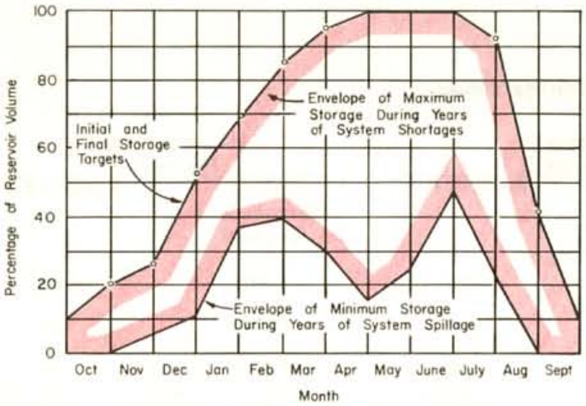


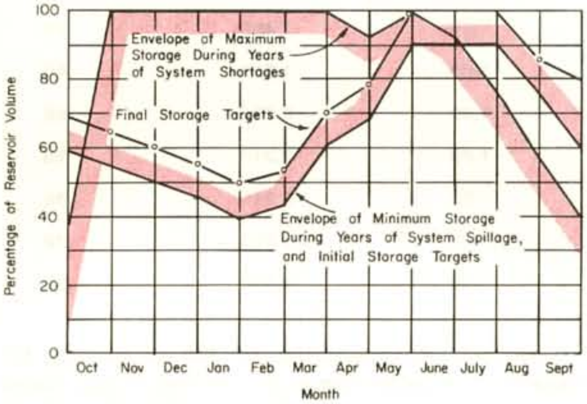
Figure 8. Configuration of the Example System Used in Formulating Reservoir Operating Rules



a. Bull Lake (Reservoir 1)



b. Caprock (Reservoir 2)



c. Marvin C. Nichols (Reservoir 4)

Figure 9. Storage Plots

procedure and SIM-IV. As such, it provides a basis upon which this procedure can be evaluated. Run 1 used the target storage levels derived directly from AL-III for reservoirs 1, 2, and 4. The improvement in system operation is noticeable in the reduced shortage penalty costs and evaporation losses. There was, however, an increase in spills from the system.

Table 3.—Summary of Cases Studied

Run	0	Base case using rules of Report 131
Run	1	Target storages from AL-III
Run	2	Adjusted target storages to reduce filling rate in reservoir 1
Run	3	Modified target storages to reduce evaporation in reservoir 1
Run	4	Increased target storages in reservoir 1
Run	5	First decrease of target storages in reservoir 1
Run	6	Second decrease of target storages in reservoir 1
Run	7	Decreased target storages in reservoir 2
Run	8	Increased target storages in reservoir 2
Run	9	Increased target storages in reservoir 4
Run	10	Decreased target storages in reservoir 4
Run	11	Second increase of target storages in reservoir 4

In Run 2 the target storages were adjusted for reservoir 1 to slow its filling rate; these targets were further adjusted in Run 3 to delay the start of filling but to allow the peak to be reached at the same time. Runs 4, 5, and 6 were made to test the cost sensitivity to changes of time of filling and adjustments to peak target storage in reservoir 1. Run 4, which had increased target storages in reservoir 1, showed no improvement in cost, while Run 5, which had decreased target storages, indicated a reduction in cost. However, with target storages further decreased in Run 6, cost again rose. As a result the target storage levels from Run 5 were selected for reservoir 1. Runs 7 and 8 involved a similar test for reservoir 2. In both cases costs rose which indicates the initial storage targets were best.

Finally, Runs 9, 10, and 11 tested variations in the target storages for reservoir 4. From this series of simulations Run 9, which had slightly increased storages, provided the lowest cost. Table 5 lists the final storage targets that resulted from this series of runs. It is significant to note that the major change in target storages from those derived from AL-III is in reservoir 1. Poor estimation of evaporation losses in AL-III is the primary cause of poor initial storage targets. If the allocation model had a better procedure for estimating evaporation losses, better initial storage targets would have resulted from Step Three.

As presently constituted the allocation model does not take reservoir storage levels into account in its estimate of evaporation losses in the optimization process and, as such, allows early filling of reservoirs even though they may have high evaporation rates and corresponding high losses of water. For the particular example investigated, evaporation was extremely important and dominated the selection of operating rules for reservoir 1.

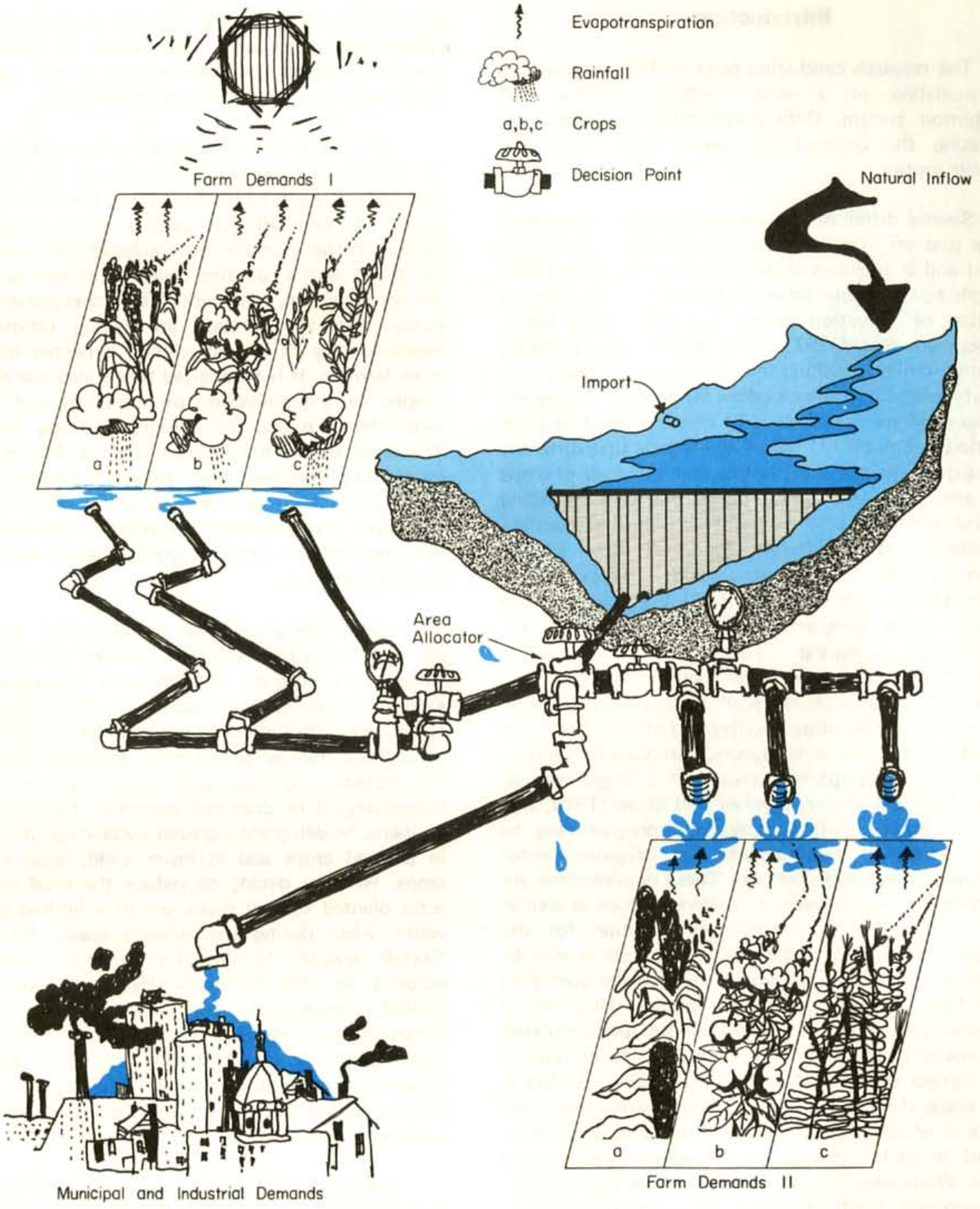


Figure 10
Competing Uses for Available Water From a Typical Surface Water Resource System

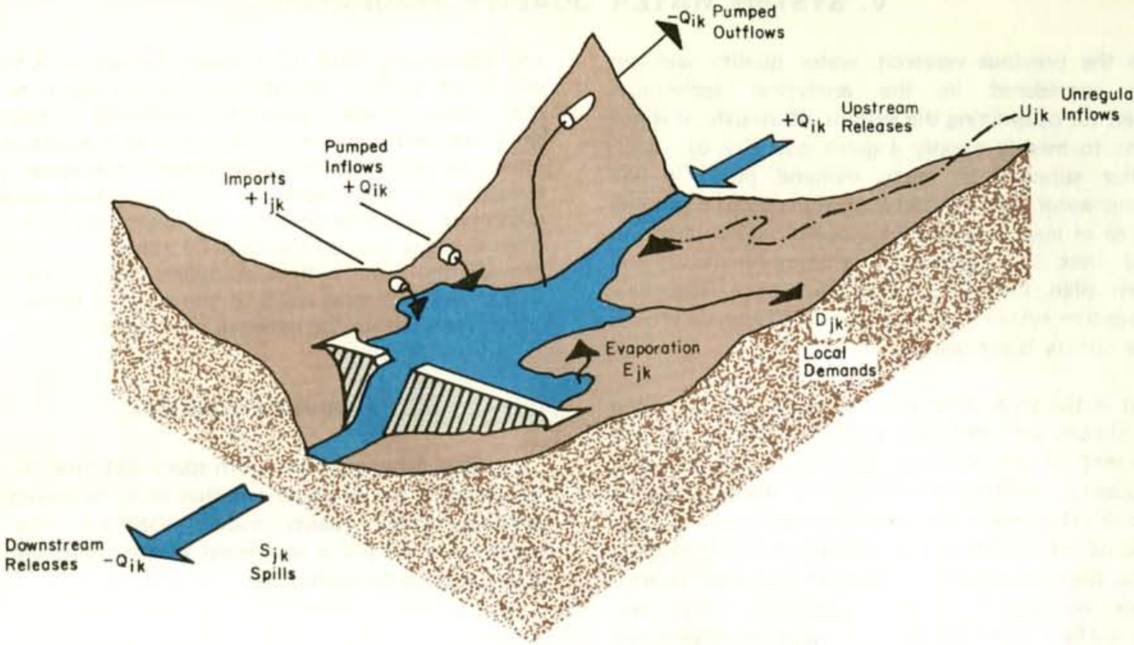


Figure 26. Basic Terms in a Mass Balance for a Reservoir

net evaporation (precipitation or evaporation) does not add mass to the system since atmospheric water is considered to have essentially zero concentration of conservative mineral constituents. The evaporation effects are taken into account by adjusting the initial and final reservoir contents at each time step before solving the equation.

In addition to reservoirs, which constitute storage nodes in the simulation model, there are two types of nodes which do not permit storage of water. These are canal and/or stream junctions and demand points on canals or streams. At the non-storage nodes, changes in storage, evaporation, unregulated inflows, and spills are not permitted.

An important step in the use of QNET-I is the definition of the quality of the unregulated inflows to each reservoir and of water imported into the system. There are two available techniques for providing this input to the simulation model. These methods are:

> Use as program input a sequence of water quality data that corresponds to a specific hydrologic sequence at a given inflow location. This is the desirable method if, for example, a complete sequence of historical water quality data are available.
>
> Alternately, the model can accept the coefficients of an equation describing the discharge-quality relationship for a given inflow and then use the hydrologic sequence at that node to generate the corresponding water quality. Several mathematical formulations can be used by this model to define the quality-discharge relationship.

Both of these formulations also include a technique that introduces a random component to the water quality data to preserve the variance inherent in the discharge-water quality relationships.

As previously discussed, QNET-I is designed to operate conjunctively with the quantitative simulation model SIMYLD-II. SYMLYD-II is based on a network representation of a water resource system where the optimum or least costly means of transferring water to points of demand is determined on a monthly basis. The resulting output from SIMYLD-II contains the unregulated inflow for each node, the beginning and ending monthly storage at each node, the volume of water transferred in each link (both river reaches and pump-canals) of the system, and the volume of water diverted from each node to supply system demands for each month in the simulation period. This information is used directly by QNET-I and forms the basis for the mass balance performed for the conservative constituents.

The water quality simulation provides the planner with a tabular listing of the concentration of each water quality constituent in every reservoir and at every demand point in the system for each month of the simulation period. This type of information can be statistically analyzed and graphically displayed as shown in Figure 27 to assist the planner in the evaluation process. For example, the recommended maximum chloride concentration for drinking water is 250 mg/l; water of poorer quality may be undesirable for the

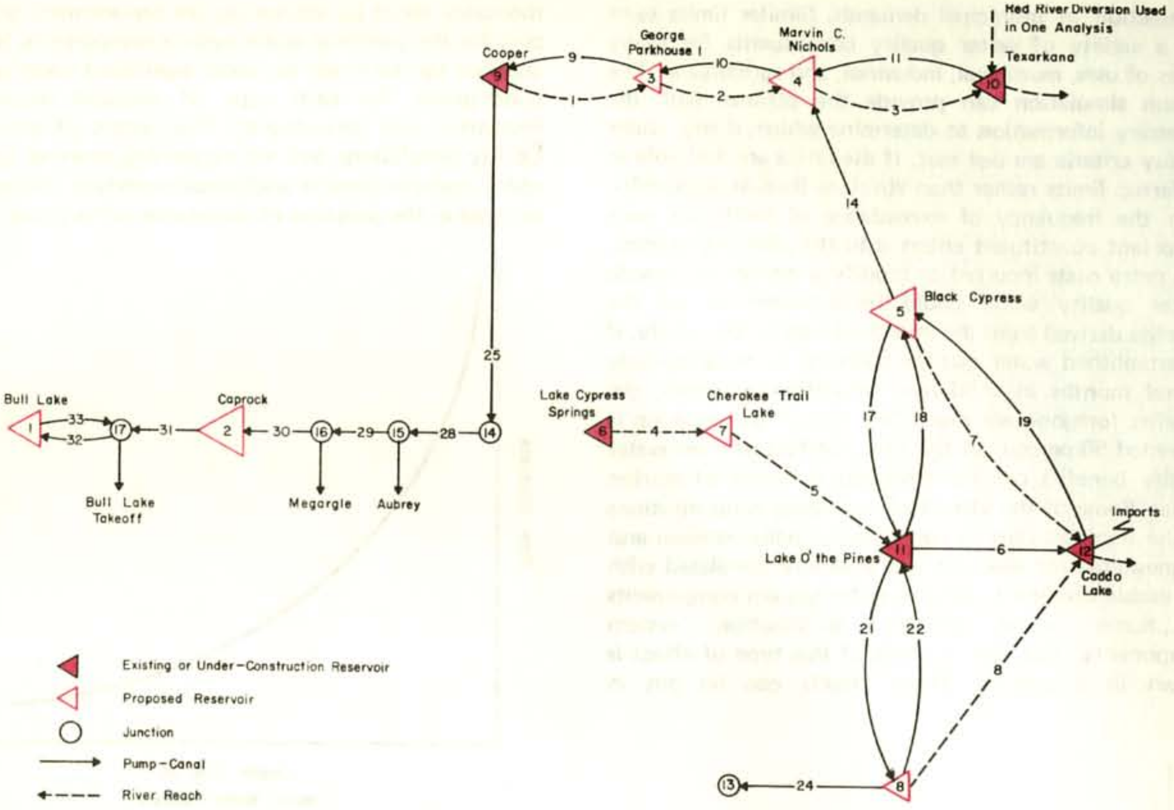


Figure 29. Example System Used in Water Quality Simulation

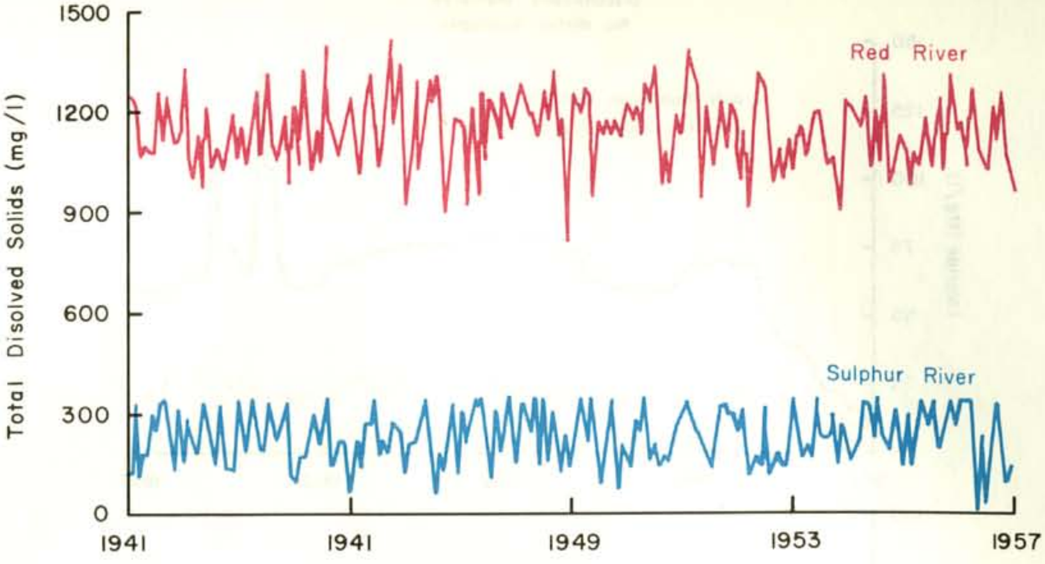
Two separate analyses were selected for demonstration of the QNET-I model. These simulations were based on the system configuration shown in Figure 29 with a total intrastate storage of approximately 14 million acre-feet. The difference between the two analyses is the inclusion of an interbasin diversion from the Red River in the second analysis.

The water quality of the Red River is significantly poorer than that of the East Texas rivers and the Mississippi River import. For example, at a flow rate of 100,000 acre-feet per month, the expected total dissolved solids concentration in the Red River is approximately six times the concentration of total dissolved solids in either the Sulphur River or Cypress Creek basins into which it would be transferred. This relationship is shown in Figure 30. Although the volume of Red River water transferred into the system is not large when compared with the other supply sources, the effects of the Red River water become critical during the drought periods. The average annual volume of water transferred from the Red River basin is approximately 700,000 acre-feet compared to a total supply in the Sulphur and Cypress basins of over 4 million acre-feet. This interbasin diversion enters the system in the Sulphur basin and represents about 25 percent of the average annual supply of that basin.

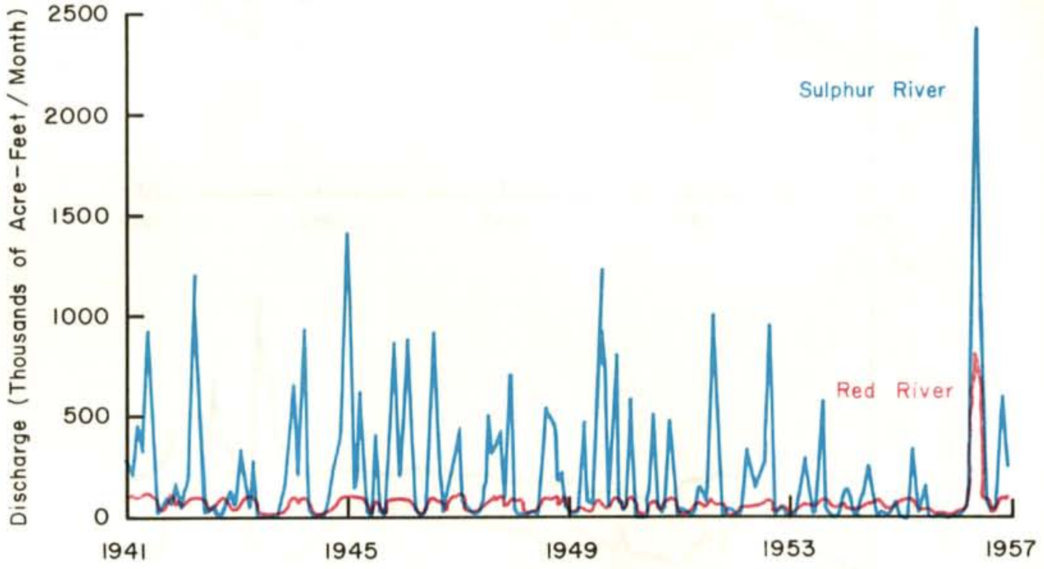
The inclusion of the Red River diversion in this example case caused a reduction of about 2 percent in shortages incurred during the dry period of the total 17-year demand. However, it was shown in this example that the import causes a deterioration in the quality of the water delivered to the principal demand node.

Figure 31 illustrates the differences in the delivered water quality at the High Plains demand site caused by the inclusion of the Red River as an import source. The sharp rise in concentrations during 1954 is a result of low-flow conditions in the Sulphur basin coupled with no import water being available from the Mississippi River. During this period the volume of the Red River diversion becomes large relative to the storage and unregulated inflow in the Sulphur basin and therefore degrades the quality of water at the terminal node. The periods of zero concentration (discontinuities in Figure 31) indicate that no water was available to meet the demands during the months shown.

Similar types of analyses can be made for each reservoir and demand location in the system being simulated. The results can be used as a basis for adjusting the operating rules in the simulation and optimization models to specify minimum flows or pumpage from areas with good quality water to those with poor water quality. This allows the inclusion, as a constraint, of a variable that cannot be explicitly considered in an objective function.



TDS Concentrations for the Sulphur River and the Red River Diversion



Unregulated Inflow for the Sulphur River and the Red River Diversion

Figure 30
Quantitative and Qualitative Comparison of the Sulphur River and Red River