MANAGEMENT ALTERNATIVES IN THE USE OF THE WATER RESOURCES OF THE PECOS RIVER BASIN IN NEW MEXICO

John W. Hernandez

New Mexico Water Resources Research Institute
in cooperation with
Civil Engineering Department
New Mexico State University

1971

ACKNOWLEDGMENTS

This study was conducted under project No. 3109-102 OWRR B-006-NMEX, through the New Mexico Water Resources Research Institute and the Engineering Experiment Station, Department of Civil Engineering, New Mexico State University. The funds to support the work were provided in part by the New Mexico Water Resources Research Institute and the United States Department of Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964.

This study was part of an interdisciplinary-inter-university research project entitled "A Comprehensive Water Resources Analysis of a Typical Overdrawn Basin in an Irrigated Semiarid Area--Pecos River Basin, New Mexico." The principal investigators were Charles E. Jacobs, hydrologist, and William K. Sumners, geologist, New Mexico Institute of Mining and Technology; Ralph d'Arge, economist, and W. H. Ellis, professor of law, University of New Mexico; and the following persons from New Mexico State University: John W. Hernandez, civil engineer; Arden Baltensperger, agronomist; Harold Dregne, soils scientist; George R. Dawson and Robert R. Lansford, agricultural economists. H. R. Stucky, Director of the New Mexico Water Resources Research Institute, New Mexico State University, served as the coordinator of all phases of the project.

Although I am solely and totally responsible for statements and conclusions in this report, many people helped me in the work, in addition to my co-investigators. Four young men did various parts of the computer programing on the project: Jefrey Oakes did the original linear program for the Roswell Basin study; Tom Nims completed the work and added the program for the dynamic model; Linden Gray did the initial river-routing program, which was finished by Girish Asher. A number of people have read and commented on individual sections: Frank Houghton, Carl Slingerland, Joe Yates, Roland Fife, Felix Corle, and Zane Spiegel. I am indebted to these men for their advice. For the editorial work I had the able assistance of Lorena Neumann. Most of all I am grateful to Dr. Ralph Stucky for his support in the search for funding for the project.

ABSTRACT

The primary purpose of the analytical studies reported in this text has been to identify those general management policies that could lead to enhanced efficiency and effectiveness of the use of the water resources of the Pecos River in New Mexico. I hope that these investigations will provide additional insight and guidance in those areas in which managment is possible, either through the joint action of individual water-users with a common problem, or through the action of government.

Part I of the report reviews the existing situation in the Pecos Basin in New Mexico and the potential value of restudying some of the elements of the supply system. Many conventional techniques used in hydrologic work have been employed in the study, but some of the newer and somewhat unproven methods have also been used--such as synthetic inflow-outflow studies, and the coupling of linear and dynamic programming models. Results of the analytical work are presented in Part II, a management-decision model for the Roswell Artesian Basin, and in Part III, a stochastic model of the storage, routing, and use of available surface-water in the Pecos Basin, New Mexico.

The fundamental problem in the Roswell Artesian Basin is that the average annual rate of use of water has for many years exceeded, and continues to exceed, the mean annual rate of supply. This over-production has resulted in declines in ground water levels and in the encroachment of saline waters into fresh-water zones. On the basis of the analysis performed, recommendations are developed for a method and program for the retirement of farm lands from production so as to reach a satisfactory equilibrium for the system. These are found at the end of Part II.

A number of major water-supply development and salvage projects are planned or currently under way for the Pecos River in New Mexico that will alter the quantity and quality of the surface supply of the system. Synthetic routing studies were used to evaluate the effects of some of these activities on the amount of water available to the Carlsbad Irrigation District. In Part III recommendations are made for the design and operation of certain project works based on analytical studies.

Four principal recommendations are offered at the close of the report:

1. The level of pumping in the Roswell Artesian Basin should be reduced by retirement of necessary lands from production.

2. Channel and delta losses between Alamogordo and the McMillan Dam should be reduced with projects to effect this reduction undertaken as soon as possible.

3. Deterioration of the quality of the surface supply in the reach from Anton Chico to Santa Rosa should be reduced; plans for any development work in the Santa Rosa area should include quality control structures for this reach.

4. A salinity-routing study should be undertaken to evaluate the combined effects of current and planned water-development projects on the quality of the surface-water supply.

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THE NEED TO IDENTIFY MANAGEMENT ALTERNATIVES IN THE USE OF WATER RESOURCES OF THE PECOS RIVER BASIN IN NEW MEXICO

Chapter 1

THE MUCH-STUDIED PROBLEMS OF THE PECOS RIVER SYSTEM

Per unit of volume of water available for use, the water resources of the Pecos River have been subjected to more study than those of almost any other river system in the country. One reason for this "interest" in the Pecos Basin is given in the introductory section of the National Resources Planning Board's 1942 report [33, p. 7], where it is noted that "with controversies over the use of water increasing with passing years, many investigations naturally have been undertaken." Controversy is an apt word to associate with the many intra- and inter-state problems that have plagued the basin from the early days of its extensive development in the late 1800s. (See figure 1 for a map of the Pecos River Basin and detailed drawing of the New Mexico portion.)

The list of the Pecos-system ills reads as if it were a compilation of all the possible problems associated with the use of a water supply (see table 1). The fundamental difficulty is the lack of an adequate and reliable water supply to meet all of the demands that are placed on the system. The river system has other shortcomings: not only is the quantity highly variable, both spatially and in time, but so is the quality; soil erosion and the subsequent problems of sediment transport and deposition are common; damaging floods continually threaten both rural irrigated-valley areas and urban areas; and much of the available water supply is lost to nonbeneficial uses.

Current Efforts Toward Improvement

Application of the water resources of the Pecos system has meant a series of confrontations between man and nature, with each effort to control the river and its waters leading to some often-predictable, but usually unexpected, response by nature. Table 2 lists the major hydraulic control structures on the Pecos in New Mexico, and location of these structures is shown in representational form in figure 2.

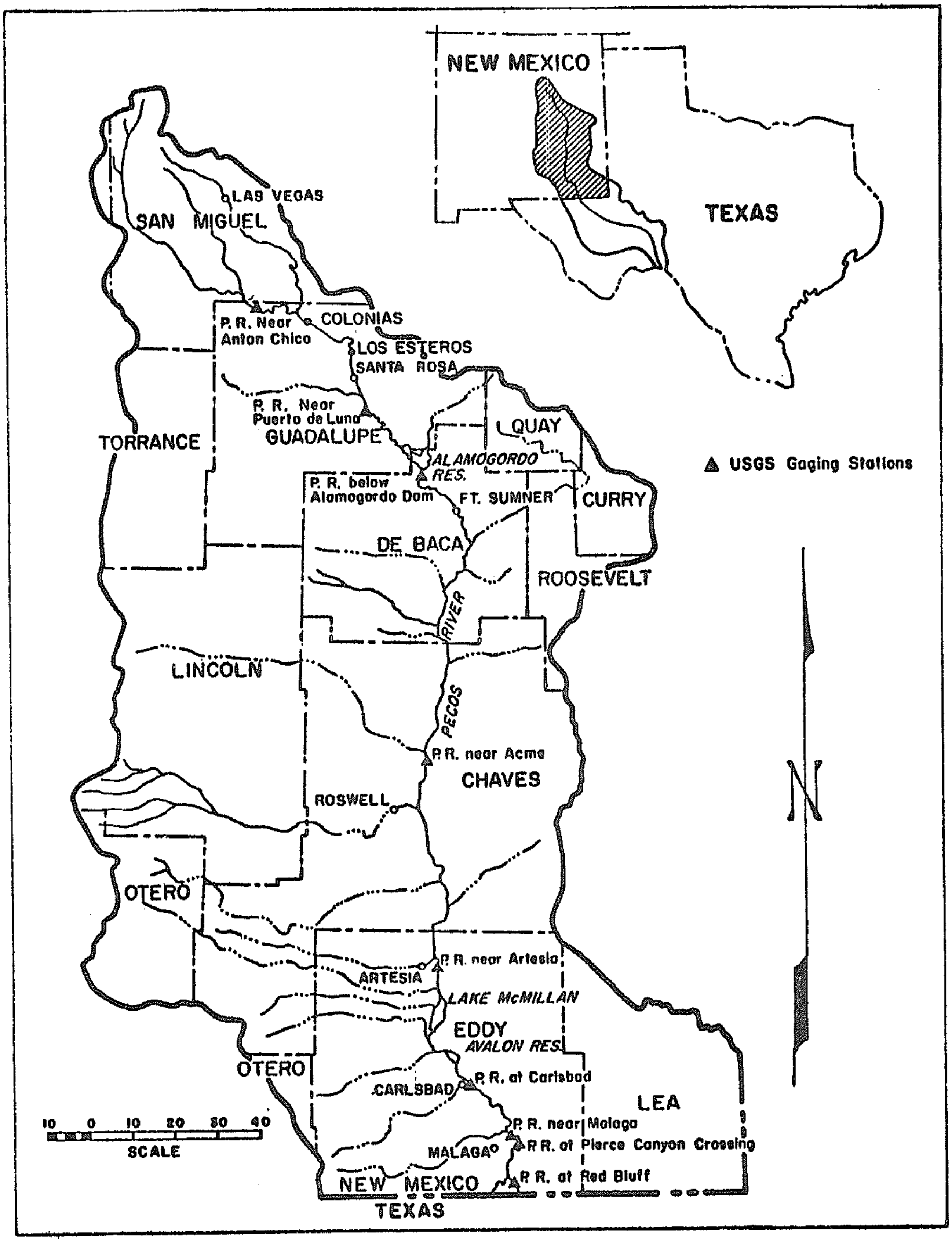

Figure 1. The Pecos River Basin with detail of New Mexico portion.

Table 1. Water resources problems of the Pecos River in New Mexico and examples of their magnitude.

Problem Related to Water Use	Examples of the Magnitude of the Problem[1]
Inefficient Use of Supply	Total supply, 600,000 acre-feet; total New Mexico use, 367,000 acre-feet; beneficial use, 182,000 acre-feet; non-beneficial use, 185,000 acre-feet; most beneficial use is single-purpose irrigation with low net return per acre-foot.
Demand in Excess of Supply - Spacially	Only 23,000 acres irrigated above midpoint of system above which 50 percent of stream flow originates. Irrigation shortages occur on most productive lands in the surface irrigation system; shortages to CID[2] ranged from 20 to 45 percent for five consecutive years.
Demand in Excess of Supply - Temporally	40 percent of flood inflow below Alamogordo Dam occurs during fall months whereas 45 percent of irrigation demand occurs in summer months; average annual flow at Santa Rosa is about 100,000 acre-feet with the standard deviation for the historical average also 100,000 acre-feet.
High Reservoir Water Losses to Evaporation	To yield 1 acre-foot by over year storage a volume of 1.5 acre-feet must be stored in Alamogordo Reservoir, 2.5 acre-feet in McMillan Reservoir; CID reservoir evaporation losses equal 30 percent of the average diversions (100,000 acre-feet) for irrigation.
Significant Reservoir Leakage	Annual seepage from McMillan Reservoir is about 28,000 acre-feet; seepage from Avalon Reservoir is three times greater annually than storage capacity (16,000 acre-feet vs. 5,000 acre-feet).
Declining Effectiveness of Reservoirs Caused by Sedimentation	Sediment yield above Alamogordo Reservoir is 2,000 acre-feet per year, causing loss of 28,000 acre-feet of capacity in 20 years; 55 percent loss of capacity of McMillan by deposition of 50,000 acre-feet of sediment in 60 years.

Table 1. Water resources problems of the Pecos River in New Mexico and examples of their magnitude continued.

Limited Choice for New Reservoir Sites	Foundation problems and high seepage losses likely to be encountered in the basin; southern New Mexico sites also suffer from high evapotranspiration losses.
Excessive Transpirtation Losses Caused by Phreatophytes	Phreatophyte growth causes channel and delta losses exceeding 100,000 acre-feet per year below Alamogordo Reservoir; new growth in basin at rate of 500 to 600 acres per year; losses could exceed 280,000 acre-feet per year at end of next 50 years if uncontrolled.
High Potential for Flood Damage	Spillway on McMillan Dam is insufficient to pass the standard project flood; channel capacity at Carlsbad is 50,000 cfs while standard project flood for the reach is 132,600 cfs; 1966 flood crest at Malaga gage estimated at 155,000 cfs.
Surface Water Quality Problems	Quality of flow in Pecos deteriorates markedly in downstream direction. Minimum and maximum for total dissolved solids (in ppm) for representative stations are: below Alamogordo Reservoir, 435 and 2,730; Acme gage, 459 and 19,870; Malaga gage, 384 and 9,100.
Declining Ground Water Levels	Safe yield from Roswell ground water basin has been exceeded by pumping during the past decade by nearly 50,000 acre-feet per year; water levels in the artesian aquifier have declined as much as 70 feet during the period 1944-1960.
Deteriorating Ground Water Quality	Along with declines in ground water level have come salt water intrusions in the artesian aquifier; in 1952 wells with chloride equal to 600 ppm had concentrations of 1,600 ppm in 1965; in other wells, in 1952, with chloride concentrations of 400 ppm, 1965 concentration was 700 ppm.

1. Figures cited are approximate, average monthly, seasonal, or annual values that have been rounded to indicate magnitude of the value.
2. CID = Carlsbad Irrigation District.

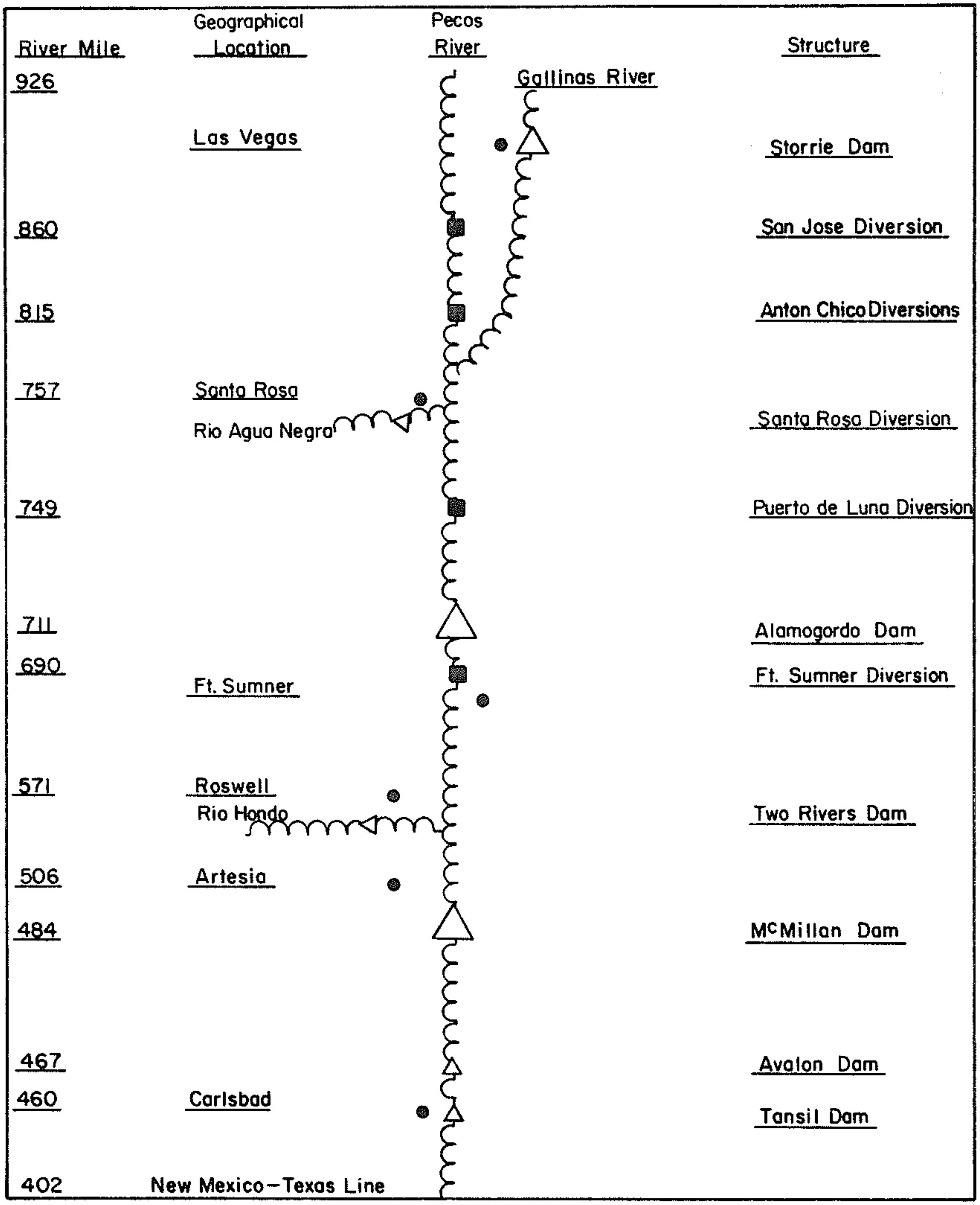

Figure 2. Representational drawing of location of major control structures on the Pecos River and tributaries, New Mexico.

Table 2. Summary of major control structures for water use, Pecos River, New Mexico.

Structure and Location	Use[1] Initial	Use[1] 1970	Date of Development[2]	Structural Improvement	Capacity	Approximate Cost[2] (dollars)
Storrie Dam, 4 mile north of Las Vegas	I	R, W, WL, F I	1913-1921*	Diversion on the Gallinas River earth fill dam with concrete core at Storrie Reservoir.	Reservoir capacity about 21,000 acre-feet, supply sufficient for about 5,000 acres, 7,343 acre-feet of water appropriated.	700,000*
Alamogordo Dam river mile 710.8	I (CID)[3]	I, R, F, FC	1936* 1956^{+}	Earth and rock fill dam with concrete shute spillway with Tainter gates.	Initial capacity 156,750 acre-feet 1964 capacity 110,655 acre-feet.	2,150,000* 1,130,000^{+}
Ft. Sumner Project, about river-mile 690	I	I	1918* 1935^{+} 1950^{+}	800-foot concrete diversion dam, 15 mile of main canal, 8 mile of highline canal.	Main canal capacity 100 cfs, project irrigates 6,500 acres, average diversion is 35,900 acre-feet annually.	150,000^{+} 1,795,000^{+}
Two Rivers Reservoir Project, 36 miles up Hondo from river-mile 571	FC	FC	1963	Earth fill dam across Rio Hondo and Rocky Arroyo.	Capacity 207,500 acre-feet at spillway crest.	4,939,000*
Kaiser Channel, approximately river-mile 530	WC (CID)	WC	1949-1953*	Canal to drain Kaiser Lake and reduce evapotranspiration losses in the reach from Artesia bridge to McMillan Reservoir.	Channel capacity 1,400 cfs.	
McMillan Dam river-mile 484 (CID)	I	I, FC W, R, F	1893* 1907-1909^{+}	Main dam and west embankment, earth fill structures, two uncontrolled spillways between embankments.	Initial capacity 91,000 acre-feet, 1964 capacity 33,600 acre feet.	455,000 (total)
Avalon Dam river-mile 467.3 (CID)	I	I, W, R, FC F	1893* 1894^{+} 1907^{+}	Earth and rock fill dam with three spillways and headworks for diversion into CID main canal.	Initial capacity 7,600 acre-feet, 1956 capacity 5,647 acre-feet, 1964 capacity 5,000 acre-feet.	333,000
CID canal and distribution system	I	I	1888* 1906-1907^{+} 1970-1971^{+}	30 mile of main canal, 153 miles of laterals, 23 miles of drains, concrete flume at river-mile 463 and siphon under Dark Canyon.	Irrigates about 25,000 acres with average annual diversions into the system of 100,000 acre-feet.	over 4,000,000
Tansil Dam river-mile 460	P	R, ID		500-foot-long, 25-foot-high concrete overflow structure.	Long, narrow reservoir a relatively small capacity.	over 150,000 for recreational development at the new Lower Tansil Dam.

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1. I = irrigation, R = recreation, W = waterfowl, WC = water conservation, WL = wildlife, F = recreational fishing, ID = industrial, P = power, FC = flood control.

2. * indicates initial development, + indicates major rehabilitation.

3. CID = Carlsbad Irrigation District.

Current programs to control the Pecos show a great concern for the effects of management of the system, demonstrated by concerted efforts of the responsible governmental agencies to evaluate these effects. Programs for solving most of the critical problems of the system are contemplated or have been undertaken. A brief summary of the more important of these activities--administrative, operational, and structural--is given in the sections that follow. Figure 3 shows the location of the principal existing and proposed control structures on the main stream of the Pecos.

Federal Government Activities

McMillan Delta Project--Bureau of Reclamation

The goals of Public Law 85-333, passed by Congress in 1958, were salinity control and water salvage on the Pecos. The two segments of the project are the McMillan floodway channelization division to reduce non-beneficial uses, and the salinity alleviation division to reduce saline-spring inflow into the Pecos in the Malaga Bend area.

Construction of the latter project was completed in 1963 with the drilling of a 220-foot production well with a 12-inch diameter plastic casing and a corrosion-resistant pump. Two miles of eight-inch asbestos-cement pipe carries the salty water pumped from the well at a rate of 400 to 450 gallons per minute to a 1,300-acre-foot-capacity natural depression for evaporation. The project initially achieved a significant reduction in the total amount of chloride ions reaching the river in the Malaga Bend area [35, p. 61], but recent evaluations are less promising.

The channelization project was still in the planning stage in 1970, with at least two versions of the basic plan having been considered. The preliminary McMillan Delta Project provided for a cleared floodway (40,000 cubic feet per second) levee and a 1,500-cfs-capacity channel that would replace the existing Kaiser channel and would carry the flow of the Pecos directly into Lake McMillan. The 16-mile-long channel would reduce losses in the reach by 15,000 acre-feet per year, partly through clearing and partly by straightening the river's path through the delta that has formed upstream from the reservoir. The project would increase the amount of water available for diversion by the Carlsbad Irrigation District (CID) by about 4,500 acre-feet per year, and it will also increase the peak flood-flow over the spillway at McMillan Dam by about 6 percent (50,000 cfs).

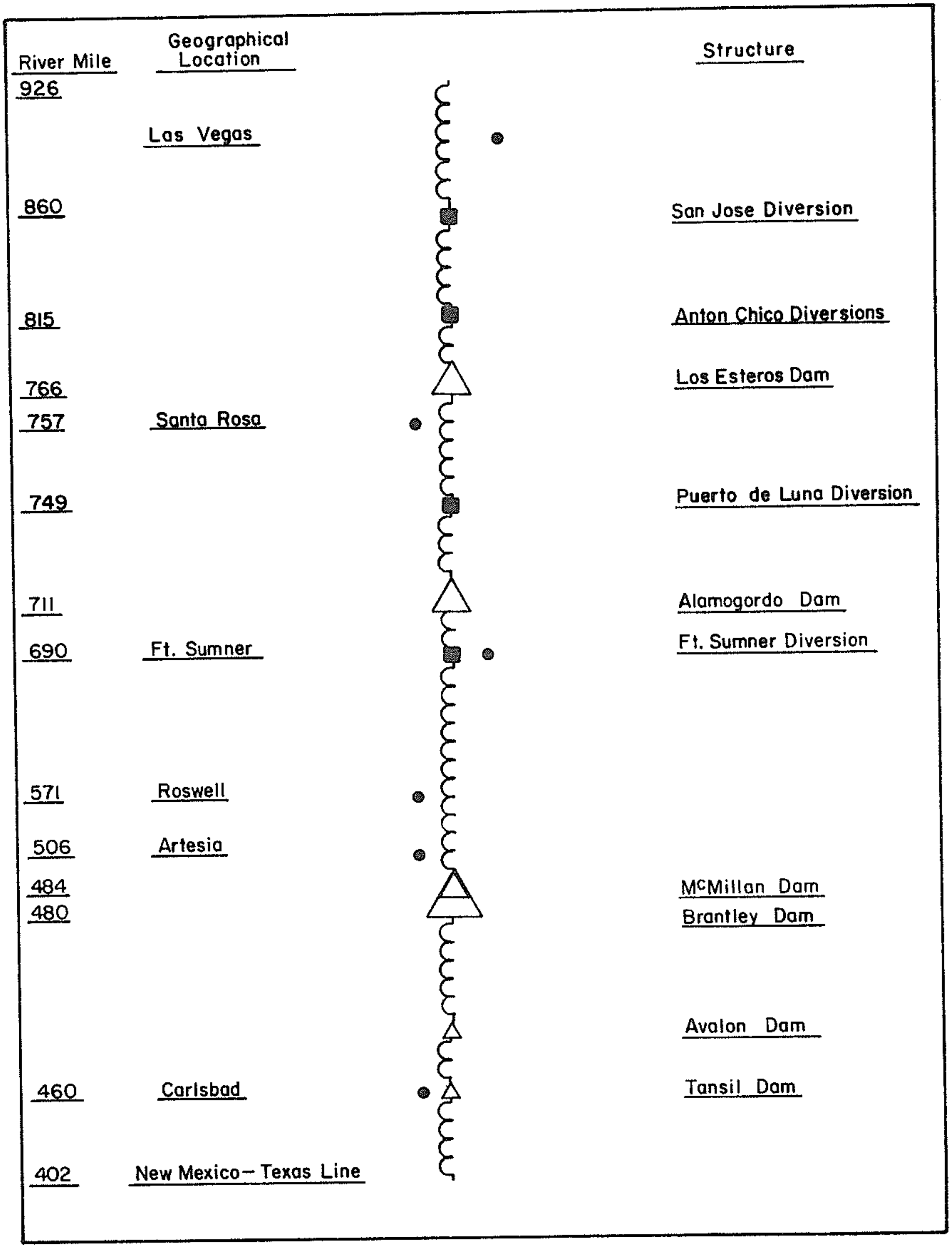

Figure 3. Representational drawing of existing and proposed irrigation and flood control structures on the Pecos River,– New Mexico.

The 1958 cost estimate for the 16-mile delta channel was $2.6 million for project construction and $55,300 a year for operation and maintenance. In mid-1959 the Bureau of Reclamation presented a revised plan to the Pecos River Commission that would reduce the cost of the project to $932,800 by incorporating parts of the existing Kaiser channel into the new system. Under this plan about 4,500 acre-feet of water would be salvaged per year. The New Mexico legislature has provided $290,000 as the state's share for right-of-way acquisition and for highway and bridge relocation. A part of the project construction costs are to be repaid by the CID over a 50-year period on a "repayment-ability" basis, with the CID debt to be in proportion to the amount of salvaged water received by the district. The state and local agencies involved will be responsible for operation and maintenance of the project. PL 85-333 provided that work on the channelization project should not start until firm plans have been made to replace any conservation storage that might be lost as a result of the work.

Brantley Reservoir Project--Bureau of Reclamation

A new dam and reservoir, is proposed at one of the few favorable structural sites remaining on the river in New Mexico, four miles downstream from McMillan and nine miles above Avalon Dam. The dam is to be located in the area of Major Johnson Springs where the Seven Rivers formation surfaces in a relatively dense carbonate that will restrict the leakage from Brantley Reservoir. These springs are the point of discharge of a part of the flow leaving the Roswell ground water basin and the point where most of the seepage from McMillan Reservoir returns to the stream.

The new structure will back up water into McMillan and replace the irrigation storage in that lake now being lost to sediment, and will provide much-needed flood protection for the City of Carlsbad. The proposed reservoir will include 500 acre-feet of dead storage, 1,500 acre-feet inactive, an active conservation pool of 142,000 acre-feet, and a total active capacity of 520,000 acre-feet, leaving 376,000 acre-feet exclusively for flood control. The active conservation capacity allows for 100 years' sediment deposit (estimated to total 116,000 acre-feet), with 102,000 acre-feet in the sediment reserve pool, 2,000 acre-feet for fish and wildlife purposes, and 40,000 acre-feet for storage of irrigation water, this last being the approximate volume now remaining in McMillan Reservoir. When the project is completed, no water will be stored in McMillan except during the winter months, when storage of up to 4,500 acre-feet will be permitted to provide additional waterfowl habitat. As Brantley will be essentially a flood control and irrigation project, the reservoir will be drawn down to a minimum pool approximately 40 percent of the time during the irrigation season from May through September. When it is full, a lake surface of 36,000 acres will result, and a still sizable water surface (4,000 acres)will be produced when it is at the top of the irrigation pool level. The new reservoir will enhance the recreational, hunting, and fishing potential of the area, with estimated annual benefits of $56,200 (1966 price level) for the latter two activities [47]. The March 1971 cost estimate for the project was approximately $46 million.

Water-Salvage Project--Bureau of Reclamation

In 1964, under PL 88-594, Congress appropriated $2.5 million for phreatophyte control on the Pecos River in New Mexico and Texas, probably about one-half of this amount will be spent in New Mexico. Continued spread of unharvested water-consuming vegetation threatens the beneficial use of the water supply of the system. It has been estimated that if adequate control measures are not instituted, nonbeneficial use will increase from the 1960 level of about 185,000 acre-feet to more than 280,000 acre-feet per year in the next 50 years [38, p. 225].

In New Mexico phreatophytes are to be cleared from the headwaters of Los Esteros downstream to the state line, excluding the McMillan delta area. The project is not to interfere with the regular flow of the river, nor change the quality adversely, and the objectives are to be accomplished with minimum hazard to fish and wildlife. Areas marked for clearing are those where areal density exceeds 10 percent, or where depth to ground water is less than 10 feet. These two conditions often occur jointly in the zones where growth will be controlled. About 70,000 acres meet these criteria, including growth in the McMillan delta. Under the initial program approximately 40,000 acres will be cleared under contracts--some of this work being already under way in 1968--with the remaining area to be cleared in an ongoing operation and maintenance program. Maintenance will be achieved mechanically in areas adjacent to farming operations (more than 50 percent of the lands to be cleared), or by ground spraying for the zone lying between one-half and one mile from cultivated lands (about 15 percent of the area), and by aerial spraying where crop damage is not likely (30 percent of the area).

Although a 30-foot fringe will be left bordering stream banks, there will be a significant loss in fish and game habitat,particularly with respect to waterfowl. In addition to depleting the already marginal fish and game resources of the basin, the clearing will cause major losses in fishing activity, hunting, and wildlife-oriented recreation [48]. The cost of these activity losses could be as high as $200,000 per year at 1966 price levels, depending on the actual phreatophyte cleaning program adopted.

An estimated 63,000 acre-feet of water can be salvaged above McMillan Reservoir by completing the delta clearing project and water-salvage program [36, p. 132]. Reimbursement for clearing costs, in proportion to benefits received, may be sought by the Federal government under terms of the authorizing legislation, if the Secretary of the Interior is able to identify those benefitting directly from the program. PL 88-594 also directs the Secretary to take necessary measures to carry out a continuing program in the basin to reduce nonbeneficial consumptive uses. The State of New Mexico is participating in the program, having appropriated $250,000 for acquisition of necessary easements and right-of-way.

Los Esteros-Alamogordo Dam Project--Corps of Engineers

This project was authorized by Congress in 1954 to provide additional flood control facilities on the Upper Pecos and to permit transfer of part of the CID's irrigation storage in Alamogordo Reservoir to Los Esteros Reservoir, releasing this capacity for flood control purposes. The authorization required arrangements at the state and local level for transfer of the conservation storage. In June 1965, the CID adopted a resolution agreeing to the exchange of irrigation storage above a given reservoir elevation in Alamogordo Reservoir for storage capacity in Los Esteros Reservoir. The latter will have a 82,000-acre-foot sediment pool, as part of a 200,000-acre-foot irrigation pool, with the remaining capacity (167,000 acre-feet) assigned for flood control. Neither temporary nor permanent storage is planned for the new reservoir, but it is possible that both can be provided in Alamogordo (3,000 acre-feet permanent and 7,000 temporary) if water-rights from lands acquired for construction of Brantley Reservoir are assigned to cover evaporation losses caused by maintenance of these recreation pools.

The proposed structure, to be located at river-mile 766 seven miles north of Santa Rosa, will be an earth fill 218 feet high and 1,865 feet long, and will have a maximum capacity of 449,000 acre-feet when the surface area will be about 11,000 acres. Spillways for the dam will be uncontrolled rock cuts, with a capacity of 149,500 cfs at the maximum-pool level.

Corps of Engineers Flood-Control Projects

In response to state and local requests, the Army Corps of Engineers has completed work on several flood-control projects in the basin and is considering a number of additional projects. The largest project was the Two Rivers Reservoir, completed in August 1963 at a cost of $4.9 million to protect the City of Roswell and other downstream areas from floods originating on the Rio Hondo and Rocky Arroyo. The dam is located a few miles west of Roswell across both of these tributaries of the Pecos. Another major Pecos River project in New Mexico is the construction of a floodway and other works on Dark Canyon.

Watershed Flood Protection--Soil Conservation Service

Under PL 566, the SCS has engineered and constructed a large number of flood control and watershed protection projects in the Pecos Basin in a cooperative program with the State Engineer Office and local agencies. The first projects were initiated in 1955 and are designed to provide protection for watersheds of less than 250,000 acres. Since 1955, thousands of stabilization and sediment control structures and debris basins have been built, hundreds of miles of stream-channel improvement and diversion dikes and ditches have been added to the existing systems, and thousands of acres in the basin have been subjected to treatments such as terracing and contour plowing. A summary of those projects is provided in table 3.

Office of Saline Water

A combined Federal, state, and local project was completed in July 1963 with the construction of a saline-water conversion plant four miles east of Roswell. The one-million-gallon-per-day plant, utilizing a forced circulation, vapor-compression distillation process, produces an essentially salt-free water from a feed of brackish water from a nearby well, having a chloride content of approximately 8,000 parts per million and total dissolved solids content of 15,400 ppm. Project costs were on the order of $2 million. The State of New Mexico

Table 3. Watershed flood protection projects under Public Law 566, as of January 1, 1970, Pecos River Basin, New Mexico.

Watershed	Direct Planning Cost (dollars)	PL-566 Construction Cost (dollars)	Total Construction and Installation Cost (dollars)
	Completed Projects		
Upper Rio Penasco	20,918	133,565	213,309
Zuber Draw	22,623	277,200	399,061
Pecos Arroyo	13,312	114,805	166,733
Hackberry Draw	19,682	490,236	704,913
	Projects Approved for Installation		
Cass Draw	10,000	281,643	405,000
Avalon-Alacran	8,000	69,482	91,720
	Projects Being Planned		
Cottonwood-Walnut Creek	141,096	3,319,100	4,147,100
Eagle-Tumbleweed Draw	49,876	2,667,600	3,181,300

provided $100,000, as well as engineering evaluation of potential seepage from the waste brine (55,000 ppm total dissolved solids) disposal ponds.

State and Local Activities

Control and administration of the water resources of the Pecos Basin are principally the responsibility of the New Mexico State Engineer, and most of the activities for improved utilization of the waters of the Pecos originate or are coordinated through this office. Cooperative efforts with local water-user gorups such as the Carlsbad Irrigation District (CID) and the Pecos Valley Artesian Conservancy District (PVACD) have led to development of many current state and Federal water programs in the basin. In cooperation with and in addition to state and Federal programs, the CID and PVACD have undertaken a number of studies and rehabilitation programs. For example the CID has a $4 million project underway that includes canal lining and replacement of structures. A summary of the principal water resources-oriented activities carried on by the state is given in the sections that follow.

Roswell Artesian Basin Hydrographic Survey

This inventory and mapping of wells and irrigated lands, undertaken in the mid-1950s, was the lead step in subsequent efforts to limit and control the amount of ground water produced from the basin's two principal aquifiers. Efforts to limit water use in the basin began in the late 1920s but had marginal success until the hydrographic survey was initiated. In 1965 meters were required to be installed on all wells by January 1, 1967 and the amount of water produced per water-right area was limited by judicial order [42]. In addition to these restrictions, well drilling and completion techniques are regulated in this and other declared ground water basins in the Pecos watershed. The Roswell hydrographic surveys were conducted in cooperation with the PVACD on an equal cost-sharing basis with the state, with a total expenditure of just over $168,000 at the end of 1967 [35, p. 19].

Efforts have also been made to increase the efficiency of use by lining ditches, installing drainage works, and levelling the irrigated lands. To help finance these activities, the state, through the Interstate Stream Commission, loaned the PVACD and the Hagerman Irrigation Company $287,449 during fiscal 1967 and 1968 [34, p. 82].

Carlsbad Underground Water Basin

This basin was declared in 1947 and has been extended on three other occasions to include an area of 1,400 square miles, where ground waters may be produced from various formations in sufficient quantities for agricultural, industrial, and municipal purposes. A hydrographic survey of the basin was undertaken in 1963 with total costs through fiscal 1968 of more than $18,000 [34, p. 21].

System Hydrologic Studies

Detailed studies of the geology and hydrology of the Pecos Basin are conducted on a continuing basis by the State Engineer Office, many of them in cooperation with the U. S. Geological Survey. These studies include water quality, sediment transport, and surface and ground water hydrologic investigations. A quantitative analysis of the Roswell ground water basin was conducted during 1962-1969, utilizing a number of study techniques including an electrical analog model to simulate system hydraulics. In the 1950s and 1960s quantitative geologic and ground water investigations were completed for San Miguel, Guadalupe and DeBaca counties. Analytical engineering studies of the water resources of the system are a continuing function of the State Engineer Office in administering the Pecos River Compact.

Ditch and Diversion Rehabilitation Program

This is a long-term program designed to enhance the efficiency of community irrigation systems and is currently funded by local, state, and Federal funds, with local labor frequently being used to match state and Federal Agricultural Conservation Program monies. The small projects developed under the program are of considerable importance in the state's efforts to increase the productivity of irrigated lands in the Upper Pecos Basin. Rehabilitation projects completed in fiscal 1967 and 1968 are given in table 4.

Table 4. Summary of expenditures in the ditch rehabilitation program, Pecos River Basin, New Mexico, fiscal years 1967 and 1968.

Community Ditch Association	County	Community Share (dollars)	State Share (dollars)	Total Project Cost (dollars)
East Puerto de Luna	Guadalupe	4,400	4,400	27,800
West Puerto de Luna	Guadalupe	1,900	1,900	11,500
Acequia de en Medio de Manuelitas	San Miguel	340	340	2,270
East Pecos Ditch	San Miguel	1,240	570	3,800
El Molino Ditch	San Miguel	1,600	1,600	10,800
Los Chupaderos Community Ditch	San Miguel	910	260	2,290
San Jose Dam and Ditches	San Miguel	5,200	2,000	17,350

Source: New Mexico State Engineer Office
<u>Twenty-eighth Biennial Report</u>
(November 30, 1968) pp. 35-38.

Chapter 2

THE NEED FOR FURTHER STUDIES

In view of the years of study that have already been devoted to the Pecos Basin and its problems, as summarized in the preceding chapter, one might reasonably question the need for additional studies of the management of water resources of this basin. Certainly there are some adverse situations which are being corrected, and many additional remedial measures are under active consideration by the local and governmental agencies involved. However, there appears to be a need for an "outside" review of the present and proposed management of the basins water resources. As justification, it should be noted that

1. Resources of the basin are extremely limited, particularly the water resources;

2. Efficiency and effectiveness of the use of the available surface supply can be improved upon when one considers the non-beneficial losses that occur in the system and the low net-benefits returned through use of this supply;

3. Management of the water supply is quite difficult, because of the legal and administrative constraints imposed and the physical limitations of the system;

4. Annual variation of the controllable portion of the supply is quite large compared with the average supply;

5. Management of the controllable part of the supply is vested mainly in the individual water-right holder and the cooperative administrative units formed by water-right owners;

6. The works available to control the supply are limited and inadequate;

7. Although multiple-use is made of the available supply, single-purpose objectives are the basis of the present development of the supply;

8. Implementation of innovative action by governmental agencies is made almost impossible by the rigidity of the legal constraints;

9. The contribution of current and proposed governmental efforts to improve the use of the basin's resources

is difficult to evaluate, because each activity or project represents a solution to a particular problem and not a part of a comprehensive plan; and

10. There is a need to identify control mechanisms that can be used to improve the use of the basin's water supply, despite the imposition of system constraints.

Study Objectives

The primary purpose of the analytical study reported in this text was to identify those general management policies that could lead to enhanced efficiency and effectiveness of the use of the water resources of the Pecos River in New Mexico. It was hoped that the study would provide additional insight and guidance in those areas in which management is possible through either the joint action of individual water-users with a common problem, or through the action of government.

With respect to the water-related problems of the basin, the specific objectives of this study were:

1. to review the persistence and magnitude of the problems;

2. to review the points of diversion and quantities of water applied to beneficial use;

3. to review the locations where extensive non-beneficial use takes place;

4. to review those places and uses that cause the quality of the supply to be degraded;

5. to review current and proposed plans for the amelioration of particular situations; and

6. to identify and propose alternate management methods where possible.

General Procedure

The areas selected for study were not the only management possibilities available, nor should the reviews of individual problems be considered as "detailed analytical studies." Rather,they represent a part of a broad-brush review of all of the principal areas of consumptive use of the water supply of the basin. Except were specified, the policy decisions identified are considered to be, within reason, in keeping with the constraints imposed by the Pecos River Compact, existing water-rights adjudication, and the water laws of the state. Wherever possible, the relative value of various alternatives is indicated in quantitative terms.

Although many of the pressing problems leading to some of the controversy associated with use of the basin's water supply have been or are being solved, most of the basic causes of these situations still exist, and probably will for years to come. Innovative management techniques, based on analytical studies, offer a means of improving the efficiency and effectiveness of the use of the resources of the basin.

As acknowledged earlier, this work is part of a coordinated, multi-university, interdisciplinary project and much of the essential basic data for this investigation comes from the companion studies. Since the inception of the work, this segment has become known as the "gross systems analysis," the implication being that here an effort is being made to evaluate the water-resources-related problems of the Pecos Basin in New Mexico from a macroscopic view, using the findings of other, more intensive studies.

Many conventional techniques used in hydrologic work have been employed in the study, but some of the newer and somewhat unproven methods have also been used--such as synthetic inflow-outflow studies, and the coupling of linear and dynamic programming models. Results of the analytical work are presented in Part II (a management-decision model for the Roswell Artesian Basin) and in Part III (a stochastic model of the storage, routing, and use of available surface-water in the Pecos Basin, New Mexico).

Part II

DECISION MODEL FOR OPERATION OF THE ROSWELL ARTESIAN BASIN

Chapter 3

THE PROBLEM AND POSSIBLE SOLUTIONS

Manifestations of the Problem

The fundamental problem is that the average annual rate of use of water in the Roswell Artesian Basin has for many years exceeded, and continues to exceed, the mean annual rate of supply. Essentially all (96 percent) of the basin's water supply is produced from wells (see figure 4 for a map of the area). The mining of water from the basin's two principal aquifiers has resulted in persistent and pervasive declines in ground water levels and, in some parts of the basin, serious deterioration of the quality of the supply. Manifestations of the imbalance between supply and demand are demonstrated by the following examples:

1. During the period 1944 to 1961 piezometric levels in the artesian aquifer have declined throughout the entire basin, as much as 80 feet near Artesia and 35 feet near Roswell.

2. The shallow ground water table has fallen more than 60 feet near Artesia and 80 feet in the vicinity of Hagerman in the years between 1938 and 1960.

3. In many of the irrigation wells producing from the artesian aquifer in the Roswell area the concentration of chlorides increased by 500 ppm, and by as much as 2,500 ppm in a few wells, in the five years 1952-1957.

4. In much of the Roswell area the choloride concentration in the shallow alluvial aquifer has reached the 1,000-ppm-level. The economic consequences to the area's irrigators are predictable--higher pumping costs and lower yields--whereas the consequences to municipalities and industry could be higher exploration and well-development costs, and higher production costs in their quest for better-quality water.

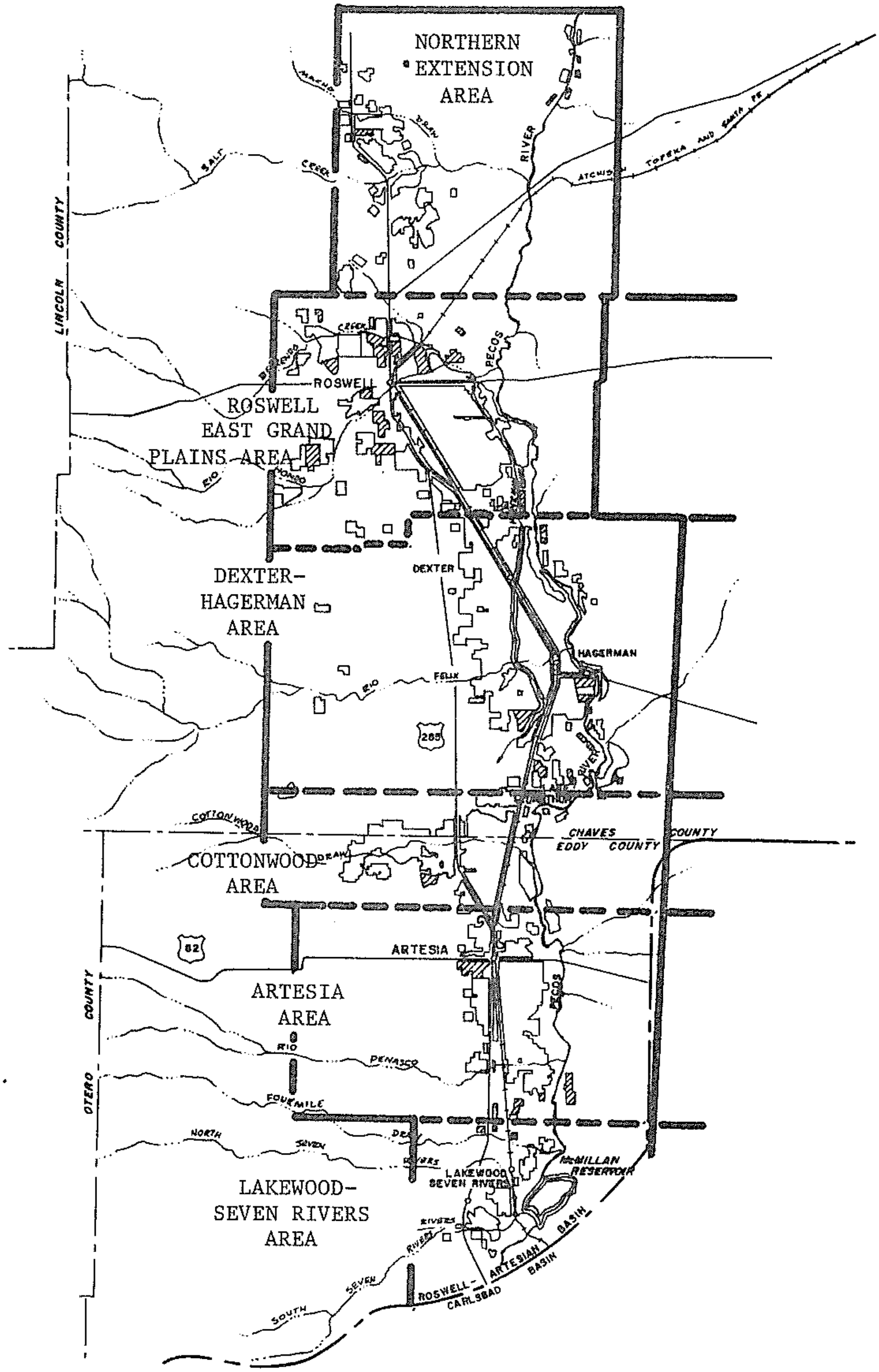

Figure 4. The Roswell Artesian Basin, New Mexico, and its division into sub-basins.

Current Efforts to Mitigate the Problem

Farmers in the Roswell Artesian Basin have been aware of the symptoms of overdraft on the system since the early days of the development of the ground water supply [38, p. 99] and have sought to curtail excessive use. Efforts by the state legislature in 1925 and 1927 to provide administrative controls were challenged in the courts. The first major success in these control efforts was the designation of the area as a ground water basin by the State Engineer Office in 1931, and organization of the Pecos Valley Artesian Conservancy District (PVACD) under a new ground water code. This act provided that "The waters of underground streams, channels, artesian basins, reservoirs or lakes, having reasonable ascertainable boundaries, are ... declared to be public waters ... subject to appropriation for beneficial use." The management of the ground water of the Roswell Basin is now shared by the State Engineer Office and the PVACD.

Although continued development of the artesian aquifer was then restricted, accelerated depletion of the reserves of the system occurred in the late 1930s because of increased irrigation from wells tapping the shallow aquifer. To guard against further overappropriation of the supply, the appropriation of water from the shallow zone was restricted in 1937 by the State Engineer Office.

There have been a number of major investigations of the situation, causing Hantush [7, p. 3] to comment, in his excellent analysis of the geohydrology of the system, that "the geology and ground water conditions in the Roswell Basin have been studied more than those of any other large area in New Mexico." Following is a summary of the principal efforts of the past fifteen years by the State Engineer Office and PVACD to limit the overdraft on the supply:

1. Institution of a hydrographic survey in the mid-1950s in order to locate all wells (other than domestic) and to map the irrigated lands for adjudication.

2. Initiation of PVACD-sponsored studies of the ground water system and agricultural practices, aimed at finding more efficient means of using the available supply and of increasing crop yields.

3. Initiation of programs to aid farmers by lining ditches and reservoirs.

4. Initiation of a program to retire water-rights in the area by PVACD purchase.

5. Initiation of technical investigations by the State Engineer and the U. S. Geological Survey [22, 40, 31].

6. Initiation of an adjudication suit to determine the extent of valid ground water-rights. This suit resulted in (a)the retirement of 12,000 acres of illegal irrigation; (b) the requirement for meters on all wells by January 1, 1967; (c) the requirement that annual individual withdrawals be reported; and (d) the establishment of a duty of three acre-feet per acre per year, averaged over a period of five consecutive years [42].

Adjudication of the Roswell Artesian Basin has broad implications in the management of the water resources of the entire Pecos River system in New Mexico. It should be acknowledged that this is the first of a series of steps needed to bring the basin into hydrologic balance. Next, in all likelihood, will be the retirement of a portion of ground water-rights. Decisions must be made on how much land and which lands are to be taken out of production. Farm efficiences and irrigation techniques must be improved as less water will be available for "salt flushing" as it should be anticipated that ground water quality will continue to deteriorate for some time before remedial measures become effective.

Will Current Efforts Be Sufficient?

Success of current efforts in returning the system to a hydrologic balance will depend on the extent to which each of these programs is pursued and on the success of the individual programs. Other factors are the demand for agricultural products in the United States during the next few decades, and the relative economic position of the farmers in the Roswell Basin in supplying a part of this demand. It is generally accepted that an imbalance continues: 120,000 acre-feet per year during 1960-1964 [27, p. 50], but somewhat less in 1967 (66,000 acre-feet) and 1968 (38,000 acre-feet) because of less pumpage and because of above-average rainfall. It has been estimated that at least 35 percent of the acreage irrigated in the basin (46,000 out of 128,245 acres when a duty of three acre-feet per acre is assumed) must be retired from production in order to limit withdrawals to balance recharge and discharge from the system [27, p. 51]. Sufficiency of the current efforts is put in doubt in view of Spiegel's 1967 conclusion [40, p. 12] that "if the withdrawal of ground water were to continue at the present rate and with the present distribution of wells, all types of quality deterioration would continue until all of the wells in the basin would be invaded by saline water...."

Possible Alternative Actions

A number of the studies of problems of the basin conducted during the past 15 years have yielded various recommended courses of action [7, 22, 40, 27]. A compilation of the most likely methods of achieving a hydrologic and salt-fresh water balance in the basin is given in the sections that follow, along with a brief discussion of the assumptions and limitations associated with each.

It is important to recognize that hydrologic equilibrium, or a balance between total recharge and total discharge from the aquifer system, can be achieved at various levels and distributions of artificial withdrawals. Each combination of levels and distribution of withdrawals will yield a particular configuration of fresh-water reservoir and saline-water interface.

The Null Hypothesis

If one believes that there must be some direct action to limit withdrawals from the faltering supply, then the null hypothesis would be that nothing be done to correct the situation for the system will "right" itself, given time. Labeled as the "laissez-faire" approach by Spiegel [40, p. 31], the basic concept (and a correct one) is that continued overdrafts on the system will lead to progressively greater pumping lifts and poorer-quality water to the point that irrigation from wells in the worst-affected areas will decline as it becomes progressively less profitable to farm these areas. Eventually sufficient lands would be taken out of production for a new hydrologic equilibrium to be attained, checking the continued salt water deterioration of the supply to the remaining wells. Spiegel's conclusion [40, p. 29] that "many (but not all) wells in the basin could then pump fresh water indefinitely" is probably accurate, although some degradation in quality might occur in almost all wells if this method is followed, as "nearly all wells in the basin would eventually be invaded vertically, or laterally, or both" by saline waters [40, p. 35]. The laissez-faire method will eventually result in a reduction of withdrawals from storage as the Pecos Valley irrigators are not insensitive to the economic consequences of the overdraft--that is, declining ground water levels, increased pumping costs, new capital investment for power supplies and pumping units, reductions in crop yields per acre-foot of water applied. These economic factors will have the effect of reducing many efficient farm units to a marginal operation and, if the effects are prolonged, then to defunct units. This will lead to a reduction in the demands on the water supply, but this type of depletion control will have the overall effect of reducing the net productivity and overall efficiency of use of the basin's water resources. Although this is a "market place" method of limiting withdrawals from storage, it is extremely unlikely that it will result in optimal management of the water supply.

Increasing the Recharge to the System

The possibility of increasing the annual recharge to the basin's ground water system is not a new idea; it has attracted sufficient interest to have merited study by Hantush [7], Hood [22, pp. 45-46], and Bean and Theis [1, 43]. The possible use of the long-abandoned, off-stream Hondo Reservoir as a potential recharge site has been considered in all three of these reports as the old Hondo dam is located on a natural sink in the highly permeable gypsiferous limestones of the Six-Mile Hill structure [1, p. 1] that freely allows water entering the reservoir to escape into the San Andres formation. Theis [43, p. 35] concluded that "the diversion of water underground through the Hondo Reservoir would not furnish encouragement for increased use of artesian water for irrigation" because the amount of water available for diversion into the reservoir is quite small, except during years of unusual flood-flows. In noting Theis's findings, Hantush [17, p. 103] adds that, while streams other than the Hondo will yield even less potential recharge, "the total effect of all the waters that could be impounded in the different areas may be significant," but he questions the economic feasibility of constructing a system of impoundments for recharge. Spiegel [40, p. 31] reinforces this conclusion by stating that "as the amount of water available for artificial recharge in the Pecos River Basin is relatively small, there is no hope of achieving steady-state conditions by recharge alone."

Increasing the Available Supply Through Water Salvage

Current and ongoing water salvage programs have been described in Chapter 1. Another version of this same program is the proposed installation of wells in the shallow alluvium along the Pecos River channel, particularly in those areas where large amounts of seepage are lost to the river from the shallow aquifer. Hantush [17, pp. 100-102] discusses the best location and the best possible value of these wells in recovering water now dissipated by evaporation and consumptive use by phreatophyte growth. Under such a program no new water-rights would be awarded, with the new wells to be based on transfers of the point of diversion from existing, less favorably situated wells in the basin. To be effective, the program would have to be carried out by an organization such as the PVACD or by a state or Federal agency. It may be necessary to install major well fields along the river and to distribute water to farm units via pipeline or canal.

More efficient farm use of water in temporary storage or in transit from the individual well to the farm fields and the application of irrigation waters on the field has received deserved attention in 1969 by Hanson [16] and by Lansford and others [28]. The importance of improving farm efficiencies is underscored by Hanson's conclusion [16, p. 27] that "differences in water management practices on individual farms were the major controlling influence on water use throughout the basin."

Increased Production from Wells Yielding Saline Waters

Before the development of wells in the Roswell Artesian Basin, springs and natural lakes acted as the points of discharge for both fresh and the more saline waters in the confined aquifer system. The route of discharge of these saline waters is now partly via irrigation wells pumping from the artesian aquifer. Spiegel notes [40, pp. 29-30] that although "some of the wells, especially those producing water from near the bottom of the San Andres formation and those located near the fresh-saline water interface, would produce water of marginal quality ... the continued production of a moderate amount of saline water locally should be considered as a necessity in attaining hydraulic and salinity equilibrium for the basin." Hood, *et al.* [22, pp. 43-45] discusses the concept in detail, assigning a figure of 15 to 20 cfs as the approximate magnitude of the original natural discharge of saline water between the mouth of Salt Creek and the Bottomless Lakes. Pumping of wells to produce salt water would have to be at or near this rate and would have to be a continuing process. Disposal of the saline waters produced from a well field for this purpose would constitute a major problem, but possibly some use could be made of this water.

Methods of Reducing the Draft on the Ground Water Supply

There is little doubt that there should be a major effort to retire some of the farm lands in the basin and to severely limit production from the artesian aquifer in critical areas. A number of alternatives are available to administrative agencies, both state and local, that are faced with problems of regulating and allocating the waters of the Roswell Basin subject to changes in existing legal constraints. These alternatives include one or more of the following:

1. Retire those farm lands developed after a given date.

2. Retire a given percentage of the irrigated lands of each farm unit.

3. Retire water-rights in the basin by random selection.

4. Retire the water-rights on strategically located lands irrigated from a particular aquifer, or part of an aquifer.

5. Retire water-rights on farming units that have productivities below certain levels for various crops or cropping patterns.

6. Reduce the allowable quantity of water applied per acre per year in certain parts of the basin.

7. Offer the opportunity for selective water-right trades on presently irrigated lands in particular areas for lands of either increased or decreased acreage allotments and either increased or decreased duty in other, more favorable parts of the basin.

The Need for a Decision Model

Even if all of the likely remedial programs were initiated, there is no real alternative in one respect: to achieve a hydrologic balance in the basin, the volume of annual withdrawals must be reduced. The question then becomes one of selecting one, or a combination, of the methods listed in the preceding section as a means of limiting the draft on the system. Changes in existing legislation would probably be required to initiate such actions. To the end that public agencies responsibile for the various facets of control, administration, and redevelopment of the basin's water supply must be able to make decisions on policy and investments that will lead to the most economical means of redeveloping the basin, what is needed is a management model that will indicate the optimum method of selecting water-rights for retirement. Here "optimum" is used in the economic sense--that is, what is needed are policy criteria that, if followed, will return the basin's aquifer system to a condition of hydrologic equilibrium and at the same time generate the greatest benefits to the area from the use of available resources for irrigated agriculture.

Questions That Must Be Answered

The scope and complexity of the problem almost demand that solutions be sought within an interdisciplinary framework. Using inputs from the other facets of this project, an effort has been made to provide guidelines through the maze of interrelated questions that must be answered. The analysis attempted to answer the key technical and economic questions listed below:

Technical Questions

1. How much land must be retired from production?

2. Can the same net results be obtained at lower cost, a) if water-rights are retired from farm units representing the acreage that must be withdrawn from production, or b) if all water-rights are reduced by a given percentage, or c) if the duty on water-rights is varied depending on land, water quality, and the crop grown?

3. Should the water-rights to be retired be a) from wells producing from the artesian aquifer and, if so, from what part of the basin, b) from wells producing from the shallow aquifer, c) from wells producing high-quality water, d) from wells producing poor-quality water, or e) a selected combination of a) through d)?

4. What geographical distribution should be achieved in a land retirement program?

5. Must certain specific wells be removed from production in order to achieve a favorable balance between the fresh and salt water zones?

6. Is it already too late to save some lands even if a balanced water budget is achieved?

7. Does the intruding salt water come predominantly from lateral or from vertical leakage, and does it make

any difference?

Economic Questions

1. What are the longterm economic implications of retirement of water-rights now, versus following a laissez-faire policy?

2. What is the best economic policy to follow in achieving a balanced water supply and a stable equilibrium at the fresh-salt water interface?

3. What are the economical trade-offs in facing decisions on conflicting technical requirements of water-right retirement?

Chapter 4

THE PHYSICAL SYSTEM OF THE ROSWELL ARTESIAN BASIN

Delineation of the Ground Water Reservoir

The Roswell Artesian Basin is a part of two hydrologic units [53, p. 390]: (1) the Rio Hondo and its tributaries, and (2) the Pecos River from the U. S. Geological Survey gaging station at Acme to below McMillan Dam and the tributaries that drain this reach, including Rio Felix, Rio Renasco, Cottonwood Creek, Eagle Creek, and North Seven Rivers (see figure 4). These two drainage basins include approximately 5,600 square miles, and in general the boundaries coincide with limits of the recharge zone of the artesian basin, although the ground water reservoir is considered to incorporate a larger area of about 7,000 square miles [1, p. 2].

Hantush [17, p. 15] is careful to make the distinction between the Roswell "ground water reservoir"--that is, the entire recharge area--, and the Roswell "artesian basin"--the zone in which most of the natural and artificial discharge of the reservoir occurs. The limits on the reservoir are the Village of Vaughn on the north, the slopes of the Sacramento Mountains on the west, the Seven Rivers Cuesta on the south, and the base of the High Plains on the east. Hantush [17, p. 16] assigns the bounds of the artesian basin as the area south of the north line of T9S, east of a north-south line through the Village of Hope, north of the south line of T20S, and west of the line of bluffs lying east of the river.

The area declared by the State Engineer to be within the Roswell Artesian Basin is a larger area than that defined by Hantush. The declared basin incorporates an area of 4,280 square miles [27, p. 3].

Irrigated Lands and Their Soils

Most of the area under irrigation lies within 8 to 10 miles of the Pecos along a belt that stretches from about 20 miles north of Roswell to a few miles south of McMillan Dam, a distance of over 80 miles. The irrigated zone of some 500 to 600 square miles is west of the river for the most part and is bounded on the west by the foothills of the Sacramentos. Elevations in the irrigated valley range from 3,300 to 3,500 feet with a west-to-east pitch and a north-to-south slope at a rate of 20 to 40 feet per mile [17, p. 4].

The alluvial valley soils have two predominant sources: erosion materials from the Sacramento Mountains to the west that have been laid down in a number of terraces reshaped by erosion, and the sediments deposited in the flood plains. This latter material is carried down the river by flood flows and is made up of highly calcareous loams and clay loams with a high content of fine sand. These soils are generally low in phosphorus, nitrogen, and organic materials. The farm lands in the basin have been surveyed by Lansford and Garnett [26] and grouped into three classifications based on their relative potential productivity. A detailed description of productivity criteria is given in the appendix to their publication, which is a part of this interdisciplinary study. A summary of their agronomic classification of the Roswell Basin soils is given in table 5, and distribution of these crop lands by farming areas is given in table 6.

Hydrogeology of the Roswell Reservoir

A number of good investigations have dealt with the hydrogeology of the Roswell Basin. Those recommended for review, in that they are concerned principally with the hydrology of the system, are reports by Hantush [17], Hood [22], Spiegel [40], Bean [1], Theis [43], and Maddox [30, 31]. Most of these studies are limited to certain aspects of the hydrogeology, but all are pertinent to the problem.

The fresh waters of the Roswell reservoir are withdrawn from two principal aquifer systems: the semi-confined, highly permeable limestone aquifers of the Permian period, and the free-surface, shallow aquifer that is made up for the most part by Quaternary alluvial valley fill. Water is produced from depths of 10 to 300 feet from the shallow aquifer and 250 to 1,200 feet from the artesian zone. The sequence of beds that are of particular interest in the Roswell Artesian Basin and a summary of their characteristics are given in table 7.

These formations are exposed in their recharge zone to the west of the Pecos in the foothills and east slopes of the Sacramentos; in general the outcrops of the younger beds appear sequentially in the downhill direction to the east. Water in these formations moves

Table 5. Criteria for Economic Classification of Soils of Roswell Artesian Basin, New Mexico.

Group	Soil and Land Characteristics	Agronomic Characteristics
I	Almost-level lands; soils are deep, well drained, medium textured, highly fertile, and easily worked.	Soils have few characteristics that restrict their use for irrigated crops grown in the basin, but structure of the soils in the group may occasionally limit choice of crops; soils have high productive capacity.
II	Lands are on moderately steep slopes, highly susceptible to water and wind erosion, with subsoils of low permeability; soils are underlain by gypsum or calcareous materials, have low moisture-holding capacity, are moderately deep (20-36 inches), have low fertility that is not easily corrected, and are generally medium textured.	Soils have moderate restrictions that narrow the choice of crops, require special management practices that are difficult to effect and to maintain;time of planting, tillage, and/or harvest may be restricted.
III	Steep slopes, highly susceptibile to water and wind erosion; severe effects of past erosion are common. Shallow soils, low moisture-holding capacity, severe sodium or salinity content, and low permeability are typically found. Often underlain by gypsum and other unfavorable accumulations.	Soils have severe limitations that restrict crop choice; careful management required. Conservation practices are difficult to apply and maintain; low productivity in relation to inputs.

Table 6. Acreages of Irrigated Cropland by Soil Productivity Groups, Roswell Artesian Basin, New Mexico, 1967.

Zone	Area	Acreages by Soil Productivity Groups			
		Group I	Group II	Group III	Unreported and Out of Production.
I	Northern Extension	6,233	659	973	2,745
II	Roswell-East Grand Plains	30,640	1,946	830	3,514
III	Dexter-Hagerman	29,988	2,323	6,014	3,235
IV	Cotton-wood	17,758	1,557	1,975	930
	Artesia	15,275	396	1,767	1,072
	Lakewood-Seven Rivers	3,044	406	0	560
Totals		102,938	7,287	11,559	12,056

Source: Garnett, Edwin T., Economic Classification of the Irrigated Cropland in the Roswell Artesian Basin, New Mexico, Master's Thesis, New Mexico State University, 1968.

Table 7. Important geologic formations in the Roswell Artesian Basin, from Acme to McMillan Dam, New Mexico.

System	Formation	Characteristic Components	Formation Constants	Potential Yield	Source of Recharge	Water Quality
Quaternary	Alluvium	Clay, sand, gravel and conglomerate; 12 to 25 miles wide; up to 350 feet thick; distorted in some areas by slumping of underlying Permian beds.	Transmissivity about 10^5 gpd per foot, specific yield 10 to 20 percent.	Up to 2,000 gpm; constitutes the shallow aquifer.	Local precipitation, stream flow; return irrigation; upward leakage from other formations.	Some wells T10S, R24E with chlorine concentration over 1,100 ppm; most wells less than 500 ppm; quality improves with depth in the alluvium and with distance from the river.
Permian	Chalk Bluff-Artesia Group Seven Rivers Formation	The gypsiferous member of the group and the uppermost beds in the group in the artesian basin; present south of Roswell, thickening to the south.	Highly permeable in places, near Major Johnson Springs transmissivity is 5 x 10^7 gpd per foot.	Considered to be a part of the shallow aquifer;some yields greater than 1,000 gpm.	Lateral and vertical leakage both from above and below; some surface recharge.	Good.
	Queen and Grayburg Formations	Beds of redshale gypsum, anhydrite, salts, fine grained sandstone; shales in formation act as confining beds; 0 to 1,000 feet thick.	Relatively impermeable compared with San Andres; lower part of Grayburg more permeable than upper zones.	Up to 2,000 gpm; a part of the artesian aquifer.	Precipitation and surface flow at outcrops, vertical and lateral leakage.	Good in general; higher concentrations of sulfates than San Andres water; over 1,000 ppm sulfates in some wells.
	San Andres Limestone	Principally limestone and dolomites with some limey shale and gypsum; 500 to 1,000 feet thick; top of formation is 400 feet below surface near Pecos River east of Roswell.	Transmissivities ranging from more than 10^6 gpd per foot in the vicinity of Roswell to less than 10^5 near Dexter and Lakewood.	Over 2,000 gpm, the principal artesian aquifer.	Precipitation and surface flow in the outcrop zone; vertical and lateral leakage.	Good in general; deterioration by saline water intrusion by lateral and vertical leakage causes high chloride content in some locations
	Glorieta Sandstone	Bluff coarse-grained, well-sorted; calcareous sandstone; 50 to 100 feet thick.	Low permeability compared with San Andres; only moderately permeable; well cemented.	Up to 700 gpm.	Precipitation and streamflow in the outcrop areas.	Good in the recharge areas; chloride concentration in vicinity of Roswell is greater than 20,000 ppm; one mile east of Pecos River chloride concentration of 141,000 ppm found.
	Yeso	Composite of limestone, sandstone, shale, and gypsum beds; formation is 1,000 to 2,000 feet thick; top of formation about 1,100 feet below surface at Roswell, 1,900 feet below near Pecos River.	Bean [1, p. 8] calls Yeso impervious; Hood [22, p. 12] calls shales impermeable, sandstone and gypsum as having greater permeability.	Up to 125 gpm.	Precipitation and stream flow on outcrops; vertical and lateral flow from adjacent aquifiers.	Suitable for stock use near recharge zone; highly saline in the vicinity of the Pecos River with quality degrading from west to east.

down dip from the recharge zone with the beds canted southeastward at 50 to 60 feet per mile, an incline that is greater than the slope of the land surface [43, p. 16]. Irregularities in both stratigraphy and structure are not unusual; particular units of the Permian period are present in some locations and missing in others, with variations in thickness, permeability, and depth below the surface being the rule rather than the exception.

For the purposes of this study, the Roswell Artesian Basin is assumed to be two aquifer systems, both of varying thickness, separated by a nonuniform, semi-confining layer that permits vertical leakage to occur in both directions between the two formations. Hood [22, p. 17] contributes to this concept by noting that in the area west of Roswell the water table in the Yeso, Glorieta, and San Andres is continuous, although sharp changes in gradient occur at the formation contacts. Hantush [17, p. 15] calls the basin a "continuous hydraulic system" where, although the preserved sequence of the different geologic units is rather poor, the various formations are hydraulically interconnected "above, below, and laterally with one another."

Natural Discharge from the System

Recharge of the artesian aquifer comes from precipitation and stream flow in the outcrop areas of the aquifer's formations. Recharge to the shallow ground water is a little more complicated; local precipitation in the valley area (about 30,000 to 35,000 acre-feet per year), ditch, stream, and canal flows, irrigation-return flow, and upward leakage from lower formations constitute the major sources, with the last three closely related to the volume of water pumped from the semi-confined zones. The volume of irrigation water that returns to the shallow aquifer has been estimated to be 20 to 40 percent of the total volume pumped from both aquifers [17, p. 57];[31, p. 133]. It should also be noted that, at certain times of the year, downward leakage from the shallow aquifer may occur in parts of the basin.

There is minor disagreement as to the magnitude of the recharge to the artesian zones and, consequently, as to the volume of water available for use in the basin. Most investigators rely on a 1933 report by Fiedler and Nye. Their estimates of the recharge to the system differ from those of Hantush [17] by about 10 percent, an acceptable difference when the annual variations in precipitation are considered.

The generally accepted value for the normal recharge to the semi-confined aquifer system is 235,000 acre-feet per year [1, p. 24]; this figure is based partly on estimates of the magnitude of the flow from major springs in the Roswell area that acted as points of natural discharge from the artesian aquifer prior to the development of irrigation wells in the valley. A summary of the approximations of the original flow from these springs, and their location in the basin is given in table 8. Included in this table are Hood's assessment [1, pp. 43-45] of the natural discharge of saline waters from beds that are continguous to the fresh water aquifer and Hantush's 1954 evaluation [17, p. 65] of the seepage losses from the shallow water table to the Pecos River within the Roswell Basin. As these estimates were made by different investigators, some overlap or duplication may exist, but if the local recharge to the shallow zone from precipitation is set at 35,000 acre-feet per year [20], then the predicted total normal annual recharge of 270,000 acre-feet to the two aquifers in the system is reasonably close to the figure obtained by summing the estimates of natural discharge given in table 8.

Hantush [10, pp. 45-59] arrived at his assessment of the average rate of recharge to the artesian zone by computing

$$\text{Recharge} = C\,\overline{R}_n \, . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (1)$$

where $\overline{R}_n$ is obtained from the expression

$$\overline{R}_n = \sum_{i=1}^{k} \frac{2(k+1-i)}{k(k+1)} R_{(n+1-i)} \, . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (2)$$

with the terms in these two equations defined as follows:

$\overline{R}_n$ = the effective average rate of precipitation at the end of the nth year, in inches per year;

k = the number of years that the rainfall of a given year is considered to be effective;

i = an index counter; and

c = a constant that depends on extent of the recharge area and on percentage of effective average rain-

Table 8. Estimated Natural Discharge from the Roswell Artesian Basin, New Mexico.

Source of Discharge	Aquifier	Location	Estimated Flow (cfs)	Estimated Annual Discharge acre-feet
Berrendo Springs	Fresh water, confined zone	Sec. 9, T10S, R24E	65	47,000
North Spring	Fresh water, confined zone	Sec. 26, T10S, R23E	85	61,500
South Spring	Fresh water, confined zone	Sec. 22, T11S, R24E	60	43,500
Salt Springs and Open Surfaces	Saline water, confined zone	Between mouth of Salt Creek and Bottomless Lakes	15-20	11,000-14,500
Seepage Along the Pecos River	Shallow	From north end of valley fill to Lake McMillan	--	116,000

fall that reaches the water table in the recharge area.

Using the average of the annual rainfalls at Roswell and Artesia as an index of the amount of precipitation on the recharge zone, Hantush [17] computed and tested a value of $C = 21{,}000$ for $k = 3$. He concluded that if the average effective precipitation is 10 inches per year, then the normal recharge would be 210,000 acre-feet per year--which compares favorably with Fiedler's and Nye's prediction of 235,000 acre-feet per year to the semi-confined system.

Artificial Discharge from the System

Historical Development

The earliest irrigation rights in the Roswell Basin have been established as dating back to 1876, with approximately a thousand acres under irrigation from surface sources by 1880 [52]. In the 1890s, the Pecos Land and Water Company and other developers of irrigation projects, built a number of dams, diversions, and canals to control and store the waters of the Pecos and its tributaries for use in the Roswell Basin and in the Carlsbad Irrigation District to the south. Floods, leaky reservoirs, and fiscal problems diminished the chances for success of these early efforts, but with the help of the Bureau of Reclamation many of the original structures and project works were rehabilitated during 1910-1940. There were also some classic failures among these early irrigation developments--for example, the Hope project and the Hondo reclamation project.

By the time of the adjudication of surface water-rights of the Pecos in the 1933 Hope Decree [52], the surface supply of the River was completely appropriated for all practical purposes, as little perennial flow was left in the Pecos below Fort Sumner, the approximate midpoint of the system in New Mexico. There was still year-round flow in some of the tributaries entering the Pecos from the west in the Roswell Basin. The lower reaches of these streams derived a part of their source from artesian springs with their flow closely related to the already diminishing ground water resources of the area.

Table 9 summarizes the historical use of surface water resources for irrigation in the basin. Irrigation rights from surface sources below Alamogordo Reservoir are held principally by the Carlsbad and Red Bluff Irrigation Districts with less than 6,000 acres in the Roswell Basin now being irrigated directly from the Pecos and its tributaries.

Table 9. Historical Development of Surface Water Irrigation in the Roswell Artesian Basin, New Mexico.

Period	Total Acres Irrigated[1]
1876-1890	14,700[2]
1891-1910	16,100[2]
1911-1923	20,800[2]
1965	19,000[3]

[1] All figures rounded to the closest 100 acres.

[2] Source of information through 1923 is the transcripts of the Hope Ditch Decree [52].

[3] Figures for 1965 include 13,500 acres receiving supplemental irrigation water from wells.

Wells were drilled to tap the artesian flow of the semi-confined zone as early as 1891, with large-scale development of the artesian aquifer coming after 1900. Almost 500 flowing wells, with capacities ranging from 500 to 1,500 gallons per minute, had been drilled by the end of 1905 with "no noticeable diminution in pressure except near Artesia" [50]. Most of the artesian wells in the basin were drilled during the next 10 years and the effect of these withdrawals was evident by 1915 in the diminished flow from some of the wells and springs [38, p. 99]. By the middle 1920s almost one-third of the artesian wells were no longer flowing. Table 10 summarizes the development of wells in the artesian zone in the early years.

The rapid development of artesian wells in the valley, waste of the supply by leaking wells, and the failing artesian flow in parts of the basin made the need for control apparent. As pressure in the artesian formations diminished and pumping became necessary, interest in the shallow water supply was shown by the rapid development

Table 10. Historical Development of Artesian Wells in the Roswell Artesian Basin, New Mexico, to 1927.

	Prior to 1901	1901-1905	1906-1910	1911-1915	1916-1920	1921-1925	1926-1927	Totals to 1927
Artesian Wells Drilled	153	332	597	210	22	75	35	1,424
Percent of Total	10.7	23.3	41.9	14.8	1.5	5.3	2.5	100

Source: Special Report on Water Utilization in Chaves and Eddy Counties, New Mexico, U. S. Department of Agriculture, Bureau of Agricultural Economics, June 1942, p. 39.

of irrigation using this source. Only eight shallow wells irrigating about 2,000 acres were reported in 1927 [50, p. 30]; in the next ten years their number had increased to the extent that more than 35,000 additional acres of land had been brought into production, or permitted. Ground water levels in the alluvium began to decline, making it necessary by 1937 to close most of the area in the basin to further appropriation. A summary of the acreage irrigated from ground water supplies between 1938 and 1960 is given in table 11, which includes the estimated volume pumped each year for farm use, from Hale's detailed report on New Mexico's water supply [15].

Present Ground Water Demands

The peak demand on the ground water reservoir occurred during the mid-1950's, but since the initiation of the hydrographic survey and the subsequent adjudication suit, the total irrigated acreage in the basin has stabilized at about 134,000 acres. Table 12 is a summary of the water-rights when there were 962 wells producing from the artesian zone, 668 from the shallow water table, and 94 irrigation wells the source of which was not classified.

Table 11. Estimated Acreage Irrigated from Wells in the Roswell Artesian Basin, New Mexico, 1938-1960.

Year	Acres Irrigated from Ground and from Ground and Surface Water Supplies	Water Pumped
	(1,000 acres)	(1,000 acre-feet)
1938	94.0	278
1939	98.3	294
1940	101.4	291
1941	103.0	168
1942	106.0	314
1943	110.0	341
1944	113.0	316
1945	114.6	376
1946	115.3	346
1947	116.0	386
1948	121.5	376
1949	126.1	358
1950	135.6	362
1951	136.5	443
1952	136.8	413
1953	136.9	429
1954	137.1	437
1955	136.9	416
1956	136.7	460
1957	136.5	449
1958	132.0	351
1959	128.0	416
1960	125.0	391

Source: Hale, W. E., L. J. Reiland, and J. P. Beverage, Characteristics of the Water Supply in New Mexico, New Mexico State Engineer Office Technical Report 31, 1965, table 14.

Table 12. Water-Rights in the Roswell Artesian Basin, New Mexico, March 1965.

AGRICULTURAL

Source of Irrigation Water	Acres
Artesian use only	59,157.84
Shallow use only	39,396.30
Artesian with supplemental shallow	9,365.47
Artesian and unclassified shallow	157.60
Predominantly artesian with some shallow	10,807.73
Artesian supplemental to surface	4,705.05
Shallow supplemental to surface	3,308.20
Surface water only, including drains	5,500.00
Surface with some supplemental well water	5,520.00

OTHER

Type of Rights	(Volume Rights) acre-feet
Municipal	
Roswell	29,252.29[1]
Artesia	7,375.20[1]
Dexter	352.00
Hagerman	1,900.00[1]
Lake Arthur	69.00
Industrial	372.00
Commercial	3,557.00[1]
Total	42,877.49

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[1] Water-rights are in well capacities in most cases and the conversion is on a 100 percent year-round pumping basis.

Additional demands on the supply come from municipal and commercial uses and from the 2,400 domestic and stock wells in the area. Table 13 summarizes the 1968 water uses in the Roswell Artesian Basin in each of its principal districts. Estimates of municipal and commercial pumping have been assigned to each zone on the basis of population of the incorporated communities in the zone.

Safe Yield from the System

Under the safe yield concept discussed below, the amount of water available for use annually from each of the two aquifers would be a function of the amount withdrawn from each and their relative water levels. This situation exists because of the interconnection of the two aquifers and the dependence of the shallow zone on the semi-confined beds for recharge from leakage and from return irrigation waters pumped from the lower zone. Because of this interconnection, diminishing water levels in the shallow aquifer may be the result of excessive artesian pumping; Hantush assigns a part of the decline of the water table in the alluvium in the Roswell area to the heavy demands on the artesian zone in the area [17, p. 74]. These complexities of the system must be taken into account in assessing the safe yield of the ground water reservoir.

Hantush defines "safe yield" as the artificial discharge that will provide long term "continuance of a good potable water supply or for the preservation of the hydrologic system from which the water comes" [17, p. 71]. He has set limits on the safe yield of the basin based on the assumption that necessary changes will be made in the amount and points of diversion of water from the system. The required conditions are that the present distribution of artesian wells be continued, and that the distribution of shallow wells be changed to correspond with the recharge to the zone. His estimates of the safe yields are:

1. Artesian aquifer -- A total safe yield of about 130,000 acre-feet per year, with 60,000 acre-feet available north of T12S and the remainder from the area south of the north line of T12S.

2. Shallow aquifer -- A total of 86,250 acre-feet per year corresponding to the recharge available to the various sections of the basin.

Table 13. Summary of Estimated Water Uses, Roswell Artesian Basin, New Mexico, 1968.

Zone	Area	Irrigated Agriculture Surface Water	Shallow Ground Water	Artesian Ground Water	Water-Right Acres	Municipal and Industrial Use
		(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acres)	(1,000 acre-feet)
1	Northern Extension	0.3	0.8	17.0	10.8	--
2	Roswell-East Grand Plains	0.3	24.2	63.4	37.4	11.3
3	Dexter-Hagerman	19.3	44.7	36.9	40.1	0.5
4	Cottonwood	2.5	19.1	42.6	22.7	--
	Artesia	--	19.0	33.6	19.0	3.4
	Lakewood--Seven Rivers	--	6.3	4.9	4.0	--
	Total	22.4	114.1	198.4	134.0	15.2

Source: Lansford, Robert R., et al., Irrigation Water Requirements for Crop Production in the Roswell Artesian Basin, New Mexico, New Mexico Water Resources Research Institute, Report 5, 1969, p. 8.

Magnitude of the Overdraft on the System

With few exceptions, there is some concurrence as to the normal recharge to the system, but disagreement as to the magnitude of the overdraft on the basin's supply. A part of the controversy in estimating the oberdraft concerns the amount of water actually consumed in irrigated agriculture and, consequently, the amount of water pumped for these uses that returns to the ground water system so that it may be recycled. Using figures available in the literature, Lansford, et al. [27, p. 51], utilized a consumptive use of 61 percent of the water pumped. This corresponds to Maddox's use of 40 percent irrigation return flow [31, p. 133], but is far different from Hantush's appraisal of 20 percent [17, p. 57].

The differences in opinion have led to varying estimates of the amount of land that must be removed from production to bring about a balanced system. In 1942 when little more than 100,000 acres were under irrigation, a U. S. Department of Agriculture study [50, p. 11] found that recharge and withdrawals from the semi-confined zones were sufficiently stable to permit indefinite use "without serious depletions" and that, although declines in the shallow ground water table had been noted in areas where demand exceeded the supply, the rate of drawdown would be "too slow to cause serious concern for a long time." Unfortunately the accuracy of this prediction cannot be checked because an additional 35,000 acres were subsequently put into cultivation.

Hantush [17, p. 100] found an excess use of about 128,250 acre-feet for 1950-1956. This is apparently considerably more than Hood's estimate of an imbalance of 13,000 acre-feet per year in the artesian supply in the two townships near Roswell where about 40 percent of the irrigation from the semi-confined zone takes place. In 1969, Hennighausen [20] reported the overdraft to be about 120,000 acre-feet per year, while Lansford, et al. [27, p. 51] assigns this overage to a period when the use rate was 3.48 acre-feet per acre. Lansford, et al. set the excess acreage at 46,000 acres when the duty is three acre-feet per acre. They set the excess water-use at 85,000 acre-feet per year. On the basis of this estimate, returning the basin to a hydrologic balance would mean reducing the cultivated acreage to pre-1938 levels.

Chapter 5

ANALYTICAL STUDIES

Basic Data

In an effort to answer the technical and economic questions posed at the end of Chapter 3, a number of varied analytical studies have been conducted. The basic information for these came mainly from the other investigations in this inter-disciplinary project. Some liberties have been taken in the generalization and further modification of the other researchers' findings, occasionally without sufficient respect for the assumptions and conditions of their derivation. This latitude should be kept in mind for the interpretation of the analyses reported. The intent is to formulate general policy, rather than to establish specific values.

Economic Data

There were two economic analyses employing related but different measures of the benefits derived from applying a particular volume of water of a given quality to a particular crop grown on a given soil type. The first evaluation is monetary: the "net benefits returned per acre to land and management." These figures, shown in table 14, are, with minor modifications, the values derived by Lansford and Garnett [26] in the agronomic section of this study. The values represent the yield obtained by the average individual farmer from a crop irrigated under specific conditions, and are the gross returns less the variable and fixed costs of farming.

The second evaluation was made using the data in table 15: the "value added" to water by its use for agriculture. These figures, prepared by Ralph d'Arge, represent the economic worth to the region--the local benefits achieved through use of a natural resource. They reflect secondary benefits or induced income that may be generated from particular crops, and consequently these values are greater than the "net benefits" and thus negative values appear much less frequently.

Soil and Water Quality

Although water quantity is the limiting factor in the Pecos Basin, there are constraints on the availability of lands with good soil and water quality. Lansford and Garnett [26] provide the basic soil quality information for the Roswell Basin, shown in table 6,

Table 14. Net return per acre to land and management for various crops, soil groups, and water qualities, for varying levels of irrigation water application in the Roswell Artesian Basin, New Mexico.

Soil Group	Water Pumped Per Acre (inches)	Water Quality as Electrical Conductivity 10^3 MICROMHOS							
		0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
					COTTON				
I	45	285.72	285.72	285.72	277.92	242.78	176.42	113.96	51.50
II	45	240.92	240.92	240.92	234.10	203.35	145.29	90.64	36.41
III	45	192.13	192.13	192.13	186.28	159.93	110.16	63.31	16.47
I	36	251.18	251.18	251.18	231.67	169.21	95.04	28.68	-41.59
II	36	207.27	207.27	207.27	190.19	135.54	70.64	12.58	-48.90
III	36	163.35	163.35	163.35	148.71	101.87	46.24	-3.53	-56.22
I	27	197.13	197.13	189.33	154.19	60.50	-25.37		
II	27	160.53	160.53	153.71	122.96	41.41	-34.15		
III	27	130.69	130.69	118.08	91.74	21.47	-42.94		
I	18	104.04	96.24	72.81	-9.17				
II	18	79.64	72.81	52.32	-19.42				
III	18	55.24	49.39	31.82	-28.66				
					BARLEY				
I	27	32.44	32.44	32.44	31.76	28.10	20.20	12.21	-5.81
II	27	15.44	15.44	15.44	14.89	12.12	6.05	-0.03	-13.84
III	27	0.01	0.01	0.01	0.01	-3.86	-8.06	-12.09	-21.83
I	18	22.04	22.04	21.36	18.47	9.80	-9.75	-28.54	
II	18	8.44	8.44	7.89	5.68	-0.95	-15.87	-30.24	
III	18	-5.16	-5.16	-5.54	-7.07	-11.66	-21.99	-31.94	
I	13	9.62	9.62	7.49	1.71	-15.63			
II	13	-0.58	-0.58	-2.24	-6.66	-19.92			
III	13	-10.78	-10.78	-11.93	-14.99	-24.17			

Table 14. Net return per acre to land and management for various crops, soil groups, and water qualities, for varying levels of irrigation water application in the Roswell Artesian Basin, New Mexico (continued).

Soil Group	Water Pumped Per Acre (inches)	Water Quality as Electrical Conductivity 10^3 MICROMHOS							
		0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
					ALFALFA				
I	88	160.61	127.09	85.84	44.59	-14.72			
II	88	125.45	96.62	60.99	25.36	-25.97			
III	88	53.12	39.37	14.34	-10.74	-39.57			
I	80	141.00	102.33	55.92	12.08	-47.22			
II	80	109.13	75.61	35.47	-2.21	-53.55			
III	80	49.35	25.68	0.03	-29.17	-65.27			
I	72	118.73	72.41	23.42	-22.09				
II	72	109.44	44.39	8.23	-32.13				
III	72	37.25	8.89	-20.88	-48.54				
I	64	94.15	42.49	-11.67					
II	64	69.45	24.91	-21.97					
III	64	22.91	-7.91	-40.96					
I	56	69.30	9.99						
II	56	48.67	-2.67						
III	56	9.76	-26.34						
					GRAIN SORGHUM				
I	39	68.79	65.95	54.60	37.57	-12.03	-13.51		
II	39	46.68	44.29	34.70	20.33	-1.23	-22.79		
III	39	26.71	24.72	16.73	4.75	-13.22	-31.18		
I	36	69.25	65.00	53.64	33.77	-6.81	-28.66		
II	36	47.36	43.77	34.19	17.41	-5.35	-35.30		
III	36	27.60	24.60	16.61	2.64	-16.32	-41.28		
I	27	46.52	39.42	16.72	-4.57	-38.62			
II	27	28.83	22.84	3.67	-14.29	-43.04			
III	27	12.86	7.87	-8.10	-23.07	-47.04			
I	18	-21.62	-37.23						
II	18	-28.03	-41.21						
III	18	-33.82	-44.80						

Table 14. Net return per acre to land and management for various crops, soil groups, and water qualities, for varying levels of irrigation water application in the Roswell Artesian Basin, New Mexico (continued).

Soil Group	Water Pumped Per Acre (inches)	Water Quality as Electrical Conductivity 10^3 MICROMHOS							
		0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
					SILAGE				
I	42	69.45	58.95	25.45	-35.05				
II	42	49.95	44.95	14.95	-39.05				
III	42	38.95	34.45	6.95	-42.05				
I	36	53.27	44.77	-12.33					
II	36	39.77	32.77	-18.73					
III	36	30.27	23.27	-23.23					
I	27	20.00	3.00						
II	27	10.50	-4.50						
III	27	4.00	-10.00						
I	18	-17.77							
II	18	-22.77							
III	18	-26.27							

Table 15. Value-added to water per acre, irrigated at stated levels for various crops, soil groups, and water qualities, Roswell Artesian Basin, New Mexico.

Soil Group	Water Applied Per Acre (inches)	Water Quality as Electrical Conductivity 10^3 MICROMHOS 0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
					COTTON				
I	45	388.53	388.53	388.53	380.51	344.36	276.08	211.82	147.36
II	45	341.94	341.94	341.94	314.92	303.26	243.48	187.21	131.37
III	45	291.87	291.87	291.87	285.85	258.70	207.41	159.14	110.88
I	36	352.67	352.67	352.67	333.32	268.34	192.03	123.76	51.46
II	36	307.85	307.85	307.85	291.27	234.00	167.18	107.39	42.77
III	36	262.85	262.85	262.85	247.76	199.50	142.18	90.90	36.60
I	27	296.75	296.75	288.73	251.94	156.19	67.84		
II	27	259.42	259.42	252.40	220.74	136.76	58.98		
III	27	228.74	228.74	215.95	188.81	116.41	50.04		
I	18	200.63	192.61	168.50	84.16				
II	18	175.84	168.81	147.71	73.85				
III	18	150.95	144.86	126.82	64.47				
					BARLEY				
I	27	66.12	66.12	66.12	65.43	61.69	53.63	45.48	27.10
II	27	48.65	48.65	48.65	48.08	45.27	39.06	32.85	18.77
III	27	31.38	31.38	31.38	30.99	29.03	24.74	20.60	10.67
I	18	54.88	54.88	54.18	51.24	42.39	22.45	3.28	
II	18	40.94	40.94	40.38	38.12	31.26	16.12	1.43	
III	18	27.14	27.14	26.75	25.19	20.50	9.95	0.52	
I	13	41.90	41.90	39.72	33.83	16.14			
II	13	31.46	31.46	29.76	25.25	11.71			
III	13	21.11	21.11	19.94	16.81	7.43			

Table 15. Value-added to water per acre, irrigated at stated levels for various crops, soil groups, and water qualities, Roswell Artesian Basin, New Mexico (continued).

Soil Group	Water Applied Per Acre (inches)	Water Quality as Electrical Conductivity 10^3 MICROMHOS							
		0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
					ALFALFA				
I	88	230.64	195.27	151.73	108.18	45.59			
II	88	191.94	161.69	124.30	86.92	33.06			
III	88	118.74	102.09	75.72	49.30	18.94			
I	80	208.99	168.18	119.19	48.77	10.34			
II	80	173.86	138.70	96.60	57.04	3.18			
III	80	111.65	86.72	59.59	28.96	-9.06			
I	72	184.56	135.64	83.94	35.85				
II	72	173.24	106.80	67.04	24.70				
III	72	97.97	68.11	36.76	7.63				
I	64	157.62	103.10	86.28					
II	64	130.35	83.61	34.43					
III	64	82.79	49.48	14.68					
I	56	130.44	47.86						
II	56	107.60	53.73						
III	56	67.15	29.14						
					GRAIN SORGHUM				
I	39	104.80	101.94	90.47	73.26	47.46	21.65		
II	39	82.66	80.24	70.55	56.03	34.23	12.44		
III	39	62.66	60.64	52.57	40.44	19.18	4.12		
I	36	105.04	100.74	89.26	69.19	41.73	6.11		
II	36	83.10	79.47	69.79	52.83	29.82	-0.45		
III	36	63.31	60.27	52.19	38.07	18.89	-4.35		
I	27	81.52	74.35	51.42	29.91	-4.50			
II	27	63.83	57.78	38.40	20.29	-8.78			
III	27	47.87	42.82	26.67	11.53	-12.71			
I	18	12.14	-3.63						
II	18	5.85	-7.39						
III	18	0.12	-10.89						

Table 15. Value-added to water per acre, irrigated at stated levels for various crops, soil groups, and water qualities, Roswell Artesian Basin, New Mexico (continued).

Soil Group	Water Applied Per Acre (inches)	Water Quality as Electrical Conductivity 10^3 MICROMHOS							
		0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
					SILAGE				
I	42	90.01	79.51	46.01	-14.49				
II	42	70.51	65.51	35.51	-18.49				
III	42	59.51	44.01	27.51	-21.49				
I	36	73.51	65.01	7.91					
II	36	60.01	53.01	1.51					
III	36	50.51	43.21	-2.99					
I	27	39.74	22.74						
II	27	30.24	15.24						
III	27	23.74	9.74						
I	18	26.41							
II	18	-3.82							
III	18	-7.32							

with the acreage of each type given by sub-zones. In his master's thesis [13] Garnett offered maps of water quality contours, expressed in ppm of chlorides. The acreage for each soil type for various water qualities as used in this study was obtained from enlargements of Garnett's maps. Conversion of chlorides from parts per million to conductivity is, according to the agronomic group,

$$EC = 2,437 + 2.8\ Cl. \qquad (3)$$

where EC is the electrical conductivity in micromhos and Cl is the chloride concentration in parts per million.

The contours on Garnett's maps do not show water qualities of fewer than 500 ppm chlorides--or about 3.8×10^3 micromhos. Changes in net benefits and in value added are available for values of conductivity of 0.75, 1.50, 2.25, and 3.00 micromhos x 10^3, all representing lower concentrations of salinity than those available on Garnett's maps. The chloride concentration in individual wells within the 500-ppm-contour ranges from fewer than 100 ppm to 500 ppm, with no regular pattern apparent. For the purposes of the analytical studies, the acreage in each soil class within the 500-ppm contour was arbitrarily assigned in equal parts to waters with electrical conductivities of 0.75, 1.50, 2.25 and 3.00 micromhos x 10^3. Table 16 divides into basic subzones the maximum acreage available of lands of a given soil group and water quality. Table 17 shows the index system used in the analysis in reference to various soil groups and water qualities.

Water Availability Data

In order to compute the proposed analyses it was necessary to assign limits to the average amount of water that may be withdrawn each year from each of the basin's two aquifer systems in each of the geographic subunits, while maintaining a hydrologic balance that allows a minimum natural discharge of 70,000 acre-feet per year [17, p. 74]. Hantush's estimates [17] of safe yield from the Roswell reservoir were extended to cover three possible levels of availability for three different magnitudes of the irrigation return flow to the shallow zone--that is, calculations were made where it was assumed that 20, 30, or 40 percent of the water pumped from the system might be used again. Results of the calculations are presented in table 18 as follows:

Columns 1 and 2 designate the zones and geographic subdivisions of the basin (see figure 4);

Table 16. Maximum acres of irrigated land available in each zone, by soil group and water quality, Roswell Artesian Basin, New Mexico.

		Acres of Farm Land							
		Electrical Conductivity in Micromhos x 10^3							
Zone	Soil Group	0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
1	I	-	-	-	-	1,100	1,100	4,850	1,350
	II	-	-	-	-	350	350	-	200
	III	-	-	-	-	100	100	100	1,000
2	I	5,075	5,075	5,075	5,075	1,700	1,700	2,400	7,800
	II	50	50	50	50	650	650	300	300
	III	75	75	75	75	250	250	100	-
3	I	6,000	6,000	6,000	6,000	1,400	1,400	2,550	3,150
	II	150	150	150	150	350	350	400	900
	III	500	500	500	500	800	800	1,300	1,600
4	I	9,050	9,050	9,050	9,050	650	650	-	-
	II	625	625	625	625	-	-	-	-
	III	750	750	750	750	450	450	-	-

Table 17. Indexing system used in referring to combinations of soil group and water quality, Roswell Artesian Basin, New Mexico.

	Water Quality As Electrical Conductivity in Micromhos x 10^3							
Soil Group	0.75	1.50	2.25	3.00	4.00	5.00	6.00	7.00
I	11	12	13	14	15	16	17	18
II	21	22	23	24	25	26	27	28
III	31	32	33	34	35	36	37	38

Table 18. Estimates of normal recharge and safe yield of aquifier system, Roswell Artesian Basin, New Mexico, by geographic zones.

											Shallow Aquifier			
											Unrecoverable Seepage Losses			
(Col. 1) Zone	(Col. 2) Geographic Location	(Col. 3) Safe Yield Semi-confined Aquifier	(Col. 4) Upward Leakage into Shallow Aquifier	(Col. 5) Area for Recharge to Shallow Zone by Precipitation	(Col. 6) Surface Water Irrigation	Estimated Irrigation Return Flow to Shallow Aquifier	(Col. 7) Recharge by Upward Leakage	(Col. 8) Recharge by Local Precipitation	(Col. 9) Recharge by Irrigation Return Flow from Surface and Artesian Sources	(Col. 10) Total Base Recharge to Shallow Zone	(Col. 11) Percent of Total	(Col. 12) Thousands of Acre-Feet.	(Col. 13) Safe Yield Available from Shallow Aquifier	(Col. 14) Total Annual Safe Yield for Irrigated Agriculture in the Zone
		(1,000 acre-feet)	(percent)	(percent)	(1,000 acre-feet)	(percent)	(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acre-feet)			(1,000 acre-feet)	(1,000 acre-feet)
1	Northern Extension (Does not have a shallow zone as such)	8	-	-	0.7	20	-	-	1.6	1.6	-	-	2.0	10.0
						30	-	-	2.4	2.4	-	-	3.4	11.4
						40	-	-	3.2	3.2	-	-	5.3	13.3
2	Roswell-East Grand Plains	52	55.8	24	0.3	20	44.5	7.0	10.4	61.9	40	28	42.4	88.8
						30	44.5	7.0	15.6	67.1	40	28	55.9	102.3
						40	44.5	7.0	20.8	72.3	40	28	74.0	120.4
3	Dexter-Hagerman	29	18.2	30	19.3	20	14.5	9.0	9.7	33.2	30	21	15.3	44.0
						30	14.5	9.0	14.5	38.0	30	21	24.3	53.0
						40	14.5	9.0	19.3	42.8	30	21	36.4	65.1
4	Cottonwood, Artesia, Lakewood-Seven Rivers	41	26.0	46	2.5	20	21.0	14.0	8.9	43.9	30	21	28.6	67.9
						30	21.0	14.0	13.3	48.3	30	21	39.0	78.3
						40	21.0	14.0	17.8	51.8	30	21	51.3	90.6
	Total	130	100	100	22.4	20	80.0	30.0	30.6	140.6	100	70	88.3	210.7
						30	80.0	30.0	45.8	155.8	100	70	122.5	245.0
						40	80.0	30.0	61.1	170.1	100	70	167.0	289.4

Column 3 is an extension, based on land area, of Hantush's estimates of safe yield from the artesian aquifer [17, pp. 72-73];

Column 4 is a modification of table 15 from Hantush [17] to coincide with geographic boundaries of the zones;

Column 5 lists estimated distribution of the area of the shallow aquifer in each zone (note that there is none, as such, in the northern extension);

Column 6 presents data from table 3 of Lansford, _et_ _al_. [27];

Column 7 multiplies the figures of Column 4 by the total estimated upward leakage;

Column 8 multiplies the figures of Column 5 by the estimated recharge from this source;

Column 9 multiplies the figures of Columns 3 and 6 by the 20, 30 and 40 percent irrigation return flow (note that values for this flow are included for Zone 1 even though it has no alluvial aquifer);

Column 10 is a summation of Columns 7, 8, and 9;

Columns 11 and 12 are a modification of Hantush's distribution of seepage [17, pp. 64-65] to fit the geographic zones, retaining a minimum natural discharge of 70,000 acre-feet from the shallow aquifer;

Column 13 subtracts Column 12 from Column 10, dividing the remainder by 0.60, 0.70 and 0.80 to correspond to irrigation return flows of 40, 30, and 20 percent; and

Column 14 offers the sums of Columns 3 and 13, less one-half of the municipal and commercial uses of table 13.

The three different estimates have been computed because it is far from clear which prediction of the percent of irrigation return flow is correct. The original safe-yield approximations made by Hantush [17, p. 73] were based on a 20 percent deep-seepage loss, a figure he reached in "studies of percolation losses in other areas having soils of the same general characteristics and growing crops of the same type" as those in the Roswell Basin [17, p. 57]. Maddox [31, p. 133] does not expand on his choice of 40 percent. Blaney and Hanson [5, table 8] give ranges for the loss of irrigation waters based on soil type: 5 to 15 percent of the volume diverted that never reaches the farm fields, 5 to 25 percent that is lost to surface runoff, and 10 to 35 percent lost to deep percolation. These last two are combined to obtain the field irrigation efficiency that has been related to consumptive use by the equation

$$E = \frac{U - R}{I} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where E is the field irrigation efficiency in percent: I is the field irrigation requirement in inches; R is the effective rainfall in inches; and U is the consumptive use in inches.

In a 1963 study of the Artesia area, Blaney and Hanson [5, p. 33] assumed field irrigation efficiencies of 60 and 70 percent in calculating consumptive use requirements. This would suggest that the amount of water applied to fields that would be returned to the ground water system by deep percolation would be 30 to 40 percent. To test the validity of any assumption based on return flow greater than 20 percent, a stepped calculation similar to that in table 18 was made for each year from 1944-1954 for 20, 30, and 40 percent returns, with the cumulative depletions from storage for each given in figure 5. The starting point used was 1944 because the basins water table was essentially unchanged in 1943, whereas water levels have continuously declined since then.

Hantush estimated the volume withdrawn from storage in the shallow zone between 1944 and 1953 to be 1.119 million acre-feet, with changes in storage in the intake area of the artesian zone of 0.457 million acre-feet during the same period. These depletions correspond to a return flow of 20 to 30 percent. A rough check was also made, assuming an area of 400 square miles for the shallow zone, a specific yield of 20 percent [17, p. 28], and an average drawdown in water levels of 20 feet between 1944-1954. This yields a depletion of a little over a million acre-feet for the shallow zone. When depletions from storage in the intake area of the artesian zone are added, a total depletion of about 1.5 million acre-feet is obtained--approximately that for a 30 percent return flow. In summary, estimates for three levels of flow are presented, with the middleground of 30 percent probably closer to the actual average for the basin than is 40 percent.

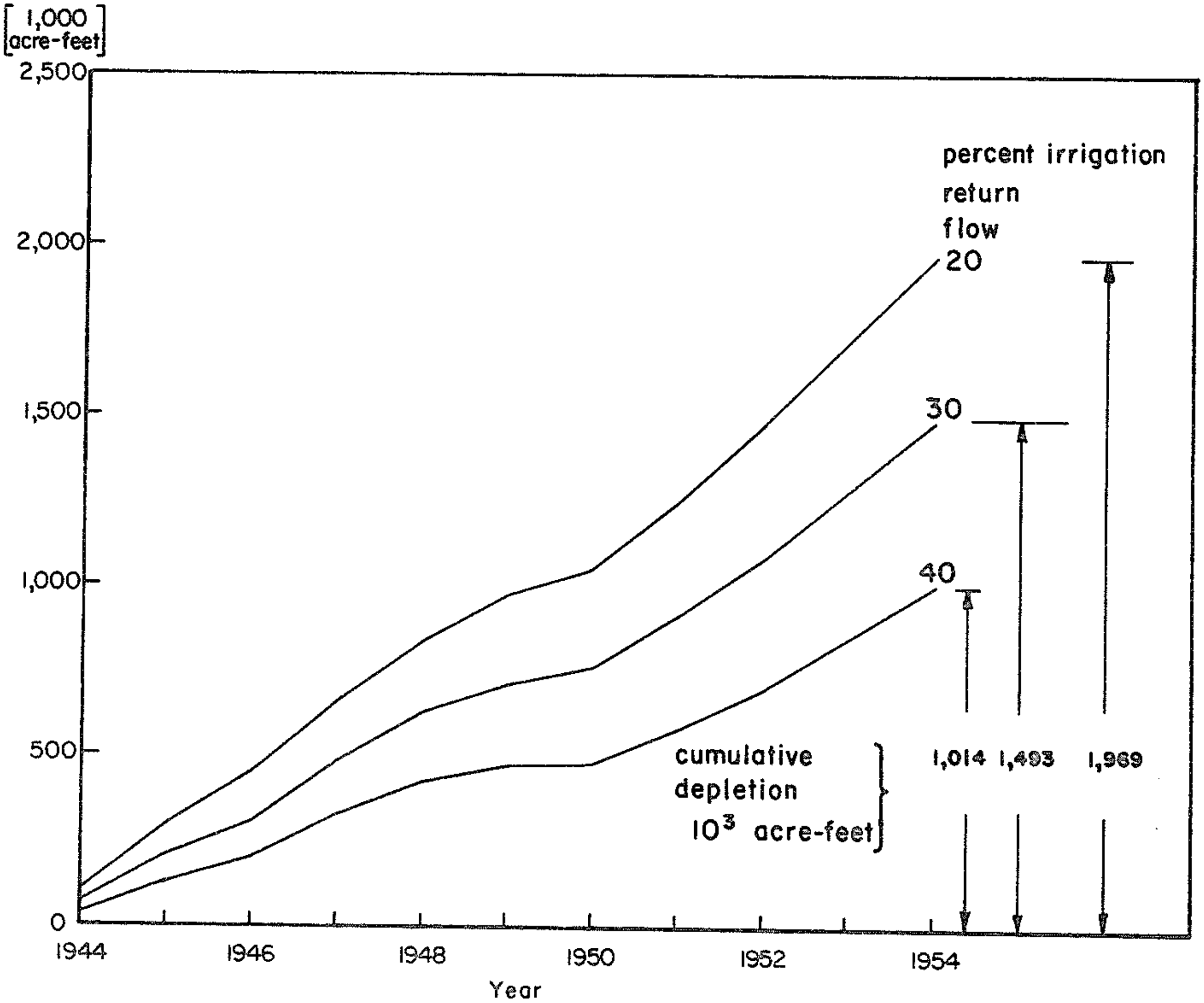

Figure 5. Cumulative depletion of ground water in storage in the Roswell Artesian Basin, New Mexico, 1944-1954.

Sources of Saline Waters

Constraints will be placed on the policy adopted for selection of lands to be retired from production, because of the need to obtain not only a hydrologic balance, but also an equilibrium at the fresh water and salt water interface. This makes the sources, magnitude, and geographic location of the interface of considerable significance. There should also be left in storage a substantial quantity of fresh water as a drought reserve.

Where Does the Saline Water Come From?

This is a valid question and one of the seven technical points posed at the end of Chapter 3. Another question is: does it make any difference? The answer: yes, it does. Figure 6, a conceptual view of a cross section of the basin, depicts possible movements of water in the aquifers. Saline waters may move upward from lower beds (Yeso and Glorieta, which contain poorer-quality water than do the San Andres and its units), or lateral encroachments may occur from the area to the east of the Pecos where less-permeable units of the San Andres contain saline waters. If saline waters come predominantly from the east, then a line of advance could be determined by a sampling program and the progressive intrusion controlled by appropriate reductions in water yields from critical areas. If the principal movement is vertical (see figure 6), the identification for a policy of irrigated-land retirement is difficult to establish because the upward movement is not readily predictable and can occur over a wide area. It would also be more difficult to monitor and evaluate progressive intrusions than would be the case with lateral encroachments.

Many factors lend credence to the concept of predominantly vertical movement--for instance, the general existence of a positive upward hydraulic gradient is found in the Yeso with respect to the San Andres; the pattern of increases in chloride concentrations is very irregular and far to the west in some cases; observation of rapid seasonal change in chloride, with higher levels occurring during irrigation periods; and the discovery of increased salinity in wells with greater depths.

Hood [22, p. 30] discusses the source of saline waters, n noting that "Although available data are inconclusive, it is believed that upward movement contributes less to the salinization of waters within the reach of wells than does lateral migration ...." The movement is probably both lateral and vertical as indicated by Spiegel [40,

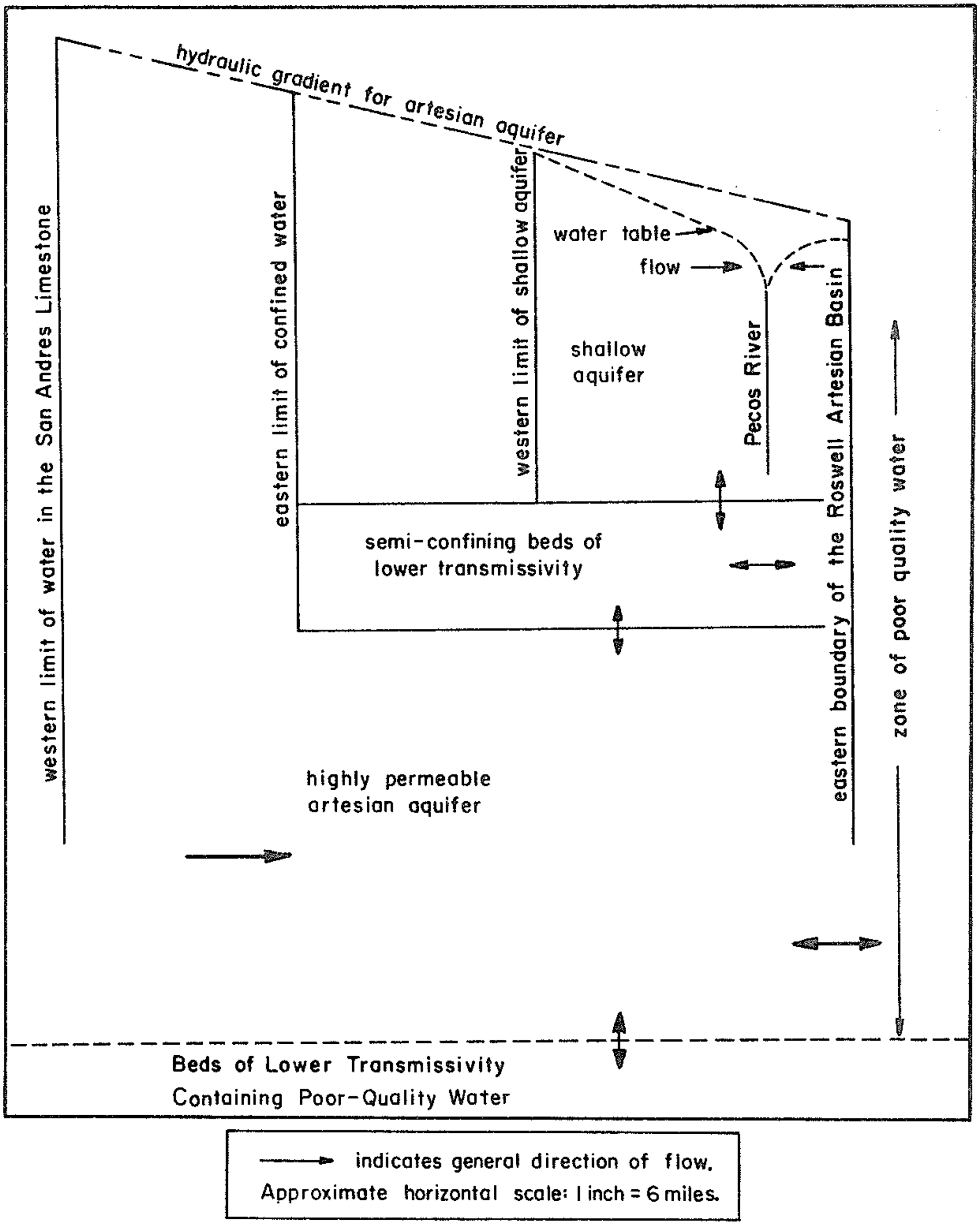

Figure 6. Conceptual view of a cross section of the Roswell Artesian Basin, New Mexico, showing general direction of water movement.

p. 27]. The relative importance of the type of encroachment to a particular well depends upon location, depth, and construction of the well in respect to the local stratigraphy and hydrology.

For purposes of developing an irrigation quality-control policy for the basin, a predominantly lateral intrusion is assumed. This is based in part on the shape of the intruding salt-water wedge into the producing formation. Spiegel [40, p. 46] presents drawings of the form of the interface that exists between the fresh and saline water-zones for a homogeneous aquifer with fully penetrating wells. He also shows two examples [40, p. 46, figures A and B] in which saline contamination does not, nor is likely to, occur beyond a certain limit. This condition is attained when there is a positive movement in the fresh water toward the saline zone. The shape of the interface changes when a natural discharge from the fresh water aquifer is not maintained [40, figures C and D].

The bedding plane permeability in the artesian zone is much greater than the vertical because zones of high transmissivity are interspersed between units of lower capacity. Wells are not fully penetrating in the classical sense, but may be terminated after going through one or more of these layers. This irregularity would partly account for the spotty nature of the chloride concentrations of wells in the semi-confined zone. Conceptually, saline waters, during periods of heavy pumping, would be drawn in the direction of a well via the most highly permeable layers. The saline water wedge that moves up these zones of high transmissivity can be quite lengthy. Todd [44, p. 281] provides an equation for this length:

$$L = \frac{k\,b^2}{2q}\left(\frac{\rho_s - \rho_f}{\rho_f}\right) \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

where K is the coefficient of permeability; b is the thickness of the confined zone in which water moves; ρ_f and ρ_s are the fresh and salt water densities, respectively, and q is the flow in the direction of the saline water zone per foot of aquifer width.

A positive flow, q, in the easterly direction toward the Pecos and the saline zone, does not exist at all times at all wells, nor at all depths in the semi-confined beds, but it does exist at many of the wells. Values of K are quite large, particularly in the Roswell area; as q becomes smaller and smaller due to pumping, the distance L that the salt water wedge moves up into the fresh water area becomes greater and the angle between the fresh and saline water interface becomes smaller--approaching a very small angle. As values for L of five miles or more would be possible in thick,highly permeable formations, it is not unreasonable to view the saline water intrusion near Roswell as being long, thin wedges the front of which moves westward during the pumping season and retreats eastward again when positive values of q obtain during the winter months. These saline wedges may move due to pumping of certain partially penetrating wells; this provides a means of localized upward intrusion.

Is It Too Late for Wells in Some Areas?

Here the question centers on particular wells that are already irretrievably on the poor-quality side of a permanently saline water front. Spiegel [40, pp. 35-37] discusses in detail the existence of an "axial trace" along a trough of depression, caused by a lowering of the potentiometric surface. Wells east of this trace and near the fresh-saline water interface act as points of discharge for excess salt flows. Even if a hydrologic balance is achieved in the basin, production from these wells is advantageous because they act as a water-quality buffer for wells on the west side [40, p. 36]. Retirement of these wells from production would not be recommended.

Policy Models

The basic economic question to be answered concerns the rate of withdrawal of water now held in reserve storage in the aquifer system. If an optimum use-policy indicates that the rate of withdrawal should be decreased below the (1960-1964) rate of depletion of ground water stocks, then a plan to select the optimal means of using the available supply and of retiring lands from production is needed. To identify the policies to be followed, an analytical model was devised that included a mathematical program for machine evaluation of the set of linear equations for maximum returns for use of water in any one year, and a so-called "dynamic program" to select the optimum policy for such uses over a 50-year planning period.

Linear Programming Model

Objective

The objective of the linear model was to determine the relative productivity of Roswell Basin lands at various levels of irrigation in order to select the best land retirement policy for a given water supply. Except where physical factors present unyielding constraints, selection of water-rights to be retired should be economically based. Several different types of policies for reducing withdrawals were analyzed, using data in tables 14 through 18, and the results are presented in the sections that follow.

Model Output

The analysis was made possible by a linear program that found the annual maximum net benefits attainable when successively greater quantities of water were made available to the acreage for each zone of a particular soil group and water quality. Table 19 is a typical data sheet giving the geographic zone, acres of land available with certain water and soil qualities, maximum dollar return possible when progressively increasing amounts of water are applied to the area, and the cropping pattern that yields these benefits. The program was run with three different limitations placed on the percent of farm lands usable for cotton--30, 35, and 40 percent. It was re-run for the same three ranges using figures for value added (table 15) rather than net benefits (table 14).

Figure 7 is a plot of two of the twenty-three combinations for maximum net benefits per acre of land for a given soil group and water quality when cotton is limited to 30 percent of the irrigated lands. A more useful form of this information appears in figures 8, 9, and 10, showing curves for the maximum net benefits per acre-foot of water pumped per water-right acre for each of the twenty-three combinations of soil and water quality possible when cotton is limited to 30 percent of the lands considered. These curves have been used in formulating policy statements on selection of lands for retirement, and may be thought of as lines of diminishing return for each soil group and water quality. As water quantity and not cultivated acreage is the limiting factor in the basin, the most efficient application is achieved when maximum benefits per acre-foot of water pumped are obtained, rather than maximum return per acre cultivated.

Land and Water Use at Three Acre-Feet per Acre

The amount of water that may be pumped per water-right acre was established by court decree [42] to be three acre-feet per acre, when withdrawals are averaged over a five-year period. Figure 11 is a plot of maximum net benefits returned for various soils and

Table 19. Typical data sheet for maximum net benefits from linear programming model, Roswell Artesian Basin, New Mexico (Soil Group I, Water Quality--2.25 x 10³ micromhos conductivity; acres in the zone = 6,000.00).

Water Applied (acre-inches)	Expected Benefit (dollars)	Crop To Be Planted	Irrigation Level (inches)	Acres Used	Crop To Be Planted	Irrigation Level (inches)	Acres Used	Crop To Be Planted	Irrigation Level (inches)	Acres Used
8,653.84	60,682.66	total fallow	0.0	5,679.48	cotton fallow	0.0	2,079.49	cotton	27.0	320.51
17,307.69	121,365.31	total fallow	0.0	5,358.97	cotton fallow	0.0	1,758.97	cotton	27.0	641.03
25,961.53	182,047.94	total fallow	0.0	5,038.45	cotton fallow	0.0	1,438.46	cotton	27.0	961.54
34,615.38	242,730.63	total fallow	0.0	4,717.95	cotton fallow	0.0	1,117.95	cotton	27.0	1,282.05
43,269.22	303,413.31	total fallow	0.0	4,397.43	cotton fallow	0.0	797.44	cotton	27.0	1,602.56
51,923.06	364,095.94	total fallow	0.0	4,076.92	cotton fallow	0.0	476.92	cotton	27.0	1,923.08
60,576.91	424,778.63	total fallow	0.0	3,756.41	cotton fallow	0.0	156.41	cotton	27.0	2,243.59
69,230.75	484,841.00	total fallow	0.0	3,600.00	cotton	27.0	1,907.69	cotton	36.0	492.31
77,884.56	544,311.88	total fallow	0.0	3,600.00	cotton	27.0	946.16	cotton	36.0	1,453.84
86,538.38	603,363.06	total fallow	0.0	3,600.00	cotton	36.0	2,384.62	cotton	45.0	15.38
95,192.19	636,574.31	total fallow	0.0	3,600.00	cotton	36.0	1,423.09	cotton	45.0	976.91
103,846.00	669,785.56	total fallow	0.0	3,600.00	cotton	36.0	461.55	cotton	45.0	1,938.45
113,765.19	694,318.00	total fallow	0.0	3,439.85	cotton	45.0	2,400.00	sorghum	36.0	160.15
124,852.50	710,838.13	total fallow	0.0	3,131.87	cotton	45.0	2,400.00	sorghum	36.0	468.13
135,939.81	727,358.19	total fallow	0.0	2,823.89	cotton	45.0	2,400.00	sorghum	36.0	776.11
147,027.13	743,878.25	total fallow	0.0	2,515.91	cotton	45.0	2,400.00	sorghum	36.0	1,084.09
158,114.44	760,398.38	total fallow	0.0	2,207.93	cotton	45.0	2,400.00	sorghum	36.0	1,392.07
169,201.75	776,918.50	total fallow	0.0	1,899.95	cotton	45.0	2,400.00	sorghum	36.0	1,700.05
180,289.06	793,438.56	total fallow	0.0	1,591.97	cotton	45.0	2,400.00	sorghum	36.0	2,008.03
191,376.38	809,958.69	total fallow	0.0	1,283.99	cotton	45.0	2,400.00	sorghum	36.0	2,316.01
202,463.69	826,478.75	total fallow	0.0	976.01	cotton	45.0	2,400.00	sorghum	36.0	2,623.99
214,733.75	844,761.13	total fallow	0.0	635.17	cotton	45.0	2,400.00	sorghum	36.0	2,964.83
228,267.50	864,926.44	total fallow	0.0	259.24	cotton	45.0	2,400.00	sorghum	36.0	3,340.77
241,801.25	881,433.31	sorghum	36.0	3,519.21	cotton	45.0	2,400.00	alfalfa	88.0	80.79
255,649.56	890,008.63	sorghum	36.0	3,252.89	cotton	45.0	2,400.00	alfalfa	88.0	347.11
269,797.19	898,769.25	sorghum	36.0	2,980.82	cotton	45.0	2,400.00	alfalfa	88.0	619.18
283,944.81	907,529.94	sorghum	36.0	2,708.75	cotton	45.0	2,400.00	alfalfa	88.0	891.25
298,092.44	916,290.50	sorghum	36.0	2,436.68	cotton	45.0	2,400.00	alfalfa	88.0	1,163.32
312,240.06	925,051.19	sorghum	36.0	2,164.61	cotton	45.0	2,400.00	alfalfa	88.0	1,435.39
326,387.69	933,811.87	sorghum	36.0	1,892.54	cotton	45.0	2,400.00	alfalfa	88.0	1,707.46
340,535.31	942,572.50	sorghum	36.0	1,620.47	cotton	45.0	2,400.00	alfalfa	88.0	1,979.53
354,682.94	951,333.13	sorghum	36.0	1,348.40	cotton	45.0	2,400.00	alfalfa	88.0	2,251.60
368,830.56	960,093.81	sorghum	36.0	1,076.33	cotton	45.0	2,400.00	alfalfa	68.0	2,523.67
382,978.19	968,854.44	sorghum	36.0	804.26	cotton	45.0	2,400.00	alfalfa	88.0	2,795.74
397,125.81	977,615.00	sorghum	36.0	532.19	cotton	45.0	2,400.00	alfalfa	88.0	3,067.80
411,273.44	986,375.69	sorghum	36.0	260.13	cotton	45.0	2,400.00	alfalfa	88.0	3,339.87
425,425.88	994,751.81	alfalfa	88.0	3,600.00	cotton	45.0	2,400.00	-	-	-

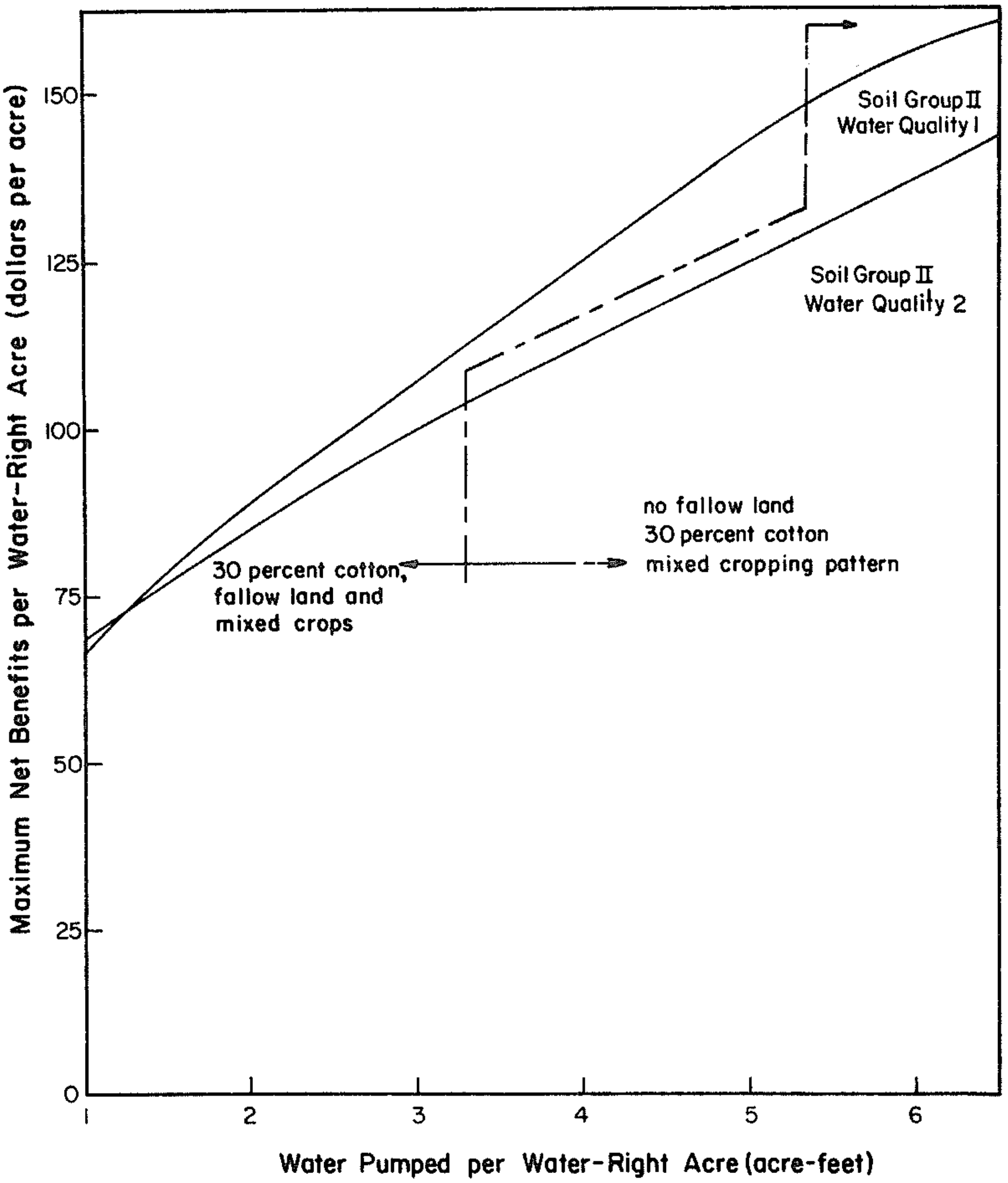

Figure 7. Typical curves for maximum benefits per acre per acre foot of water pumped for the indicated soil group and water quality when cotton is limited to 30 percent of acreage available.

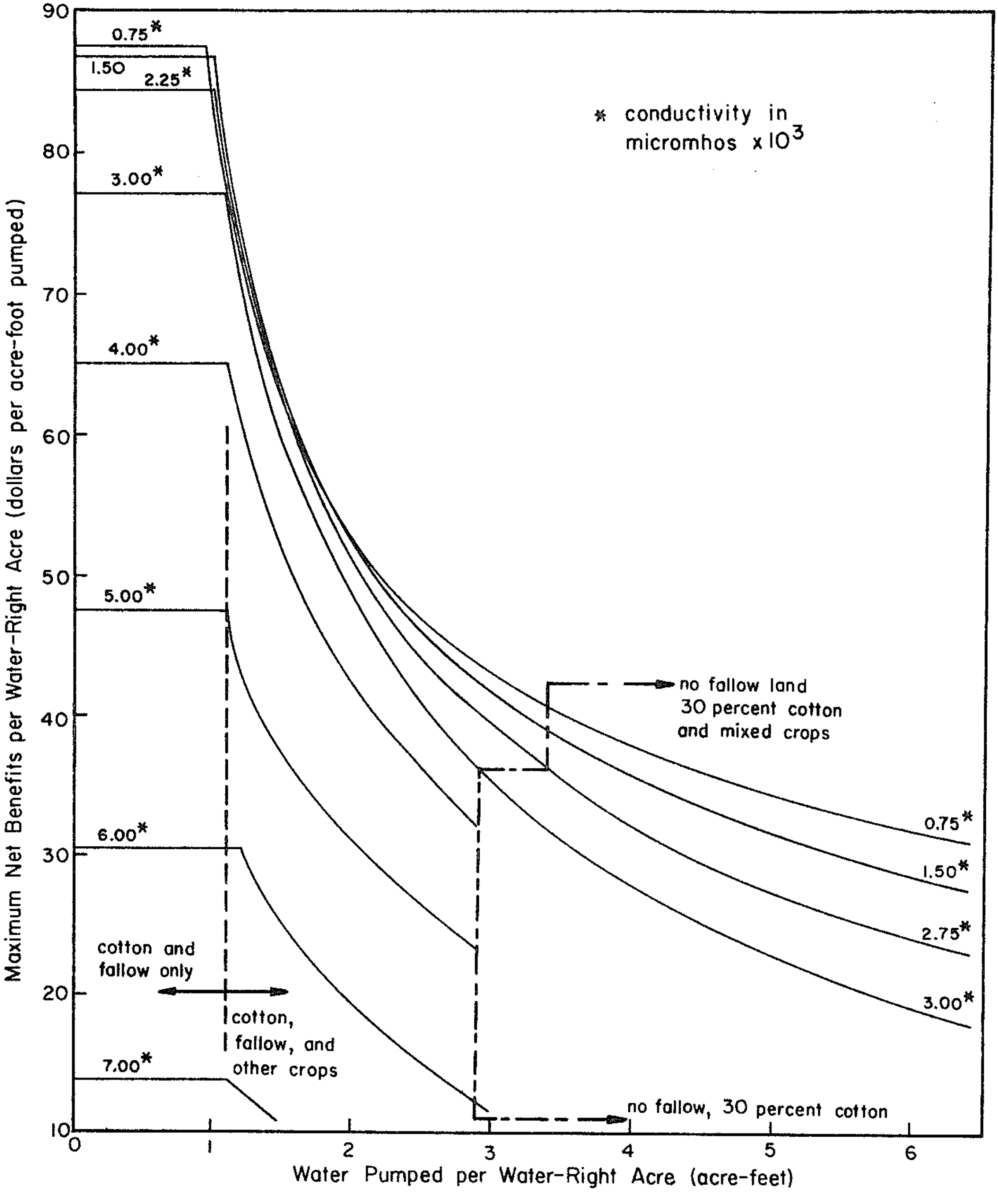

Figure 8. Curves for Soil Group I for maximum net benefits for various water qualities from 0.75 to 7.00 micromhos x 10^3 conductivity for varying quantities of water pumped in acre-feet per water-right acre for limitation of 30 percent of crop land in cotton.

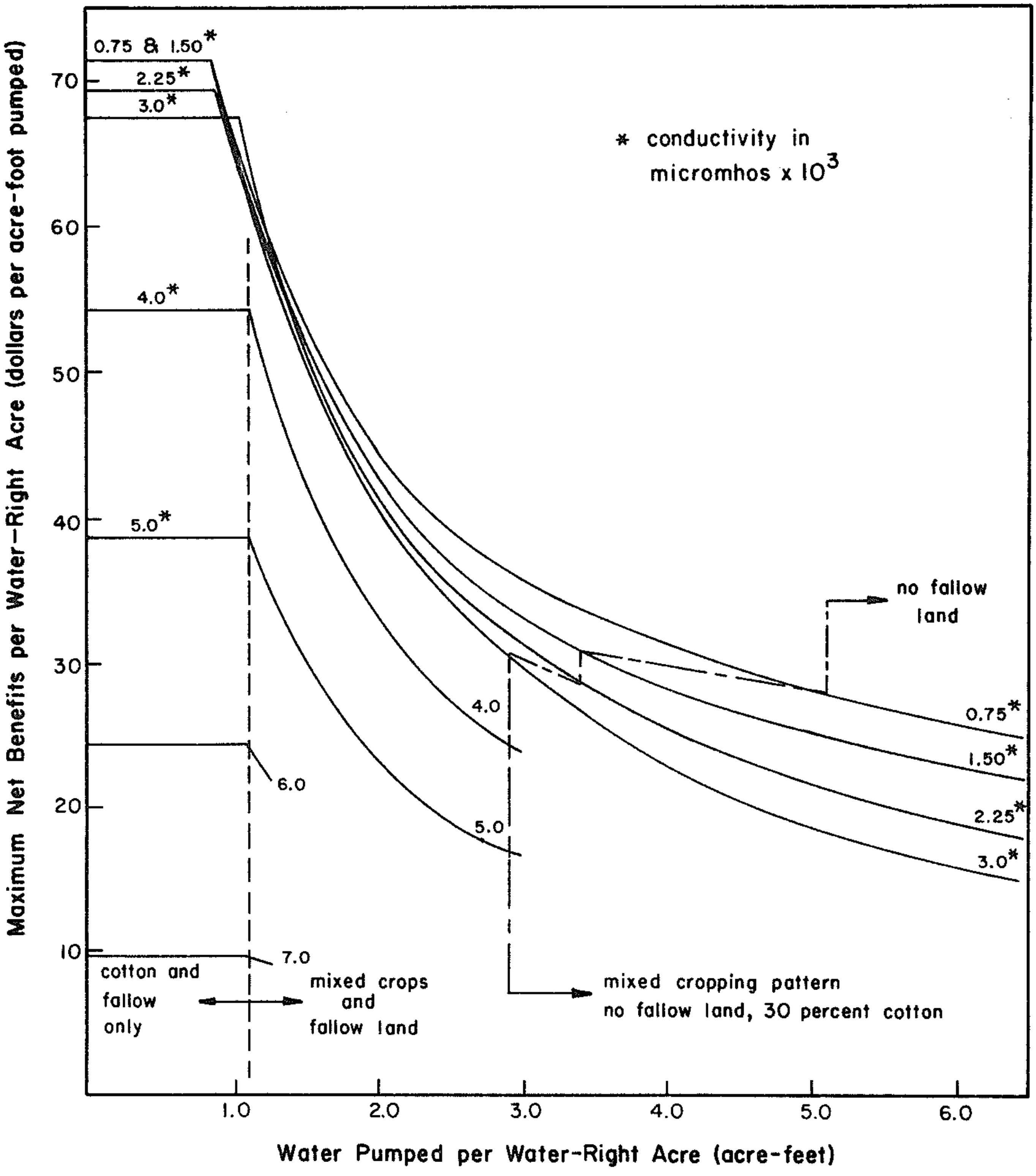

Figure 9. Curves for maximum net benefits for Soil Group II lands for various water qualities from 0.75 to 7.00 micromhos x 10^3 conductivity for varying quantities of water pumped per water-right acre when cotton production is limited to 30 percent of the crop land available.

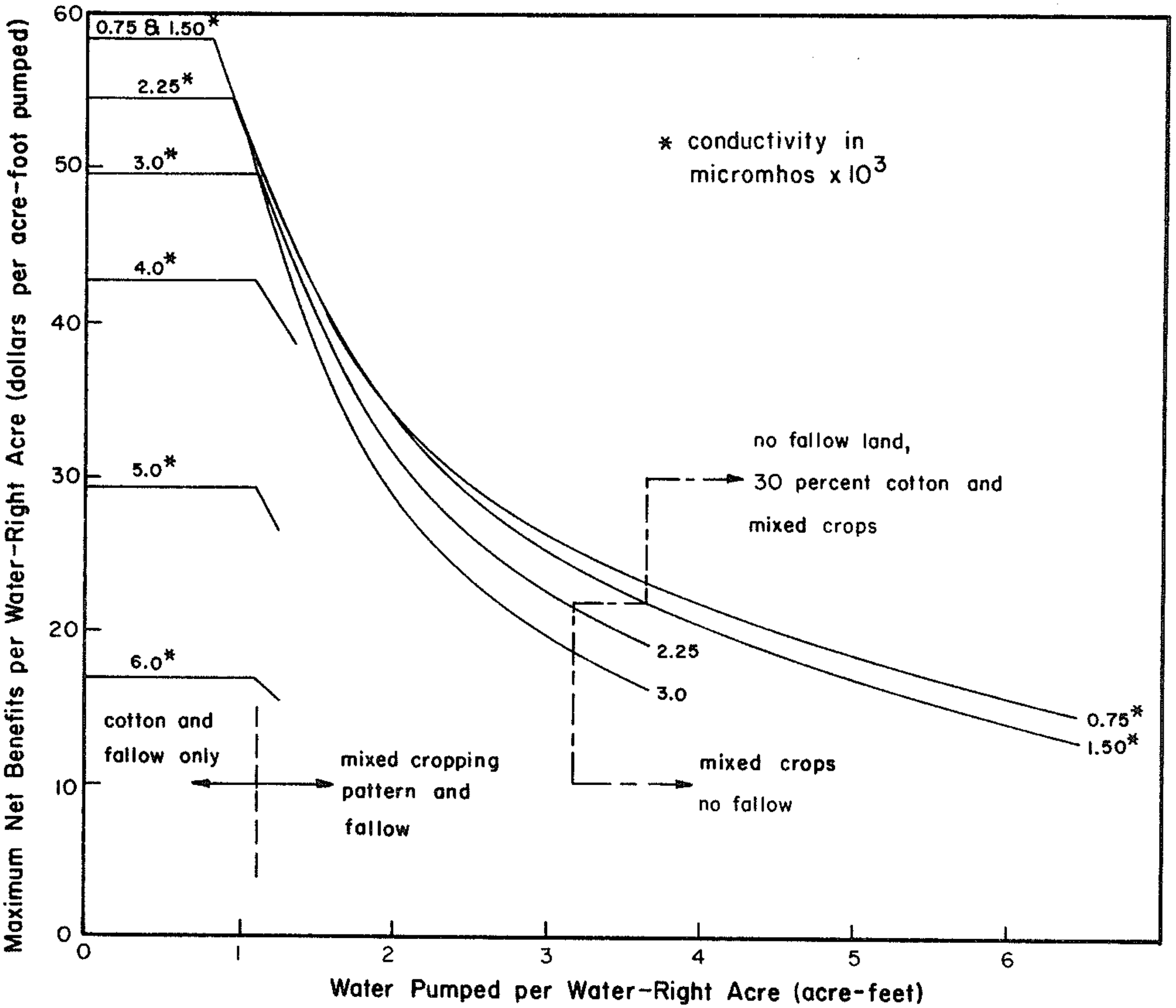

Figure 10. Curves for Soil Group III showing maximum net benefits for various water qualities from 0.75 to 7.00 micromhos x 10^3 conductivity for varying quantities of water pumped per water-right acre when cotton is limited to 30 percent of available crop land.

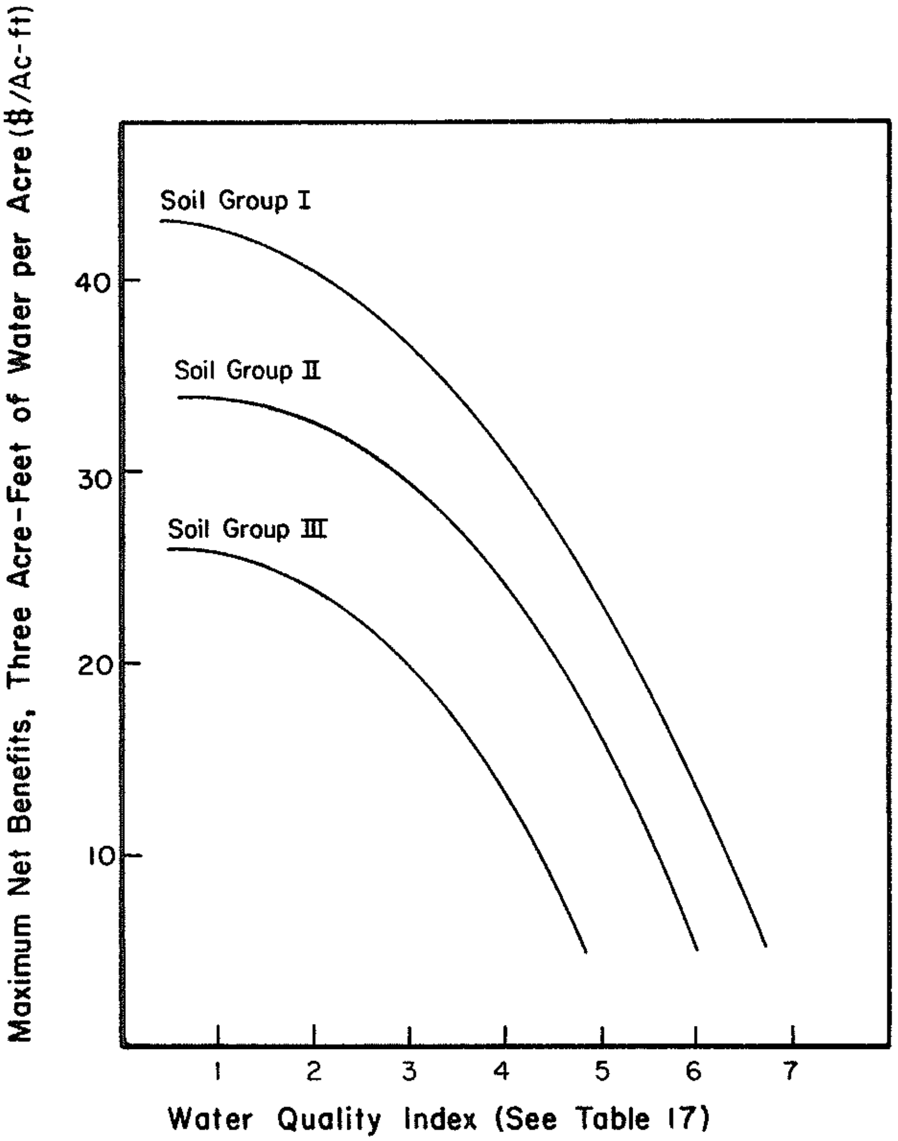

Figure 11. Maximum net benefits from three acre-feet of water applied per acre to lands with various soil groups and water qualities when cotton is limited to 30 percent of cultivated lands.

water classes at an application of three acre-feet per acre. To develop a land-retirement policy for this pumping rate, the information in figures 8 through 11 has been used to rank the irrigated lands in each zone by relative levels of productivity for different qualities of water available in the zone, assuming that cotton is limited to 30 percent of the irrigated lands. This ranking is given in tables 20, 21, 22, and 23, which represent Zones 1, 2, 3, and 4, respectively. The first column in each of these tables gives the water available to the zone under each of the assumed levels of irrigation return flow--20, 30, and 40 percent. The available water is progressively assigned to the acreage of cultivated lands of a given soil group and water quality in the order of their maximum dollar productivity per acre-foot of water. All available water is used in each zone, except Zone 2 where 9,700 acre-feet remain unassigned because of insufficient lands when a 40 percent irrigation return flow is assumed.

In several cases the optimum cropping pattern leaves some land fallow at three acre-feet per acre (see indicated levels in figures 8, 9, and 10 and table 24), and there are some where no crop other than cotton can be profitably grown because of poor soil and water quality. Cropping patterns used for comparison of productivity at three acre-feet per acre are given in the last column of table 21 and in all examples, except those with very poor soil and water quality, no fallow land is included in the pattern used to obtain the relative productivities. Thus, these cropping patterns represent full utilization of the cultivated acreage in question. Because small percentages of fallow land are included in the optimal cropping patterns at three acre-feet per acre, the net benefits returned that were used in the rankings in tables 20 through 24 are slightly below optimum values in these cases. Net benefits used range from $43.00 to $9.50 per acre-foot, with the average depending upon the acres of land available in various soil and water classes in the zone.

These tables may be used to guide policy-making with respect to land retirement. For example, in table 22, if 53,000 acre-feet are available to Zone 3, assuming an irrigation return flow of 30 percent, then, within the physical constraints imposed, we would recommend for continued cultivation only lands of Soil Group I with water quality indexes of 1, 2, and 3 (less than 500 ppm of chlorides). The average return per acre-foot of

Table 20. Progressive land utilization in Zone 1 for various estimates of water availability when application is limited to three acre-feet per acre and cotton is restricted to 30 percent of irrigated lands, and where soil and water quality permit a mixed cropping pattern.

Zone 1 Water Available	Indexes for Soil and Water Classification (see table 17)	Land Used and Available in the Zone of the Class Indicated	Maximum Net Benefits at Irrigation Level of 3 acre-feet per acre	Maximum Net Benefits per Water-Right Acre	Total Net Benefits to the Zone	Water Used in the Zone on the Indicated Land Class
(acre-feet)		(acres)	(dollars per acre-foot per acre)	(dollars per acre)	(1,000 dollars)	(acre-feet)
10,000 (20 percent irrigation return flow assumed)	15	1,100	31.00	93.00	102.2	3,300
	25	350	23.50	70.50	24.7	1,050
	16	1,100	23.00	69.00	75.9	3,300
	26	350	16.50	49.50	17.3	1,050
	17	433	12.00	36.00	15.6	1,300
Totals and Averages		3,333	23.57	70.60	235.7	10,000
11,400 (30 percent irrigation return flow assumed)	17	467	12.00	36.00	16.8	1,400
Totals and Averages		3,800	22.20	66.50	252.5	11,400
13,300 (40 percent irrigation return flow assumed)	17	633	12.00	36.00	22.8	1,900
Totals and Averages		4,433	20.70	62.20	275.3	13,300[1]

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[1] Note that all of the water available to Zone 1 (13,300 acre-feet) is allocated.

Table 21. Progressive land utilization in Zone 2 for various estimates of water availability when application is limited to three acre-feet per acre and cotton is restricted to 30 percent of the irrigated lands, and where soil group and water quality permit a mixed cropping pattern.

Zone 2 Water Available	Indexes for Soil and Water Classification (see table 17)	Net Benefits at Irrigated Level of 3 acre-feet per acre	Land Used and Available in the Zone of the Class Indicated	Net Benefits per Water-Right Acre	Total Net Benefits to the Zone	Water Used in the Zone on the Indicated Land Class	Cropping[1] Pattern by Percentages (approximate)
(acre-feet)		(dollars per acre-foot per acre)	(acres)	(dollars per acre)	(1,000 dollars)	(acre-feet)	
	11	43.00	5,075	132.00	670.0	15,205	30%C,64%G,6%A
88,800	12	42.00	5,075	126.00	640.0	15,225	30%C,66%G,4%A
	13	39.00	5,075	117.00	594.5	15,225	30%C,66%G,4%A
	14	36.00	5,075	108.00	548.0	15,225	30%C,22%G,48%B
(20 percent irrigation return flow assumed)	21	34.00	50	102.00	5.1	150	30%C,70%G
	22	33.00	50	99.00	5.0	150	30%C,70%G
	23	31.50	50	94.50	4.7	150	30%C,70%G
	15	31.00	1,700	93.00	158.0	5,100	30%C,70%B
	24	29.50	50	88.50	4.4	150	30%C,24%B,46%G
	31	26.00	75	78.00	5.9	225	30%C,70%S
	32	25.00	75	75.00	5.6	225	30%C,70%S
	25	23.50	650	70.50	45.8	1,950	30%C,70%B
	16	23.00	1,700	69.00	117.0	5,100	30%C,70%B
	33	22.50	75	67.50	5.1	225	30%C,70%G
	34	20.00	75	60.00	4.5	225	30%C,70%G
	26	16.50	650	49.50	32.2	1,950	30%C,70%B
	17	12.00	2,400	36.00	77.4	7,200	30%C,70%B
	35	42.00	250	126.00	31.5	750	cotton only
	36	29.00	250	87.00	21.8	750	cotton only
	27	24.00	300	72.00	21.6	900	cotton only
	37	17.00	100	51.00	5.1	300	cotton only
	18	14.00	800	42.00	3.4	2,400	cotton only
Totals and Averages		33.40	29,600	101.70	3,006.5	88,800	
102,300 (30 percent irrigation return flow assumed)	18	14.00	4,500	42.00	189.0	13,500	cotton only
Totals and Averages		31.20	34,100	93.60	3,195.5	102,300	
120,400	18	14.00	2,500	42.00	105.0	7,500	cotton only
(40 percent irrigation return flow assumed)	28	9.50	300	28.50	8.5	900	cotton only
Totals and Averages		30.00	36,900	89.70		110,700[2]	

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[1] A=alfalfa, B=barley, C=cotton, G=grain sorgum

[2] Note that not all of the water available to Zone 2 (120,400 acre-feet) is used because of insufficient lands in the zone.

Table 22. Progressive land utilization in Zone 3 for various estimates of water availability when application is limited to three acre-feet per acre and cotton is restricted to 30 percent of the irrigated lands, and where soil group and water quality permit a mixed cropping pattern.

Zone 3 Water Available	Indexes for Soil and Water Classification (see table 17)	Land Used and Available in the Zone of the Class Indicated	Maximum Net Benefits at Irrigation Level of 3 acre-feet per acre	Maximum Net Benefits Per Water-Right Acre	Total Net Benefits to the Zone	Water Used in the Zone on the Indicated Land Class
(acre-feet)		(acres)	(dollars per acre-foot per acre)	(dollars per acre)	(1,000 dollars)	(acre-feet)
44,000	11	6,000	43.00	132.00	792.0	18,000
(20 percent	12	6,000	42.00	126.00	756.0	18,000
irrigation return flow assumed)	13	2,666	39.00	117.00	312.0	8,000
Totals and Averages		14,666	42.40	127.00	1,860.0	44,000
53,000 (30 percent irrigation return flow assumed)	13	3,000	39.00	117.00	351.0	9,000
Totals and Averages		17,666	41.75	125.30	2,211.0	53,000
65,100	13	333	39.00	117.00	39.0	1,000
(40 percent irrigation return flow assumed)	14	3,700	36.00	108.00	400.0	11,100
Totals and Averages		21,700	40.60	122.00	2,650.0	65,100[1]

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[1] Note that all of the water available to Zone 3 (65,100 acre-feet) is allocated.

Table 23. Progressive land utilization in Zone 4 for various estimates of water availability when application is limited to three acre-feet per acre and cotton is restricted to 30 percent of the irrigated lands, and where soil group and water quality permit a mixed cropping pattern.

Zone 4 Water Available	Indexes for Soil and Water Classification (see table 17)	Land Used and Available in the Zone of the Class Indicated	Maximum Net Benefits at Irrigation Level of 3 acre-feet per acre	Maximum Net Benefits per Water-Right Acre	Total Net Benefits to the Zone	Water Used in the Zone on the Indicated Land Class
(acre-feet)		(acres)	(dollars per acre-foot per acre)	(dollars per acre)	(1,000 dollars)	(acre-feet)
67,900	11	9,050	43.00	132.00	1,195.0	27,150
(20 percent irrigation return flow assumed)	12	9,050	42.00	126.00	1,140.0	27,150
	13	4,533	39.00	117.00	530.0	13,600
Totals and Averages		22,633	42.30	126.60	2,865.0	67,900
78,300	13	3,467	39.00	117.00	406.0	10,400
(30 percent irrigation return flow assumed)						
Totals and Averages		26,100	41.80	125.20	3,271.0	78,300
90,600	13	1,050	39.00	117.00	123.0	3,150
(40 percent irrigation return flow assumed)	14	3,050	36.00	108.00	330.0	9,150
Totals and Averages		30,200	41.10	123.20	3,724.0	90,600[1]

[1] Note that all of the water available to Zone 4 (90,600 acre-feet) is allocated.

Table 24. Ranking of lands with various water and soil qualities for maximum net benefits returned at 3 acre-feet of water per acre.

Order of Maximum Net Benefit of Soil-Water Quality Classes at 3 acre-feet per acre	Level at Which No Land is Left Fallow (acre-feet per water-right acre)		Level at Which the Availability of Additional Water Fails to Increase Income (acre-feet per acre)	
	Net Benefits	Value Added	Net Benefits	Value Added
Column 1	Column 2	Column 3	Column 4	Column 5
11	3.40	2.03	6.45	6.45
12	3.40	2.03	6.45	6.45
13	3.40	2.30	6.45	6.45
14	2.91	2.30	6.45	6.45
21	5.34	5.37	6.45	6.45
22	3.40	2.03	6.45	6.45
23	3.40	2.30	6.45	6.45
15	2.91	2.30	2.91	2.71
24	2.91	2.30	6.45	6.45
31	3.64	2.71	6.45	6.45
32	3.64	3.20	6.45	6.45
25	2.91	2.30	2.91	2.71
16	2.91	2.71	2.91	2.71
33	3.40	3.20	3.64	6.45
34	3.64	2.30	3.64	6.45
26	2.91	2.71	2.91	2.71
17*	2.91	2.71	2.91	2.71
35*	does not pertain	2.30	1.25	2.71
36	does not pertain	2.71	1.25	2.71
27	does not pertain	2.71	1.25	2.71
37**	does not pertain	2.71	1.25	2.71
18**	does not pertain	2.71	1.25	2.71
28	does not pertain	2.71	1.28	2.71

* Interchange these indexes when "Value Added" is used.
**Interchange these indexes when "Value Added" is used.

water applied would be $39.00. A check for Zone 4 (table 23) indicates a similar policy recommendation, but because of a lack of lands with high-quality water in Zone 1 (table 20) the policy there is quite different.

The same general policy holds even when the percent of cotton lands allowed in a zone increases. There is, however, an upward change to higher levels of water applied per acre before no land is left fallow. This may be seen in figure 12, which gives curves for maximum net benefits for Soil Group I lands with Water Quality 2 for three different percentages of land in cotton--30, 35, and 40.

The comparisons of productivity in tables 20 to 23 are based on net benefits returned. A similar analysis was made using value added data rather than net benefits. Here again, the general ranking of lands is the same (see footnote, table 24), but with associated higher dollar values (see figure 13 and table 25). One interesting change may be found in table 24 and figure 13. The level of water application in acre-feet per acre at which no land is left fallow occurs at a much lower level in the case of value added figures (compare column 2 with column 3 of table 24). This implies that when a policy is sought that will yield a maximum value to the region (that is, when value added is used to formulate policy), no land should be left fallow when the water available per water-right acre is equal to or greater than that given in column 3 of table 24.

Should More Than Three Acre-Feet Be Used?

As previously noted (figures 7, 8, and 9 and table 24), fallow land is included in optimal cropping patterns. This is the same as saying that, in actuality, the rate of application of water should be more than three acre-feet per acre to generate maximum returns from the lands that are planted. Table 21 offers one version of the allocation of the water in Zone 2, whereas table 26 offers another on the basis that a uniform rate of return per acre-foot (with varying rates of water application) will generate greater benefits than the arbitrary assignment of three acre-feet per acre as the duty.

Two levels of water availability are considered in table 26--88,800 acre-feet (20 percent irrigation return flow) and 102,300 acre-feet (30 percent return flow). In the first case, all available water may be allocated by uniform net return of $34.00 per acre-foot. The rate of application on the 22,970 acres farmed varies from 5.15

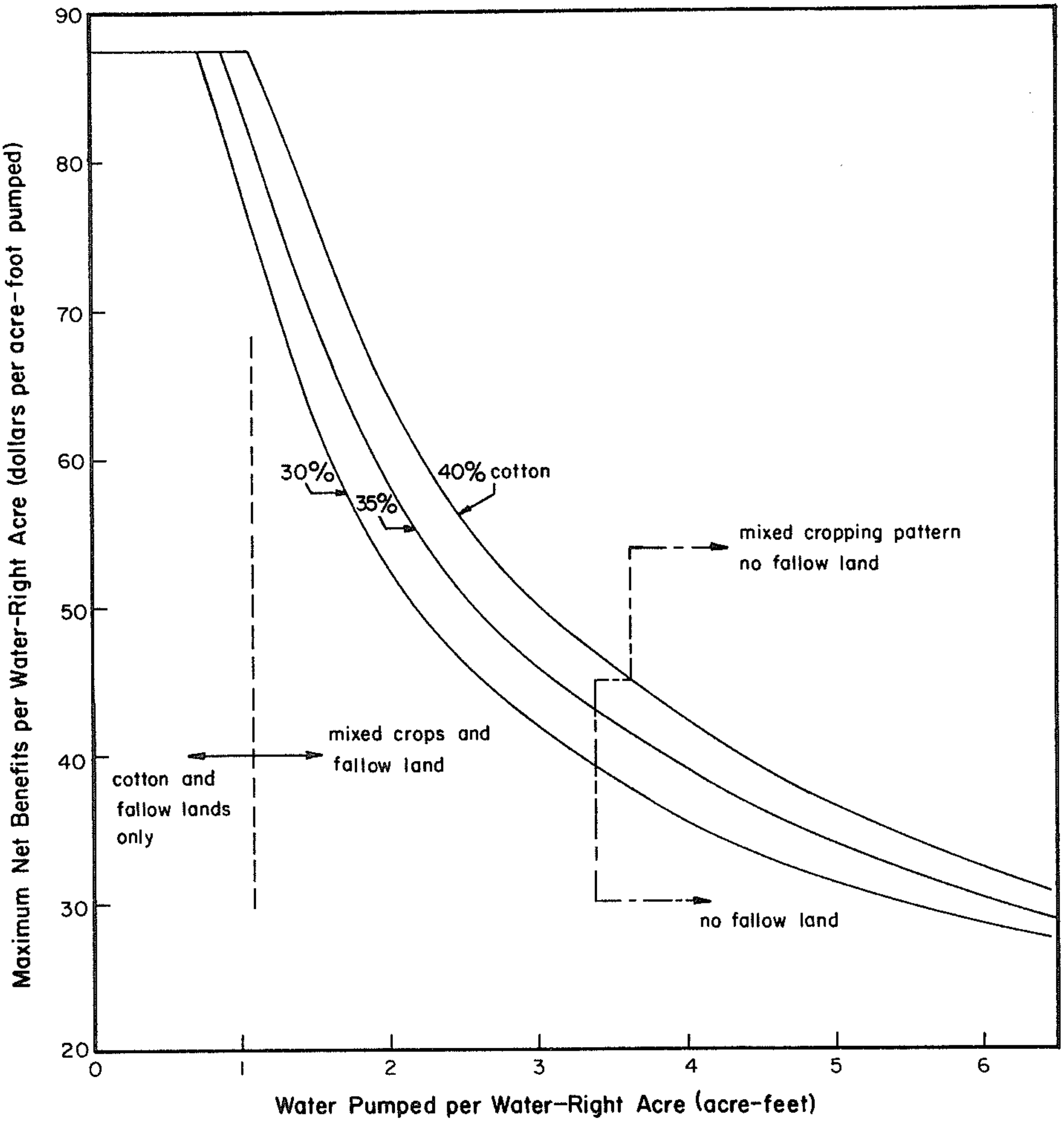

Figure 12. Maximum net benefits per acre-foot of water pumped per acre to lands with Soil Group I, Water Quality Index 2, for various percentages of lands in cotton.

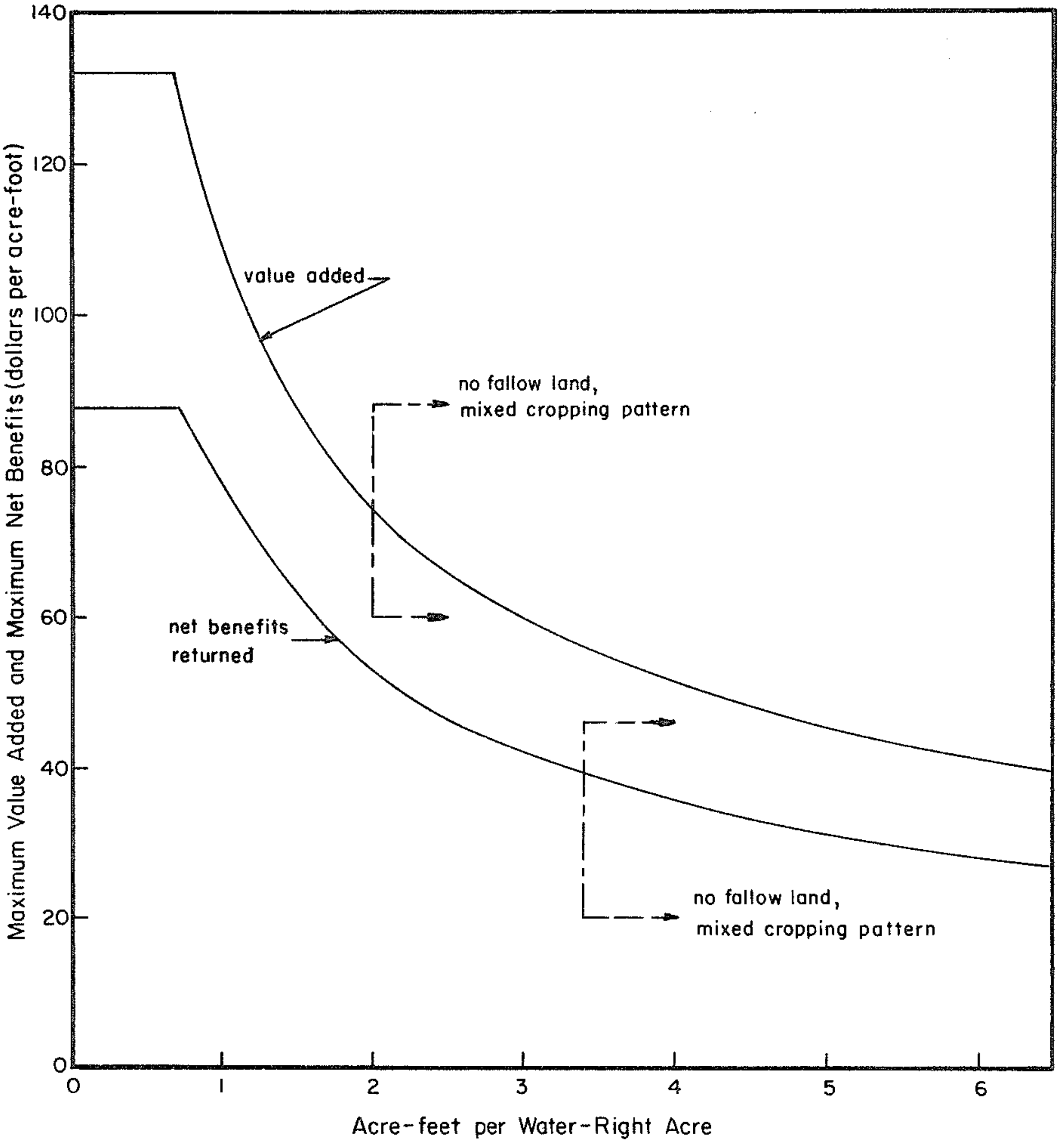

Figure 13. Comparison of curves for net benefits returned and for value-added to water to lands of soil Group I, Water Quality Index 2, with cotton limited to 30 percent of farmed area.

Table 25. Maximum valued added to water per acre-foot pumped per acre at three acre-feet per acre to lands with various soil groups and water qualities when cotton is limited to 30 percent of the cultivated lands.

Water Quality Index (see table 17)	Maximum Value Added per Water-Right Acre at Three Acre-Feet per Acre					
	Soil Group I		Soil Group II		Soil Group III	
	Dollars per Acre-Foot Pumped per Acre	Dollars per Water-Right Acre	Dollars per Acre-Foot Pumped per Acre	Dollars per Water-Right Acre	Dollars per Acre-Foot Pumped per Acre	Dollars per Water-Right Acre
1	61.40	184.00	52.50	157.00	42.70	128.00
2	60.50	181.00	51.30	154.00	42.00	126.00
3	58.30	175.00	49.50	149.00	40.00	120.00
4	54.80	164.00	44.00	132.00	37.30	112.00
5	48.80	146.00	41.00	123.00	32.60	98.00
6	40.00	120.00	33.80	100.00	26.60	80.00
7	31.80	95.00	26.40	79.00	17.50	52.00
8	21.00	63.00	17.60	52.00	--	--

Table 26. Selection of lands to be irrigated in Zone 2 at optimum levels for the volume of water available for use in the Zone, on the basis of maximum net benefit returned when cotton is limited to 30 percent of the water-right lands in the zone.

Zone 2 Water Available	Indexes for Soil and Water Classification (see table 17)	Maximum Net Benefits at Indicated Rate of Water Use	Average Rate of Application of Water	Maximum Net Benefits Per Acre	Land Used and Available in the Zone in the Class Indicated	Total Net Benefits to the Zone	Water Used in the Zone on the Indicated Land Class	Cropping Pattern (Approximate) Crops[1]	Cropping Pattern (Approximate) Water Applied per Acre
(acre-feet)		(dollars per acre-foot per acre)	(acre-feet per acre)	(dollars per acre)	(acres)	(1,000 dollars)	(acre-feet)	(percent)	(inches)
88,800	11	34.00	5.15	175.00	5,075	889.0	26,150	C - 30 G - 26 A - 44	45 36 88
(20 percent	12	34.00	4.50	153.00	5,075	777.0	22,800	C - 30 G - 40 A - 30	45 36 88
irrigation return flow assumed)	13	34.00	3.70	125.80	5,075	639.0	18,800	C - 30 G - 58 A - 12	45 36 88
	21	34.00	3.35	114.00	50	5.6	160	C - 30 A - 36 F - 34	45 72 0
	14	34.00	3.20	108.80	5,075	552.5	16,240	C - 30 B - 20 G - 50	45 27 39
	22	34.00	2.85	97.00	50	4.9	143	C - 30 G - 56 F - 14	45 36 0
	15	34.00	2.70	91.70	1,670	153.0	4,507	C - 30 B - 69.5 F - 0.5	45 27 0
Totals and Averages		34.00	3.84	131.50	22,970	3,021.0	88,800		
102,300	11	31.00	6.85	197.00	5,075	1,000.0	32,200	C - 30 A - 68 G - 2	45 68 36
(30 percent	12	31.00	5.35	165.50	5,075	840.0	27,180	C - 30 A - 49 G - 21	45 88 36
irrigation return flow assumed)	13	31.00	4.25	131.50	5,075	667.0	21,550	C - 30 A - 25 G - 45	45 88 36
	21	31.00	4.05	125.50	50	6.3	200	C - 30 A - 50 F - 20	45 72 0
	14	31.00	3.60	111.50	5,075	565.0	18,270	C - 30 A - 10 G - 60	45 88 39
	22	31.00	3.40	105.00	50	5.3	170	C - 30 A - 4 G - 66	45 88 36
	23	31.00	3.00	93.00	50	4.6	150	C - 30 G - 68 F - 2	45 36 0
	15	31.00	3.00	93.00	860	80.0	2,580	C - 30 B - 70	45 27
Totals and Averages		31.00	4.80	148.70	21,310	3,168.2	102,300	-	-

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[1] A = alfalfa, B = barley, C = cotton, G = grain sorghum, S = silage, F = fallow.

to 2.70 acre-feet per water-right acre, and the cropping patterns range from those with no fallow land (soil and water indexes 11, 12, 13, and 14) to as much as 34 percent fallow (soil and water index 21). The total net dollar return to the zone when 88,800 acre-feet are used at these varied rates is $3,021,000, while a uniform application of three acre-feet per acre on 29,600 acres (table 21) yields a return of $3,006,500--a rather small difference.

When 102,300 acre-feet are used in the zone, the allocation can be made at a uniform rate of $31.00 per acre-foot, with application varying from 6.35 to 3.00 acre-feet per acre to an irrigated area of 21,310 acres. Here the total net return is $3,168,200, compared with $3,195,500 when the rate of application is a uniform three acre-feet per acre on 34,100 acres.

The basic idea of using more than three acre-feet per acre fails at one cricial point: it is not the crucial irrigable land that is in short supply, but water. To apply more water to one parcel of land in order to increase benefits to a maximum is to forego the opportunity of benefits from another parcel, because sufficient water is lacking for all areas. For example, to be able to irrigate one acre of land having favorable soil and water quality at six acre-feet per acre requires that net returns per acre at this level be equal to or greater than the return for irrigating one acre of this land at three acre-feet per acre and a second acre with presumably poorer soil and water quality at three acre-feet per acre. A check of figures 8, 9, and 10 shows that this is possible only when the land to be irrigated at six acre-feet per acre is of Soil Group I and Water Class 1 or 2 and the second acre has very poor soil and water quality.

Dynamic Programming Model

The linear programming model was designed to find the optimal method of allocating the water supply available during any single given year. This guide would serve to derive policy when no stock is on hand, that is, when no water is held in storage that could be made available for use. To answer the question of when and how these ground water reserves should be used, a policy for optimal management of the supply over a long period of time is needed. This segment of the Pecos River project assumes no major change in the provision for industrial, municipal, and commercial demands. Companion studies by Ralph d'Arge, on the other hand, consider allocations over a period when a shift from agriculture to other uses is contemplated.

Theoretical and computational techniques necessary to formulate a policy for agricultural use in ground water basins over time have been derived during the 1960s, the work of Oscar Burt being most germane to the Roswell Basin [6, 7, 8, 9]. Our analytical methods are from his Hilgardia paper [7], modified by the physical constraints imposed by the basin. One should note that Burt's model took into account the depth to ground water and the resulting increase in pumping costs. These aspects have been assigned to another segment of this project.

Basic Concepts of Dynamic Programming

As in Burt [7], the management policies for the ground water were reached via a dynamic programming model. The general approach was originated by Richard Bellman [2, 3] as a multi-stage decision process, through which the resources available in each time period are used optimally, beginning with the first. This recursive computational process is based on Bellman's principle of optimality [2, 3]: "An optimal policy has the property that, whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."

Application to the Roswell Basin

The objective of this model is to obtain a maximum value for the total cumulative benefits from use of the available water supply for irrigated agriculture over a given time period or planning horizon. In the version of the model described below, recharge to the ground water system is treated as deterministic, while effective precipitation that supplements the pumped supply is treated as stochastic. Benefits for succeeding years are multiplied by the probability of receiving the average effective precipitation for the area.

The inputs of the model are the outputs of the linear program--that is, the maximum benefits possible in each zone when a given amount of water is made available for use. For example, if 410,000 acre-feet may be pumped from the aquifer system each year, with cotton limited to 30 percent of the acreage, maximum benefits would be achieved when 4 percent goes to Zone 1, 38 percent to Zone 2, 30 percent to Zone 3, and 28 percent to Zone 4, so that the total yield exceeds $11 million per year for an average return of $27.26 per acre-foot of water pumped.

To explain in part the computational steps followed in the dynamic program, typical results for two consecutive years are given in table 27. The example is for the cumulative maximum net benefits returned for land and management when the average annual net recharge to the ground water system is assumed to be 200,000 acre-feet per year, with cotton limited to 30 percent and an interest rate of 5 percent assigned to obtain the "present value" of the benefits. The time stream of benefits returned is discounted so that comparisons may be made on a common basis.

One should note that data in table 27 are for 2017 and 2018. A 50-year planning horizon was used in the computations of the dynamic program from 1971 to 2020. In such a program, benefits for the last year of the horizon are optimized first, followed by those for preceding years in reverse sequence, with cumulative benefits over the period made maximum at the end of each year for the resource conditions available at the start of the year.

In 2020 all available water in storage should be used, under the constraints imposed by limitation on cultivated land, with none remaining for the next year. By making the net benefits a maximum in that year, the first policy decision is optimal. Then for 2019, decisions are made that will maximize the net benefits in that year, based on available resources--as were the previous ones for 2020.

Following is an explanation of the results given in table 27. Note that the computations involved are not made in columnar sequence.

Column 1: Each entry represents a possible level of ground water storage at the beginning of the year, with values ranging from 200,000 to 500,000 acre-feet. The low limit is equal to the assumed one-year base recharge, while the upper limit reflects the assumed amount that could be withdrawn from storage in excess of the recharge--without a serious change in quality. In selecting 500,000 acre-feet as the maximum storage level, it was recognized that much more than this is held in storage, but it was chosen as the amount that will be depleted in approximately five years at the 1960-1964 rate of use. If more water than that is lost from

Table 27. Typical results for the dynamic programming model for two sequential years, for a 5 percent discount rate, an average ground water recharge of 200,000 acre-feet per year, and cotton limited to 30 percent of acreage.

(Col. 1) Ground Water Storage Available at beginning of year	(Col. 2) Net Ground Water Withdrawal in Year	(Col. 3) Ground Water Pumped in Year	(Col. 4) Ground Water Left at End of Year	(Col. 5) Maximum Benefits This Year	(Col. 6) Cumulative Maximum Benefits Next Year	(Col. 7) Penalty for Over Use	(Col. 8) Cumulative Total Maximum Benefit Over Time
(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acre-feet)	(millions of dollars)	(millions of dollars)	(millions of dollars)	(millions of dollars)
YEAR 2018							
200	200	240	200	9.016	18.551	0.0	27.568
210	200	240	210	9.016	18.655	0.0	27.672
220	200	240	220	9.016	18.759	0.0	27.776
230	200	240	230	9.016	18.862	0.0	27.879
240	200	240	240	9.016	18.965	0.0	27.982
250	200	240	250	9.016	19.068	0.0	28.085
260	200	240	260	9.016	19.173	0.0	28.190
270	200	240	270	9.016	19.281	0.0	28.298
280	200	240	280	9.016	19.391	0.0	28.408
290	200	340	200	10.410	18.551	0.520	28.529
300	300	360	200	10.631	18.551	0.531	28.651
310	310	370	200	10.741	18.551	0.537	28.777
320	320	380	200	10.850	18.551	0.542	28.902
330	330	390	200	10.959	18.551	0.547	29.027
340	340	400	200	11.068	18.551	0.553	28.152
350	350	420	200	11.285	18.551	0.564	29.271
360	360	430	200	11.393	18.551	0.569	29.396
370	370	440	200	11.501	18.551	0.575	29.520
380	380	450	200	11.609	18.551	0.580	29.645
390	390	460	200	11.717	18.551	0.585	29.769
400	400	480	200	11.933	18.551	0.596	29.887
410	410	490	200	12.036	18.551	0.601	30.001
420	410	490	210	12.036	18.655	0.601	30.105
430	410	490	220	12.036	18.759	0.601	30.209
440	410	490	230	12.036	18.862	0.601	30.312
450	410	490	240	12.036	18.965	0.601	30.414
460	410	490	250	12.036	19.068	0.601	30.518
470	410	490	260	12.036	19.173	0.601	30.623
480	410	490	270	12.036	19.281	0.601	30.731
490	410	490	280	12.036	19.391	0.601	30.841
500	400	480	300	11.933	19.619	0.596	30.955
YEAR 2017							
200	200	240	200	9.016	26.759	0.0	35.776
210	200	240	210	9.016	26.862	0.0	35.879
220	200	240	220	9.016	26.967	0.0	35.984
230	200	240	230	9.016	27.076	0.0	36.093
240	200	240	240	9.016	27.187	0.0	36.204
250	200	240	250	9.016	27.301	0.0	36.318
260	200	240	260	9.016	27.417	0.0	36.434
270	200	240	270	9.016	27.534	0.0	36.551
280	200	240	280	9.016	27.652	0.0	36.669
290	200	240	240	9.016	27.770	0.0	36.787
300	200	240	300	9.016	27.888	0.0	36.905
310	200	240	310	9.016	28.006	0.0	37.022
320	200	240	320	9.016	28.122	0.0	37.139
330	200	240	330	9.016	28.237	0.0	37.254
340	200	240	340	9.016	28.350	0.0	37.367
350	350	420	200	11.285	26.759	0.564	37.480
360	360	430	200	11.393	26.759	0.569	37.604
370	370	440	200	11.501	26.759	0.575	37.729
380	380	450	200	11.609	26.759	0.580	37.853
390	390	460	200	11.717	26.759	0.585	37.977
400	400	480	200	11.933	26.759	0.596	38.096
410	410	490	200	12.036	26.759	0.601	38.209
420	440	490	210	12.036	26.862	0.601	38.312
430	400	400	220	12.036	26.967	0.601	38.417
440	410	490	230	12.036	27.076	0.601	38.526
450	400	480	250	11.933	27.301	0.596	38.638
460	400	480	250	11.933	27.417	0.596	38.754
470	400	480	270	11.933	27.534	0.596	38.871
480	400	480	280	11.933	27.652	0.596	38.989
490	400	480	290	11.933	27.770	0.596	39.107
500	400	480	300	11.933	27.888	0.596	39.225

storage, a quality change may be expected that will cause these economic analyses to be invalid. It should also be noted that this amount is equal to one-half to one-third of the excess withdrawals during the peak pumping period of 1944-1954 (see figure 5).

Columns 2 and 3: To obtain the third column, an optimal amount of water to be pumped during the year was selected; for column 2 this value was divided by 1.20. This calculation reflects a usable irrigation return flow of at least 20 percent, making it possible to pump more water (column 3) while being charged for only the net withdrawal (column 2).

Column 4 shows the base recharge (200,000 acre-feet per year in this case), plus the storage available (column 1), less the net withdrawal (column 2) equals the ground water left at the end of the year. Water left in storage at the end of 2017 becomes that available for use at the beginning of 2018. For example, if 420,000 acre-feet are available at start of this year (2017) and the recharge is 200,000 acre-feet, then the water available for use is 620,000 acre-feet. When the machine searches for the optimum use for this year that will bring the total cumulative benefits to a maximum (column 8--year 2017), it selects a total pumpage of 490,000 acre-feet (column 3--year 2017), or a net pumpage of 410,000 acre-feet (column 2--year 2017). This leaves 210,000 acre-feet in storage at end of the year (column 4--year 2017) and available for the next year (column 1--year 2018), when an optimal policy is again followed.

Column 5: The value obtained this year (from the linear program) when the ground water pumped (column 3) is optimally used for irrigated agriculture.

Column 6: The present value (discounted at 5 percent and modified by a probability statement) of the cumulative total maximum benefits obtainable as of the next year (column 8--year 2018), given the ground water storage available at start of the next year (column 1--year 2018). To follow the calculations, take the ground water storage available at start of the year (2017) to be 420,000 acre-feet, which shows the maximum net benefit for the following year (column 6--year 2017) to be $28,862 million when 210,000 acre-feet are left in storage at end of that year (column 4--year 2017). Thus, the amount available at beginning of the next year--210,000 acre-feet (column 1--year 2018)--will yield a total cumulative maximum benefit of $27.672 million (column 8--year 2018) which, when discounted at 5 percent and modified by the probability of obtaining a full water supply, yields the entry for maximum benefits for the next year (column 6--year 2017).

Column 7: The dollar penalty assigned for overuse during any year, an arbitrary means of assessing a loss in this year's maximum benefits when the net amount pumped is more than is recharged each year (5 percent loss in benefits) and when less is left in storage at end of the year than the average annual recharge (a 10 percent loss). For example, when 410,000 acre-feet are stored at the start of the year (column 1--year 2017) and the net pumpage is the same amount (column 2--year 2017), then a penalty of 5 percent of the year's maximum net benefits (column 5--year 2017) is assigned, or $601,000 (column 7--year 2017).

Column 8: The sum of column 5 plus column 6, less column 7.

In summary: For each year in the planning horizon, the dynamic program finds the optimum means of using the water available (both that in storage at the start of the year and the recharge), beginning with the end year. Based on the policy followed that year to make maximum the benefits returned, each subsequent year is made optimal by increasing the present value of the total cumulative benefits to its maximum.

The policy converges quickly in the time sequence. In most runs the policy to be followed does not vary for the first 40-years of the time horizon. It is only in the final 10-years as we approach the year 2020 that differing policies are recommended for use of the supply. This occurs when the volume that may be withdrawn from storage without serious changes in quality is relatively small compared with the average annual recharge, so that it is only in the last few years of the basin's life that a policy of complete withdrawal is recommended.

In the example presented, the decisions are stabilized by 2011, with the optimal use pattern to be followed from 1971-2011 as given in table 28. For examply, if the available storage at the start of 1971 is 500,000 acre-feet (column 1), then the optimal policy that year would be to pump 480,000 acre-feet (column 3), leaving 300,000 acre-feet (column 4) available for 1972 (column 1). Then the best policy would be to pump

Table 28. Policy to be followed in the optimal use of ground water, Roswell Artesian Basin, New Mexico, between 1971 and 2011, if cotton is limited to 30 percent, the discount rate is 5 percent, and the average annual recharge is 200,000 acre-feet.

(Column 1) Ground Water Storage Available at Beginning of Year.	(Column 2) Net Ground Water Withdrawal During Year.	(Column 3) Ground Water Pumped During Year.	(Column 4) Ground Water Left in Storage at End of Year.
(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acre-feet)	(1,000 acre-feet)
100	100	120	200
110	110	130	200
120	120	140	200
130	130	150	200
140	140	160	200
150	150	180	200
160	160	190	200
170	170	200	200
180	180	210	200
190	190	220	200
200	200	240	200
210	200	240	210
220	200	240	220
230	200	240	230
240	200	240	240
250	200	240	250
260	200	240	260
270	200	240	270
280	200	240	280
290	200	240	290
300	200	240	300
310	200	240	310
320	200	240	320
330	330	390	200
340	340	400	200
350	350	420	200
360	360	430	200
370	370	440	200
380	380	450	200
390	390	460	200
400	400	480	200
410	410	490	200
420	410	490	210
430	410	490	220
440	410	490	230
450	410	490	240
460	410	490	250
470	410	490	260
480	400	480	280
490	400	480	290
500	400	480	300

240,000 acre-feet (column 3) and leave 300,000 acre-feet in storage to begin 1973. Here the policy converges and remains stationary until the year 2012 when increased use of storage begins. Figure 14 is a plot of the rate of change in cumulative maximum net benefits for this same example when the ground water in storage at start of the year (column 1 of table 28) is changed by 1,000 acre-feet.

Variations in the Dynamic Program

In addition to the trial described in the example above, each of the following versions of the dynamic program were run:

Using Net Benefits Returned

Acre-Feet Base Recharge	Percent Cotton Allowed	Percent Discount Rate
100,000-150,000-200,000	30-35-40	4-5-6-7-8

Using Value Added to Water

Acre-Feet Base Recharge	Percent Cotton Allowed	Percent Discount Rate
100,000-150,000-200,000	30-35-40	4-5-6-7-8

Chapter 6

SUMMARY AND POLICY STATEMENTS

Proposed Water and Land-Use Policies

On the basis of results of the mathematical computer models devised for the basin, I propose a set of water and land use policies. In defense of each suggested policy statement I offer an analytical review of the alternatives, which should provide the basic answers to the questions posed at the end of Chapter 3. The analysis has been made on the assumption that, over a 50-year horizon,

1. the basin's water supply will continue to be used principally for irrigated agriculture;

2. the relative price structure and demand for various crops will continue, as will Federal crop support;

3. if the ground water reserves available in 1971 are depleted by more than 500,000 acre-feet, the quality of water remaining in storage will be significantly altered, yielding lower cumulative benefits to the basin;

4. if the supply is not depleted by 500,000 acre-feet, water quality will remain constant as will the relative yields for the various crops;

5. including pumping costs in the analysis will not significantly alter the recommended policy decisions when storage deplections after 1971 are limited to an aggregate of 500,000 acre-feet;

6. the penalties assigned for lowering of the ground water table are reasonable; and

7. corrective measures to bring the basin to a hydrologic and salinity balance will be undertaken.

Of these seven assumptions, one in particular requires additional documentation: that the "available" storage held in reserve is only 500,000 acre-feet. The years between 1952 and 1957 constituted a period of maximum withdrawals from the basin (table 11) during which the quality of the supply greatly deteriorated. Hood [22, plate 10] found chloride increases of 100 ppm in water from the semi-confined aquifer over a large part of the Roswell-Grand Plains subzone and increases of 500 ppm over a smaller, but significant, area. Between 1960 and 1965, the chloride concentration in 53 good-quality wells (450 to 500 ppm chlorides) in the area north of T13N increased by 200 ppm, while the increase in poorer-quality wells was from about 1,000 to over 1,700 ppm.

During 1960-1964 the annual overdraft on the system has been estimated at about 120,000 acre-feet [27, p. 50]. A shift in water quality from 3×10^3 to 4×10^3 micromhos of conductivity constitutes an economic depreciation of $6.00 per acre-foot of water when the rate of application is three acre-feet per acre on lands of Soil Group I (see figure 8). Even more serious from an economic view point is the cost of a quality change from 5×10^3 to 6×10^3 micromhos, when the net benefits decrease from $23.00 to $12.00 per acre-foot for a duty on three acre-feet of water per acre on Soil Group I. Change of this magnitude occurred during 1960-1964 when the net depletion was about 600,000 acre-feet. Converted to present value at a discount rate of 5 percent over the 50-year horizon, this change represents a serious loss in value per acre-foot pumped. A $6.00 loss at 5 percent over 50 years is equal to a loss with a present value of over $100 per acre-foot. If one-half of the Roswell Artesian Basin's supply is assumed to originate north of T13N in the area where the most noticeable quality changes have occurred, the annual prediscounted loss will be $600,000 or roughly 7 percent of the maximum annual benefits (see table 27) from the basin.

These estimates represent changes that could recur when the next 500,000 acre-feet of reserve supply is expended. Considering successive changes in quality as more and more water is withdrawn from storage, it becomes apparent that there must be an upper limit on the total amount that may be drawn from present reserves. Based on this assumption, a maximum "available" storage of 500,000 acre-feet was used.

Policy on Depletion of Ground Water Reserves

To delineate a policy leading to maximum cumulative net benefits when water is to be withdrawn from storage, we must specify the following:

1. the average annual recharge to the system from precipitation available for use;

2. the annual safe pumpage from the aquifer system above which continuing depletion of fresh water takes place;

3. the volume of available ground water supply held in storage at the start of the planning horizon;

4. the appropriate discount rate; and

5. the constraints imposed on the use of water, such as allowable limits on cotton acreage.

The policy statement that follows is based on the following numerical values for the above items:

1. 200,000 acre-feet;

2. 240,000 acre-feet;

3. 500,000 acre-feet;

4. 5 percent interest; and

5. 30 percent cotton.

Policy Statement

During the first 40 years of the planning period, year-to-year variations in volume of available ground water reserves should be permitted, based on variations in effective precipitation and recharge to the system, but with cumulative depletion in storage not to exceed 500,000 acre-feet. If at the end of this period the policy is to deplete completely the remaining stock, then an optimal arrangement for this purpose may be specified.

In Support of Proposed Policy

Table 28 and figure 14 both confirm the optimal net annual depletion to be 200,000 acre-feet (column 2, table 28) for the conditions assumed. If storage at the start of any year falls below 200,000 acre-feet (column 1), the optimal policy directs that the minimum reserve storage (column 4) be returned to that level and maintained there. If during periods of unusually high precipitation the ground water storage increases to levels greater than 320,000 acre-feet, the optimal net depletion will be more than 200,000 acre-feet but will fall back to that level the next year. Figure 14 shows that, at levels between 200,000 and 320,000 acre-feet, the change--increase or decrease--in maximum net returns is nearly at a minimum when the level of the reserve supply fluctuates by 1,000 acre-feet. One should also note that no net annual depletion occurs in this range under the proposed management policy.

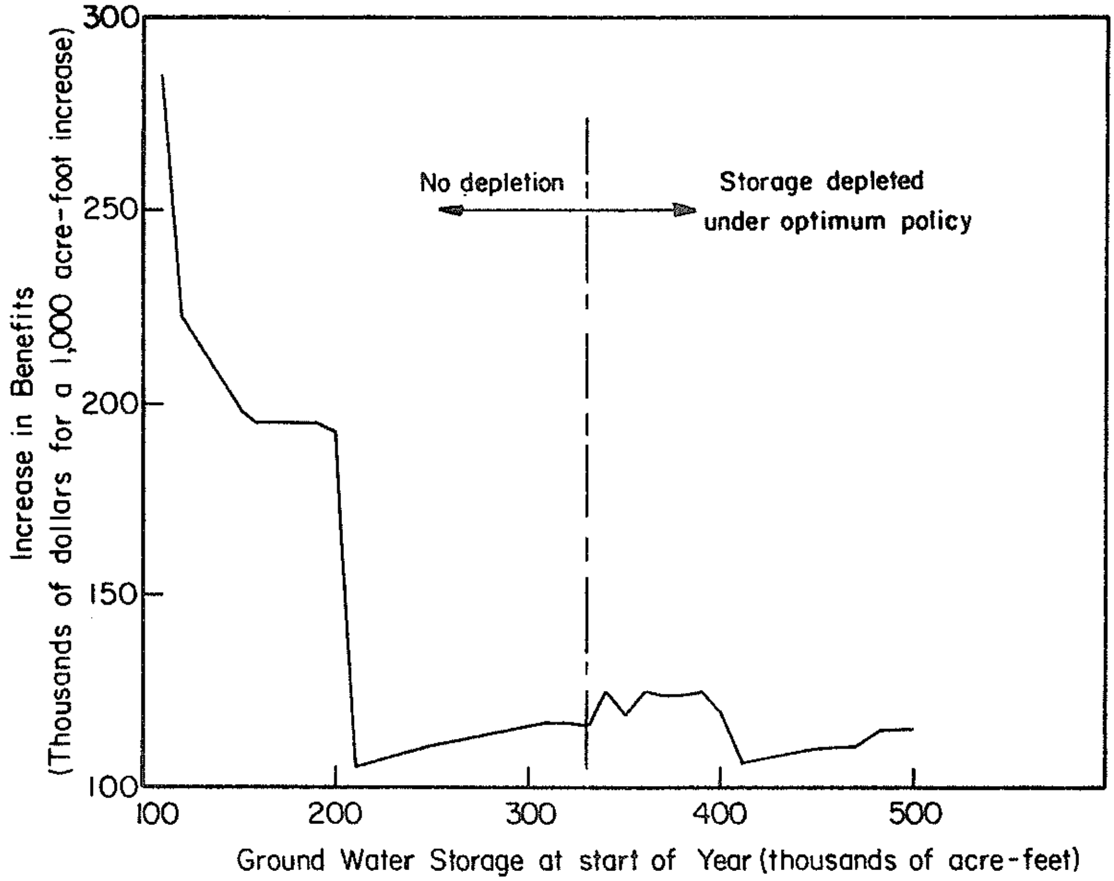

Figure 14. Plotted increase in cumulative maximum benefits when storage level at start of year is increased by 1,000 acre-feet, with 5 percent discount rate, 30 percent cotton, and 200,000 acre-feet recharge annually.

Variations in Policy

Both measures of the productivity of water that were considered (net benefits returned for land an management, and the value added to water) yield the same recommended policy, which does not change with changes in the discount rate--as in Burt's study [6, p. 84], the "optimal policy is not sensitive to interest rate." The same approach is also valid for increased percentages of irrigated acreage in cotton, although variations occur as the end of the planning horizon nears.

The policy is quite sensitive to changes in ratio of annual recharge to amount of water in storage. When the amount of water in storage at the beginning of a year is four or five times greater than the annual recharge, the optimal policy is to withdraw a part of the reserve. In succeeding years it continues to call for depletions in storage until a stable policy is reached, as shown in table 28, for initial levels of 200,000 to 320,000 acre-feet in storage.

Policy on Use of Three Acre-Feet per Acre

As noted previously, a duty of three acre-feet per acre per year, averaged over a five-year period, has been instituted in the Roswell Artesian Basin by a judicial decision [42]. A possible administrative decision would be to seek to alter this level of application to admit higher levels on certain lands with particular soil and water qualities. This might be done to increase the benefits returned.

Policy Statement

As a common administrative base, the three-acre feet duty should be retained. The modification of basin-operating regulations should be sought that would permit short-term transfers of water rights between producing wells within certain geographic proximities of each other, when prescribed aquifer restraints are met.

In Defense of the Policy

It is true that most of the basin lands can yield higher benefits per acre when additional water is made available up to the point where pumping costs exceed returns (see figure 7). Water, however, and not land is in critical supply. Figures 8, 9, and 10 depict declining returns per acre-foot as more water is applied.

As shown by Lansford [27, table 40], additional parcels of land must be retired if higher application rates per acre are permitted. If public policy is based on the value added to water, then as many acres as possible would be cultivated within water supply constraints (see figure 13 and table 24, column 3). The permitting of variable duties, depending on soil and water quality, would be difficult to establish.

One way to achieve higher yields per acre would be to allow a marketplace transfer of water-rights for a single season. Here a willing buyer could negotiate with a willing seller to obtain additional supplies at a fair market price based on the returns anticipated by each. Constraints would have to be placed on the geographic proximity of transfer permits, allowable drawdown, and aquifer compatibility. To expedite transfers, a local water-users' group might conduct an annual auction where availability and price of transferred water could be established for various subregions in the basin. Administrative costs for regulating such a program could be recovered from the water-right buyer and excess revenues could be applied to land retirement programs.

Policy Decisions on Land Retirement

Assumptions

The policy statement on land retirement is given by zones to meet physical limitations on available water supply (see column 14, table 18) and is based on an average annual safe pumpage of 245,000 acre-feet (30 percent irrigation return flow) at a water-application rate of three acre-feet per water-right acre, so that the allowable long-term cultivated acreage is 81,700. When the 1967-1968 level of irrigated farming from ground water sources in the basin is taken to be 127,700 acres, the acreage that must be retired from production is approximately 46,000. Table 29 gives the approximate present acreage and long-term allowable acreage by zones and aquifers.

Policy Statement

Zone 1: Retire approximately 7,000 acres now taking their supply from the limestone aquifer. All Soil Group III lands, and Soil Group I and II lands with chloride concentrations greater than 1,500 ppm, should be retired (see table 20), as should some Group I lands with chloride concentrations between 1,000 and 1,500 ppm. Where

Table 29. Approximate estimates of present and long-term allowable irrigated lands in order to maintain an adequate reserve supply of freshwater in storage in each zone by source of supply, Roswell Artesian Basin, New Mexico.

Geographic Zone	Land Irrigated at Three Acre-Feet per Acre: Shallow Aquifer: 1967-68 Level	Shallow Aquifer: Long-Term Allowable	Semi-confined Aquifer: 1967-68 Level	Semi-confined Aquifer: Long-Term Allowable	Difference Between Long-Term Allowable and 1967-68 Level of Irrigated Farming: Shallow Aquifer	Semi-confined Aquifer
	(acres)	(acres)	(acres)	(acres)	(acres)	(acres)
Northern Extension 1	700	700	10,000	3,000	--	-7,000
Roswell-East Grand Plains 2	10,000	18,000	27,000	16,000	+8,000	-11,000
Dexter-Hagerman 3	19,000	8,000	16,000	10,000	-11,000	-6,000
Cottonwood Creek-Artesia 4	15,000	12,000	30,000	14,000	-3,000	-16,000
Totals	44,700	38,700	83,000	43,000	-6,000	-40,000

choice exists, lands to the north and west should be selected for retirement first.

Zone 2: Retire approximately 11,000 acres that now receive their supply from the semi-confined aquifer. Retire Soil Group I and II lands with water qualities poorer than 1,000 ppm chlorides, and all Soil Group III lands with more than 500 ppm chlorides in their water supplies (see table 21). The farther west the lands lie, the more favorable their withdrawal from cultivation. Lands to the east of Spiegel's axial trace [40, pp. 35-37] should probably not be retired except by attrition. Should insufficient land be available for retirement that meets these criteria, then lands with the following soil and water quality indexes (see table 17) should be removed in the order given: 26, 34, 33, 16, 25, 32, and 31 (see column 2, table 21).

Zone 3: Retire water-rights for 11,000 acres of land supplied from shallow wells, and water-rights for 6,000 acres of land using water from the semi-confined zone. Make water available to 8,000 acres via canal or pipeline, or a combination of these, from a well field supplied from the shallow aquifer near the Pecos River in Zone 2, Roswell-East Grand Plains area.

Water-rights to be retired should come from all lands of Soil Groups II and III, and Group I lands with water poorer than 300 ppm chlorides (see table 22). Lands to lie fallow should be selected from those as far west as possible that meet this criterion. Group I lands should be chosen to receive the well-field water supply made available to the zone via pipeline and canal.

Zone 4: Retire 3,000 acres supplied from the shallow water table and 16,000 acres withdrawing water from the artesian aquifer. Retire all Soil Group II and III lands and those of Group I with chloride concentrations greater than 300 ppm (see table 23). Where choice is possible, western lands should be retired first.

In Support of the Policy

Selection of lands for retirement is based on their relative economic productivity as ranked in tables 20 through 24. The total acreage of land to be retired is based on the difference between 1967-68 level of farming, and on the allowable long-term acreage based on the safe yield from the system. It should be noted that the 46,000 total acreage proposed for retirement coincides with Lansford's recommendation [27, table 40], although a somewhat different route was taken to the conclusion. The acreage to be retired in each zone, irrigated from each aquifer, is based on the safe-yield calculation of table 18.

The most unusual, and so far unsupported, aspect of the policy statement is a proposal to install a well field along the river in the Roswell area, transmitting the water to the Dexter-Hagerman area via canal or pipeline. Hantush [17, p. 101] and others have indicated the need to redistribute the pumping in the basin and in particular to salvage some of the water now lost to evaporation and phreatophytic growth near the river in the vicinity of Roswell.

The need to control salt cedar growth in the area has received wide attention, serving as the basis of current Bureau of Reclamation projects (see Chapter 1). I feel that the clearing techniques proposed by that agency are inadequate because they fail to fulfill a key requirement: that the ground water table be significantly lowered. Continued large loss to evaportranspiration will accompany any effort that fails to drop water levels in the vicinity of the river. Clearing programs also require high maintenance costs to remain effective. Hughes [25], in a report funded through the Pecos River study, estimates the annual maintenance cost as $8.71 per acre, after an average clearing cost of $63.00. He found it economically feasible to remove salt cedar between Acme and Carlsbad.

There are several advantages to using a well field to recover the water now being lost. First, it is relatively easy to identify those who benefit, since they receive the water and can be charged for operation and maintenance costs. Second, the amount salvaged can be directly measured. Third, the design and rate of pumping in a well field may be quite flexible, permitting the preservation of certain phreatophyte zones for fish and wildlife habitat.

A well field will have the apparent (and short term) effect of reducing the flow in the river; for this reason it would be opposed by surface water-right holders. However, when viewed as part of a program designed to reduce withdrawals from the basin's aquifer system, the measure should be readily accepted.

Initial financing of wells, drains, and canals could conceivably be carried out under current Bureau of Reclamation projects. The Federal legislation authorizing the Bureau's participation appears to be quite broad [36, p. 131], but changes may be needed for the development of a well field. Modifications to and extension of the Hagerman Canal could provide a means of transporting water from Zones 2 and 3. I feel that development of a well field offers the best long-term solution to a part of the basin's problems.

Policy for the Individual Farmer

Of the three preceding proposed policy statements, none is directed at the people who make most of the management decisions [16, p. 27]: the individual farmers. The farm manager does need a policy to set the amount of water that may be pumped in any one year and the rate of application during the irrigation season for each of the crops he has selected.

Policy Statement

In 1972 at the start of the new five-year averaging period for pumping from the Roswell Artesian Basin, a farm manager should begin the year with the intention of irrigating his water-right lands during that irrigation season at what is then the legal average application rate, using an optimal cropping pattern for the predominant soil and water quality that prevails. Based on an analysis of area rainfall records it may be noted that, if at the end of May the total precipitation (Artesia gage) for the first five months is less than 2.5 inches, the manager should expect the cumulative rainfall for the next four months to be below normal 60 percent of the time (years). If rainfall for the first five months exceeds 2.5 inches he may expect rainfall for the next four months to be above normal (60 percent of the time). The irrigator should maintain a flexible position that permits him to respond to precipitation levels by making frequent but light applications, depending on moisture levels in the upper root-zone, and depending on soil characteristics. Decisions for withdrawals during the next four years will be based on how much is pumped the first year, but in general the manager should start the second, third, and fourth years with the same intentions as for the first year in the five-year averaging period.

In Support of the Policy

Under present judicial decisions irrigators in the Pecos Basin may use more than the legal amount of water per acre in any one year, but the total during a specific five-year period may not exceed five times the legal yearly rate. The concept that the irrigator should start each season as though he were going to use three acre-feet per acre (or whatever the legal average application rate happens to be) is founded on the fact that use of this amount each year represents the best long-term policy. If he uses much more than this one year, then he must leave land fallow in subsequent years. He has no way of knowing what the rainfall will be to supplement the pumped supply. The only advantage of averaging use over five-year periods is that some leeway is possible, once the irrigation season is underway and proves to be either a wet or dry year.

The cropping patterns computed in this study for various rates of application (see tables 21 and 26), yield the optimal strategy for the use of water when the total amount available is constrained. If the total available supply during a five-year period is 15 acre-feet, then the best procedure would be to use three acre-feet per year. For example, if a farmer has fair-quality water and good land (Soil Group I and water quality 4) and 30 percent of his land is in cotton, he would obtain net benefits of $108.00 per acre when 2.95 acre-feet per acre are pumped to optimally cropped lands as follows: 30 percent of farm land in cotton at 3.75 acre-feet per acre, 25 percent in sorghum at 3.25 acre-feet per acre, and 45 percent in barley at 2.25 acre-feet per acre. In five years he would net $540.00 per acre. As an alternative plan this irrigator could apply 3.40 acre-feet per acre each of the first four years and make $109.80 per year per acre (30 percent cotton at 3.75 acre-feet and 70 percent sorghum at 3.25 acre-feet per acre). During the fifth year he would use the remaining water, planting cotton on 30 percent of his land at 3.75 acre-feet per acre, 13 percent in barley at 2.25 acre-feet per acre, and leave the remaining 57 percent of the farm fallow to earn $85.80 per acre, or a total of only $525.00 per acre with the same 15 acre-feet employed.

The proposed policy includes a rainfall probability estimate. Writing probability statements for farm management is frought with danger, yet the farm manager will provide his own version of a likelihood statement based on experience. He has little choice at the start of each irrigation season except to go on the premise that climatically it will be a normal year. Even if the preceding year was wet, he can assume nothing about the coming year. The precipitation received by the basin each year must be considered as a random variable. Historic annual rainfall records at many stations in the Roswell area were analyzed for serial correlation. For Roswell a correlation coefficient of 0.15 was obtained for the relationship of each year to the next; for Lake Avalon, 0.041; Artesia, 0.012; and Carlsbad 0.087--all indicating low correlation.

Lansford [28, p. 21] provides an equation that relates the irrigation water pumped to the annual precipitation in the basin. Over a range of 5 to 17 inches of rainfall the average withdrawal $\underline{Y}$ in acre-feet per irrigated acre is

$$Y = 4.05 - 0.097X \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

where $\underline{X}$ is the annual precipitation in inches. A single inch difference in rainfall alters the amount that must be pumped by approximately 0.10 acre-foot.

A difference of this magnitude may be predicted in rainfall over the four-month period, June to October. A 60-year record of precipitation at Artesia was analyzed. The median for the period January through May is about 2.5 inches; that for the next four months is 5.6 inches. When probability plots are made (see figure 15) for rainfall for June through September, two distributions are obtained--one for those years when the rainfall for the first five months was above the median, and another for the years when it was less than 2.5 inches. The median rainfall for June through September is about 4.8 inches for the years with below-normal periods (see figure 15). The hypothesis that these two distributions come from the same family may be rejected at the 10 percent significance level on the basis of a nonparametric "ranking sum test" [24].

The concept of frequent irrigation applications comes from Hanson's work [16, p. 25]. Using a number of light applications would give the farmer several chances to decide how much to use, based on temperature and rainfall conditions then existing in the area.

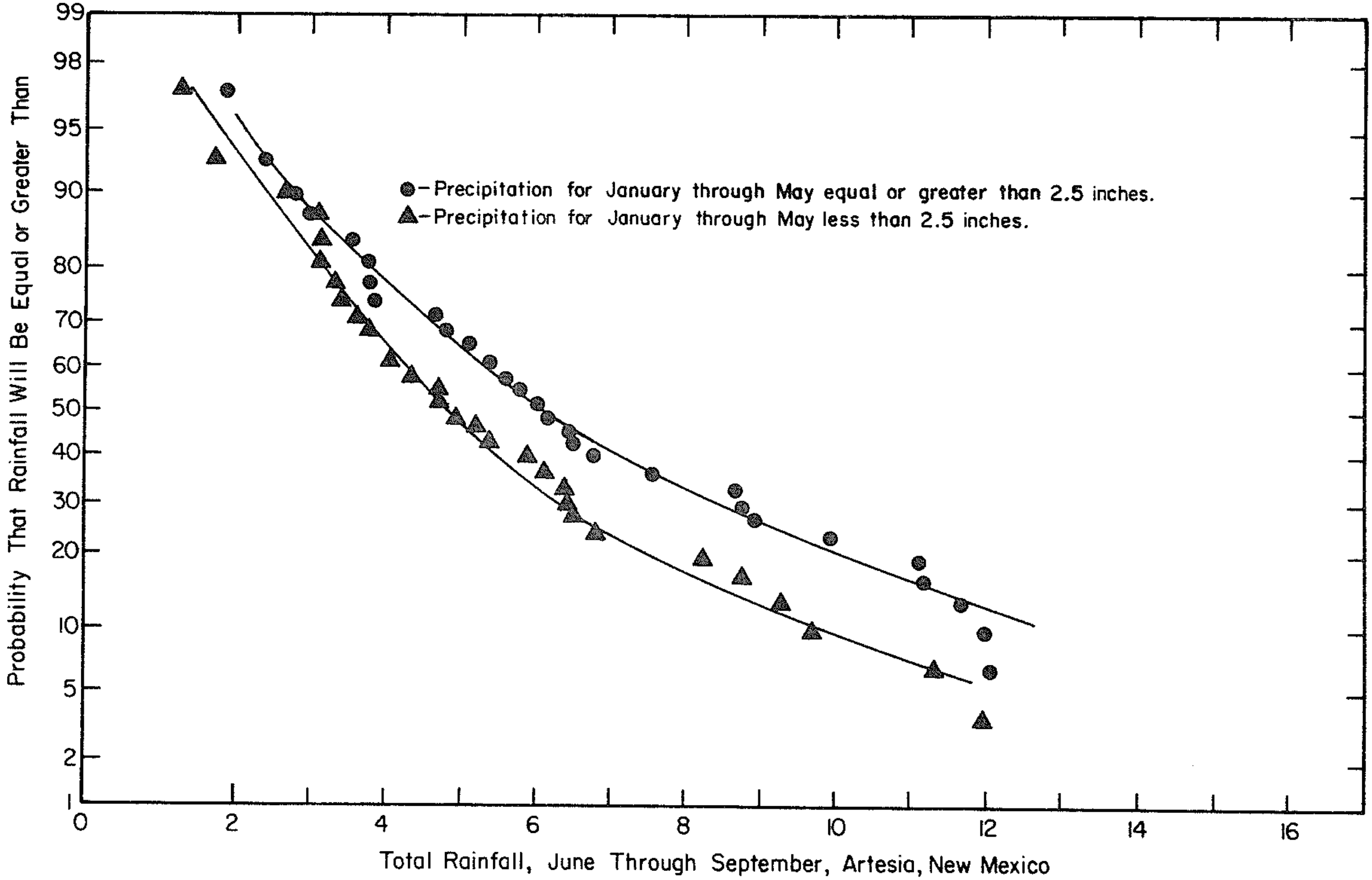

Figure 15 . Probability distribution for precipitation at Artesia, New Mexico, June to October.

Finally, an optimum cropping pattern for an individual farm can be readily determined if the cotton allotment, soil group, water quality, depth to ground water, pump efficiency, and farm size are known. The difference between the net returns to the basin actually achieved and those possible with optimal cropping patterns has been presented by Lansford, *et al*. [27, p. 38].

Part III

MANAGEMENT OF THE SURFACE WATERS OF THE PECOS RIVER IN NEW MEXICO

Chapter 7

PROBLEMS AND POSSIBLE SOLUTIONS

The Pecos River and its tributaries yield an average of almost 600,000 acre-feet per year. Of this amount, 40 percent leaves the state under an interstate compact, 30 percent is lost to nonbeneficial uses, and the remaining 30 percent is used to supply beneficial consumptive use--mostly for irrigated agriculture. The basic problem is the variability and the quality of the supply aggrevated by high river and evaporation losses; solutions to the problem are frustrated by physical, economic, legal, social, and political complications. A summary of some of the physical and climatalogical characteristics of the basin is provided in Appendix A.

Principal Problems

Low Economic Returns

The net benefits returned to most users of surface water in the Pecos Basin are low in comparison to those obtained by ground water pumpers in the Roswell area. Tables 22, 23, and 24 indicate that net returns exceeding $30 per acre-foot are possible in the Roswell area at a ground water diversion rate of only three acre-feet per acre. Table 30 gives average returns for irrigation in three sub-basins of the Pecos, ranging from $30.00 to $75.00 per acre. The information in this table was developed by Lansford, *et al*. [26] as a part of the Water Resources Research Institute Pecos Basin Study. Table 30 also summarizes the major problems in three of the four irrigation districts in the basin that are the source of the low economic land-classifications.

Water Shortages

During dry years water shortages are a common problem, even in the headwater country of the Upper Pecos. The Storrie project was initially ment to support 12,000 acres, but the supply has proven inadequate for a developed acreage of half that size. Upper-basin irrigators who divert water from the river and its tributaries report

Table 30. Summary of surface water and ground water uses for irrigated agriculture in the Pecos River Basin, New Mexico, 1966-1967 level.

Sub-Basin[1] Geographic Location, and 1966-1967 Level of Water Diversions	1966-1967 Land Under Cultivation By Economic Land Classification (acres)			1966-1967 Average net Returns for Land and Management By Economic Land Classification[2] (dollars per cultivated acre)			1966-1967 Principal Crops by Approximate Percentages	Percent of Cultivated Lands Irrigated for Surface Sources	Principal Agronomic Problems
	I	II	III	I	II	III			
Upper Pecos Basins San Miguel and Guadalupe Counties 78,980 acre-feet	-	-	12,500	-	-	30	alfalfa 37, small grains 9, forage and pasture 32, fallow 11, and fruits and vegetables 11	99	extremely small farm-size, farm shape, short growing season, limited crop selection, and soil quality
Ft. Sumner Area DeBaca County 33,281 acre-feet	-	5,229	2,750	-	55	30	alfalfa 35, grain sorghum 9, forage crops and pasture 22, fallow 22	75	small farm-size, high per-acre investment, low productivity of some soils requiring higher levels of management to maintain crops
Carlsbad Basin Eddy County 91,521 acre-feet	-	27,664	5,144	-	75	30	cotton 35, alfalfa 37, forage crops and pasture 4, fallow 19	80	insufficient water supply in all years, poor water quality, marginal soil productivity

[1] Roswell Basin omitted as surface water-rights constitute just slightly more than 6,000 acres with 21,617 acre-feet diverted.

[2] Economic land classifications from Lansford *et al.* [26].

deficiencies in the early summer months [26, p. 14]. These deficiencies are due in part to the lack of adequate diversion and ditch facilities. Below Anton Chico the Pecos is dry at times, with low flows completely disappearing near Colonias. Regarding the flow near Santa Rosa, the 1942 Joint Investigation Report [33, p. 136] noted that "at this point the entire flow of the Pecos is in use and great scarcity is felt during the irrigation season".

The Fort Sumner project diverts its water from the river a few miles below Alamogordo Dam (figures 2 and 3); still, the volume withdrawn in any one year is quite variable, ranging from 21,300 to 45,900 acre-feet during 1919-1961 [46, pp. 4-11]. In the Roswell area, where an average of 16,400 acre-feet is taken from the Pecos by pumping, variations in the same period were from 10,700 to 27,200 acre-feet. Shortages to river pumpers are estimated to be about 3 percent of the average demand [46, tables 1-11].

The principal user of surface waters is the Carlsbad Irrigation District (CID). Its diversion demands are extremely high--5.2 acre-feet per acre to about 25,000 acres--partly because of high consumptive use and nearly year-round irrigation, but mainly because of low farm irrigation efficiencies (55 to 60 percent) and high canal losses (35 to 40 percent) [46, p. A-12]. Historically, shortages have averaged 25 percent of the full supply; insufficient irrigation water is experienced almost every other year; maximum deficits have exceeded 60 percent of the demand; and prolonged periods of inadequate supply have been experienced. The available diversions during 1949-1953 were 2.24, 2.56, 2.45, 2.15, and 1.39 acre-feet per acre, respectively.

Water Quality

Lansford cites poor quality and short supply as the two principal factors in his economic assessment of the lands irrigated from surface water in the Carlsbad area. Their joint effect is to reduce the average return from lands with good soils from more than $100 to $75 per acre per year (see figure 11 for the change in benefits according to water quality). The low farm irrigation efficiencies are partly the result of high application rates to flush salts from irrigated lands. Lower yields and higher irrigation diversion rates combine to produce lower net benefits per acre-foot of water.

Good quality is maintained in the headwaters of the upper basin, but large increases in sulfates and chlorides are encountered in the reach between Colonias and Puerto de Luna (figures 1, 2, 3, and 16). As there is no storage in the main stem of the river above Alamogordo Dam, this degradation in quality adversely affects irrigated agriculture in the vicinity of Santa Rosa during the months when low flows predominate.

System Losses

Details of the losses from the Pecos will be given in Chapter 8. They include evaporation loss, use by phreatophytes, and channel and canal losses. Most of these occur below Alamogordo Dam. The salvage of water now used by phreatophytes is the goal of current Bureau of Reclamation projects and a $4 million CID project is designed in part to reduce canal losses (see Chapter 1).

Inadequate Storage Capacity

The presently inadequate storage facilities on the system are being further depleted by sediment deposition. Variable inflows make over-year storage a necessity if a sufficient supply is to be provided for periods of prolonged drought. About one-half of the water supply to the CID originates below Alamogordo Dam, with little residual capacity available to store this water in McMillan Reservoir and little in Avalon. Flood control and supplemental and replacement storage are included in proposed Crops of Engineers and Bureau of Reclamation projects (Chapter 1) that will result in new structures at Los Esteros above Santa Rosa and at Brantley Dam site above Carlsbad (figures 2 and 3).

Flood Damage

Historically, most of the Pecos Basin has been subject to occasional rains of high intensity--for example, 5.5 inches fell in one day at Artesia [45, p. 39], a rainfall with an average return period of over 100 years.

Floods in the basin have resulted both from local thunderstorms and from heavy rains covering a large part of southeastern New Mexico. On at least 12 occasions since 1900 floods have wrought major damage. Based on 1950 price levels, potential losses for the standard project flood (132,600 cfs) have been estimated to be over half a million dollars in the reach between McMillan Dam and Carlsbad [51, p. 3].

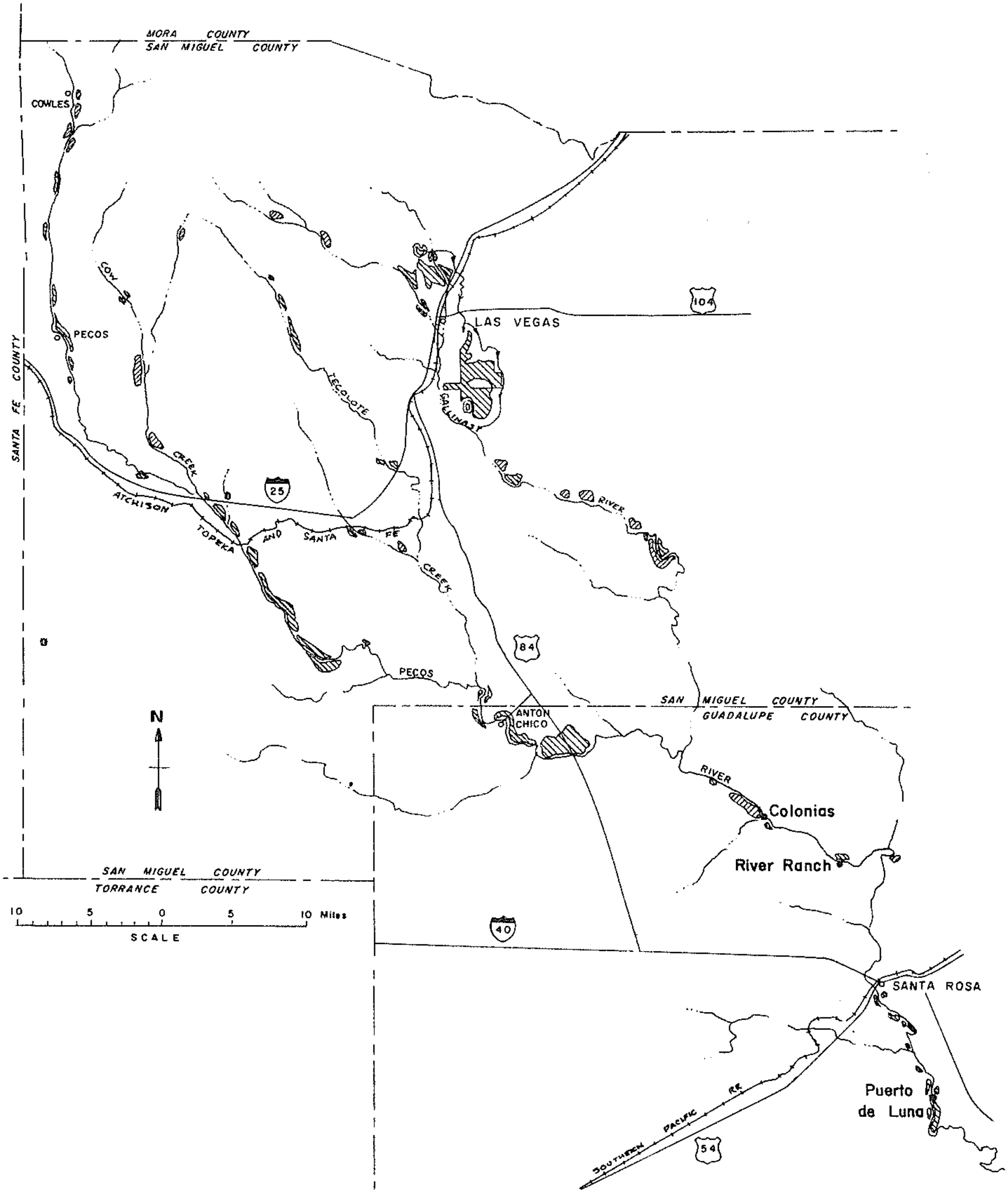

Figure 16. The Upper Pecos Basin, New Mexico.

Should project floods occur at any of a number of locations in the basin, significant damages may be expected, particularly at Carlsbad and Las Vegas. In August 1966, heavy rains in the Artesia-Carlsbad area produced record flood discharges at several stations. Carlsbad suffered most; total storm losses included two lives and more than $4 million in property losses were claimed.

Active and Proposed Programs

There has been almost continuous effort by private, local, state, and Federal interests to manage or resolve the most persistent of the basin's problems. A review of the more important current,active and proposed projects has been presented in Chapter 1. Basically, these would provide (1) storage in reservoirs such as Los Esteros and Brantley for storage being lost to silt accumulations in other reservoirs; (2) flood protection and temporary storage at these two reservoirs; (3) partial control of saline water inflows in the Malaga Bend area; (4) salvage projects to clear salt cedar growths from the head waters of the Pecos to the state line and in the McMillan delta area; (5) flood and sediment control measures in the upper reaches of the Pecos tributaries under Public Law 566, The Small Watersheds Act; (6) minor contributions to fishing, waterfowl, and recreation at the two proposed reservoirs, Los Esteros and Brantley; (7) improve delivery efficiency and reduce canal losses on the CID project; and (8) rehabilitation of the small irrigation systems in the Upper Pecos under combined state and Federal programs.

Alternatives to the construction of the two new dams designed to increase the storage on the system have previously been considered and, for the most part, rejected. Some of these are [38, p. 220] to raise McMillan and Avalon Dams, dredge the McMillan reservoir, or develop underground storage downstream from McMillan near Major Johnson Springs. Other alternatives would be raising Alamogordo and dredging the reservoir.

In addition to these approaches to the basin's problems, two other possibilities warrant study: (1) intra-basin transfer of water from the upper basin to the Roswell-Carlsbad area, and (2) use of channel lining to limit loss in both quantity and quality. Between Anton Chico and Colonias as much as 60 to 100 percent of low-flows is lost into the underlying limestone formation and part of the flow regained in the vicinity of the Colonias and the remainder probably returns to the river in the Santa Rosa area. Degradation in quality occurs in the reach below Colonias when this water returns to the stream (see figure 16). Not all of the water quality deterioration that takes place in the reach is caused by the return of this water to the river. Springs discharging from the Bernal formation add extremely poor-quality water to the river between Colonias and Santa Rosa. Channel losses also occur between Alamogordo and Acme.

Questions To Be Answered in Analytical Studies

The principal studies to be reported in the next chapter were conducted as a review of the efficacy of the two proposed new major structures on the system, Los Esteros and Brantley Dams, and also to provide insight into operation of the system when these units become functional. An indicative, if superficial, review was made of the problems of quality loss in the Colonias-Santa Rosa area.

Two other topics considered briefly are the feasibility of intrabasin transfers and the possibility of developing any unappropriated floodwaters that may exist. The Texas-New Mexico Pecos River Compact of 1948 [38, pp. 243-254] provides for the division of the water supply under 1947 conditions. The agreement provides that unappropriated floodwaters must originate above Red Bluff Dam and that their use and impoundment must not deplete the amount of water available for use with the diversion and storage facilities on the system under the 1947 condition. Beneficial consumptive use of unappropriated floodwaters is to be divided into equal shares by the two states.

The analyses were directed to the following questions:

1. With respect to water quality deterioration in the Colonias-Santa Rosa reach,

    a. What economic loss is involved?

    b. Can this loss be prevented?

    c. Will the construction of Los Esteros Dam midway in the reach increase the degree of deterioration?

2. Are intrabasin transfers of water feasible?

3. What is the extent of unappropriated floodwaters and can they be economically developed?

4. Is additional storage needed on the system?

5. What storage and routing-management of system reservoirs will yield the greatest average-annual water supply for the Carlsbad Irrigation District?

6. Are there operating policies that will permit better intra-year management of water stored in the system's reservoirs?

Chapter 8

ANALYTICAL STUDIES

Simulation Techniques

Reservoir-routing studies based on historical data have been used to predict the consequences of various changes in operating policies and available storage on the Pecos system [46]. These Bureau of Reclamation analyses have been quite limited because of the system's complexity and the time required for individual calculations, so that many possible variations have not been considered.

A hydrologic technique that has received attention in recent years is the use of simulation models and synthetic hydrology. The originator of this science was Allen Hazen, who in 1914 generalized the flows in many northeastern United States streams in terms of their coefficients of variation, and then combined the records of flow for some of these rivers to obtain a much longer and more reliable estimate of the probability of future discharges [18].

Interest in this approach was renewed with publication of Design of Water-Resource Systems in 1962 [11]. Hufschmidt and Fiering, two of the contributing authors, have also written a good text on the use of modern versions of simulations technique [24] as applied to the Lehigh River Basin. They regard the process as one of duplicating the essence of a system "without attaining reality itself." The basic methodology is to describe historical records by a statistical distribution that is similar to that already experienced. Stochastic techniques are then used to generate a new or synthetic hydrograph. But simulation does not end here; it also implies the reproduction of the probable behavior of the entire system--a complex union of multiple stochastic and deterministic functions.

The uses of such models are

1. to identify the response of the system to patterns of flow that are as likely to occur as is the historical sequence;

2. to determine complex, interdependent relationships between system variables;

3. to permit experimentation that is not possible with the actual system;

4. to allow intensive analyses of critical flow sequences, such as those provoking droughts and flood peaks;

5. to afford extrapolation that could not be extended from historical data; and

6. to generate an analysis that is directed at identifying and evaluating design-decisions rather than the physical aspects of the actual system.

Pecos River Simulation Model

To accomplish the objective of providing a set of decision functions for operation and use of the surface waters of the Pecos, I employed a simulation model. The basin inputs are stochastic predictions of the various inflows into the system and deterministic approximations of the losses and uses. Conclusions were based on studies that included both intra-year and inter-year models. Main sources of information were the Bureau of Reclamation reservoir-routing study [46] and the Report on Review of Basic Data to the Engineering Advisory Committee of the Pecos River Commission [14]. The basic historical data in these two reports include modifications that represent 1947 conditions.

The Engineering Advisory Committee has calculated the historical flow that would have entered Los Esteros Reservoir between 1919 and 1961. This 43-year record was obtained by subtracting 7,200 acre-feet from the recorded annual flows at Santa Rosa to reflect the average inflow between the dam site and the gaging station. This account was used as the starting point for the model. Figure 17 is the time-flow graph of the calculated historical flow-sequence for the period.

Relationship Between System Inflows

In addition to the river flow at Los Esteros, nine other major tributary or ground water sources discharge into the stream above Red Bluff Reservoir. Figure 18 is a conceptual map of the basin, indicating the average annual magnitude of the gains, the areas of loss, and the average residual flow at several points. Figure 19 provides the same basic information, but is the Bureau

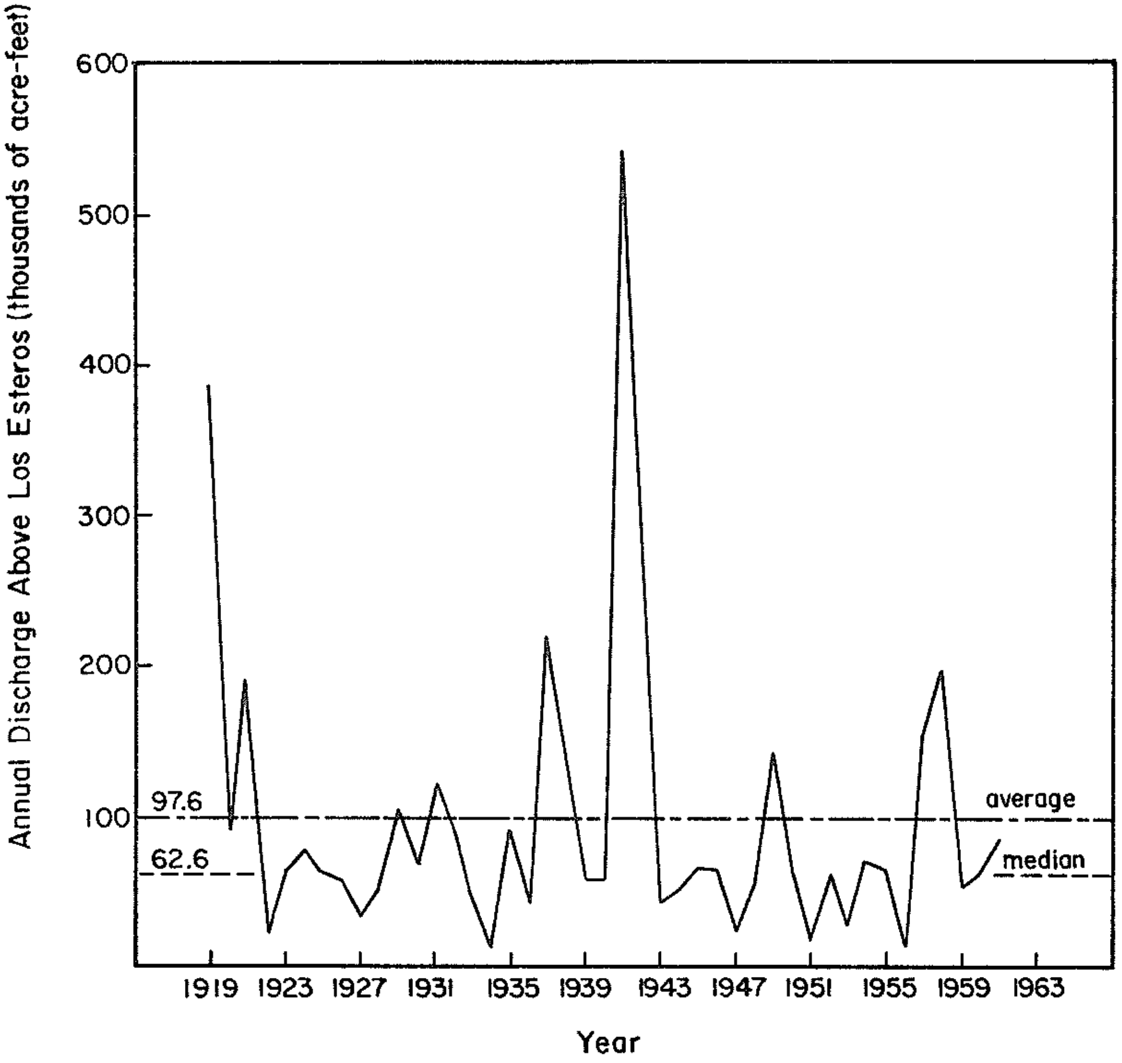

Figure 17 . Historical time-flow sequence 1919-1961 at Los Esteros Dam Site , New Mexico.

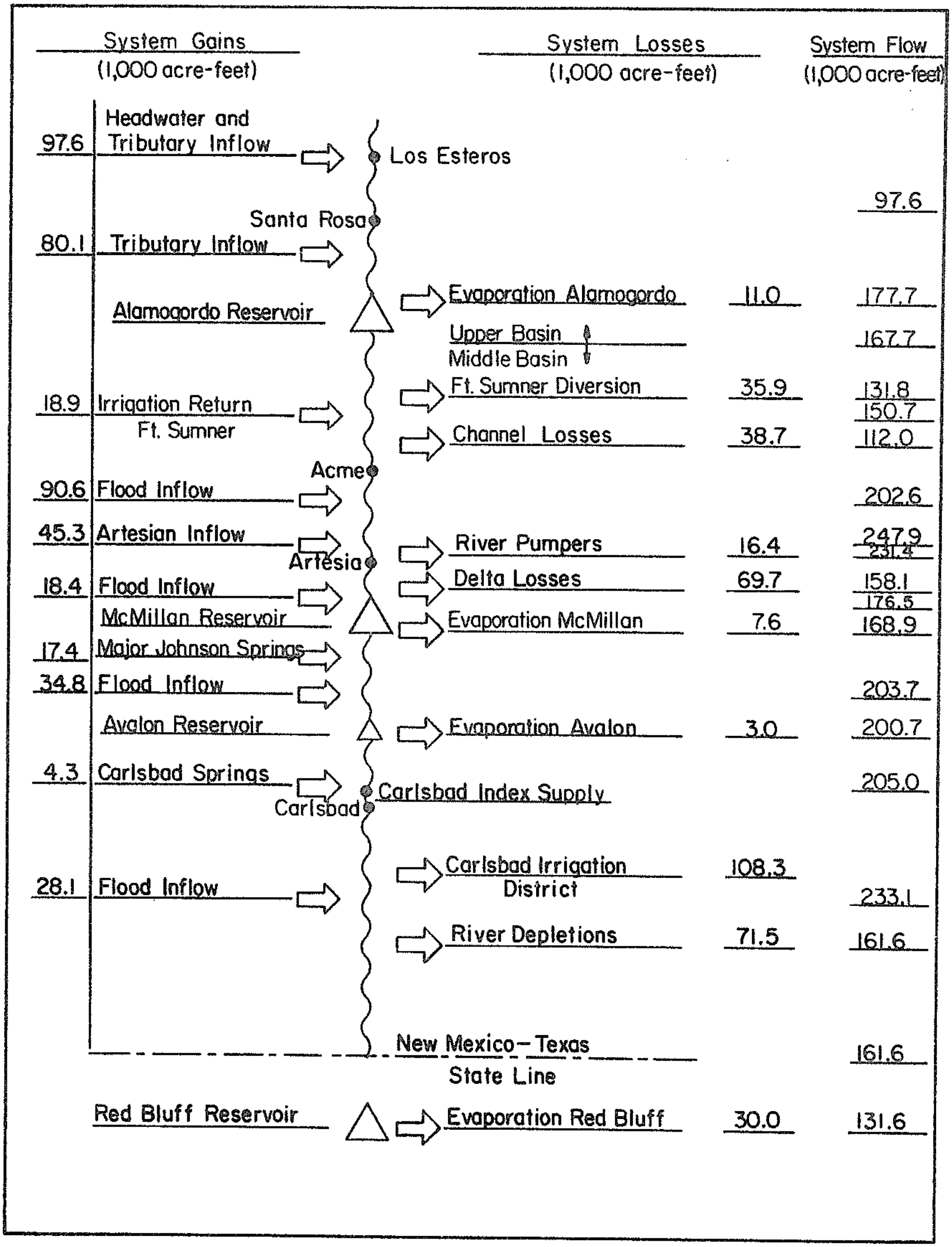

Figure 18. Present average annual flows, gains, and losses from the surface supply of the Pecos River, New Mexico (1919-1961).

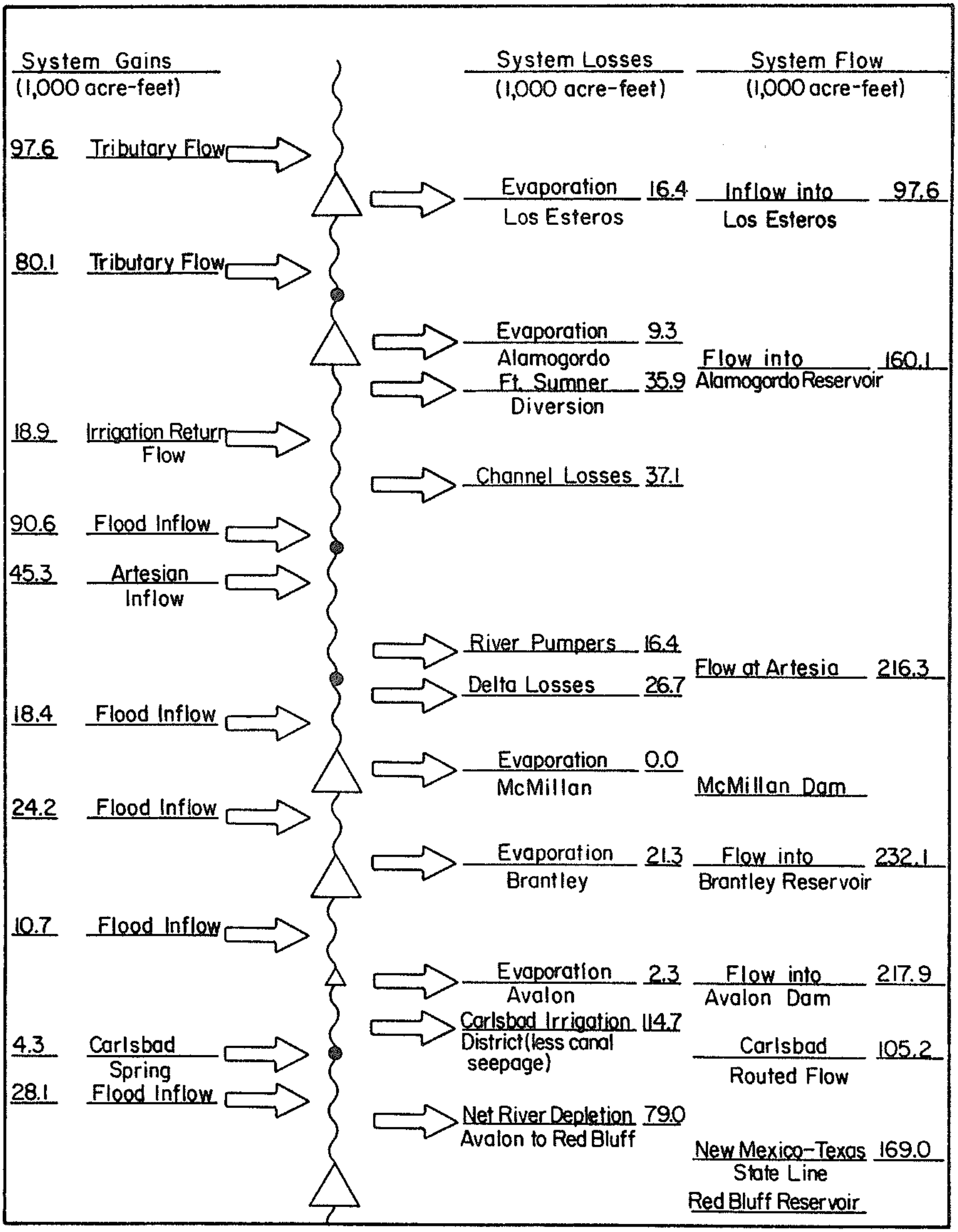

Figure 19 . Average annual flow, gains, and losses for proposed Pecos River system in New Mexico, based on historical data.

of Reclamation's projection of conditions that will exist when both dams are functioning [46].

In order to design a model that would react much as would the real stream system, relationships between the various gains to the system were required. To meet this need correlation expressions were developed to relate the inflow to Los Esteros to each of the other inflows to the Pecos for the 43-year period. Table 31 lists the coefficients for these relationships, along with the intercept (a) and the regression coefficient (b) for each. The equations all take the form

$$T = a + b\,(I) \qquad (7)$$

where $\underline{T}$ is the particular inflow to the system and $\underline{I}$ the flow into the Pecos at Los Esteros. Some of the correlations are good, while others are merely acceptable. The relationships seem reasonable on two counts: (1) the general observation that in wet years most of the basin's stations have above-normal flows, and (2) statistical studies show a high degree of correlation in annual precipitation for many of the weather stations.

The general concept is that, if one knows the inflow into Los Esteros, then the other inflows into the system may be predicted. The application of this concept involves some risk of being wrong and it is relatively easy to take the records for any particular inflow into the system to show that inconsistencies do, or will, exist. However, when all of the individual inflows are considered and typical behavior is predicted, it is felt that no major inaccuracies will have been initiated. This, of course, implies that certain limitations are inherent in the model; the model is not designed to predict extremes, and is most accurate when used to estimate the average behavior of the system.

Synthetic Distribution of Inflows into Los Esteros

The next step in developing the model was to find a method of synthesizing the annual inflow hydrograph for Los Esteros. This would require random generation of a flow sequency that has essentially the same characteristics as the historical record. In the section on hydrology in Appendix A, I show that the frequency of annual stream flow at most stations approaches a log-normal distribution.

Figures 20 and 21 are a frequency and a log-probability distribution of the annual discharge at Los

Table 31. Statistical parameters for multiple regression analysis of various stream system inflows and gains, Pecos Basin, New Mexico.

Historical Data for Stream Flow at Los Esteros Versus That for Indicated Stations[1]

Station or Geographic Location	Correlation Coefficient	Student's T Value	Regression Coefficient "b"	Standard Error for Regression Coefficient	Intercept "a"
Tributary Inflow Los Esteros Reservoir to Alamogordo Reservoir	0.492	3.61	0.118	0.033	68.93
Total Inflow into Alamogordo Reservoir	0.831	9.57	0.637	0.067	105.47
Flood Inflow Alamogordo Reservoir to Artesia	0.801	8.55	0.947	0.110	0.912
Artesian Inflow Acme to Artesia	0.666	5.72	0.111	0.019	34.81
Total Flow past Ft. Sumner Project	0.810	8.83	0.629	0.071	81.58
Total Flow at Artesia	0.868	11.20	1.643	0.147	67.10
Flood Inflow Artesia to McMillan	0.758	7.45	0.136	0.018	5.52
Total Flow into McMillan Reservoir	0.876	11.60	1.676	0.144	26.96
Flood Inflow McMillan Reservoir to Brantley Reservoir	0.741	7.04	0.175	0.025	7.07
Flood Inflow Brantley Reservoir to Carlsbad	0.744	7.14	0.078	0.011	3.09
Flood Inflow Carlsbad to Angeles gage	0.780	7.98	0.284	0.036	0.358

[1] Data for points downstream from Los Esteros reflects historical data as modified for conditions when Los Esteros Reservoir is in operation to sustain a minimum downstream flow.

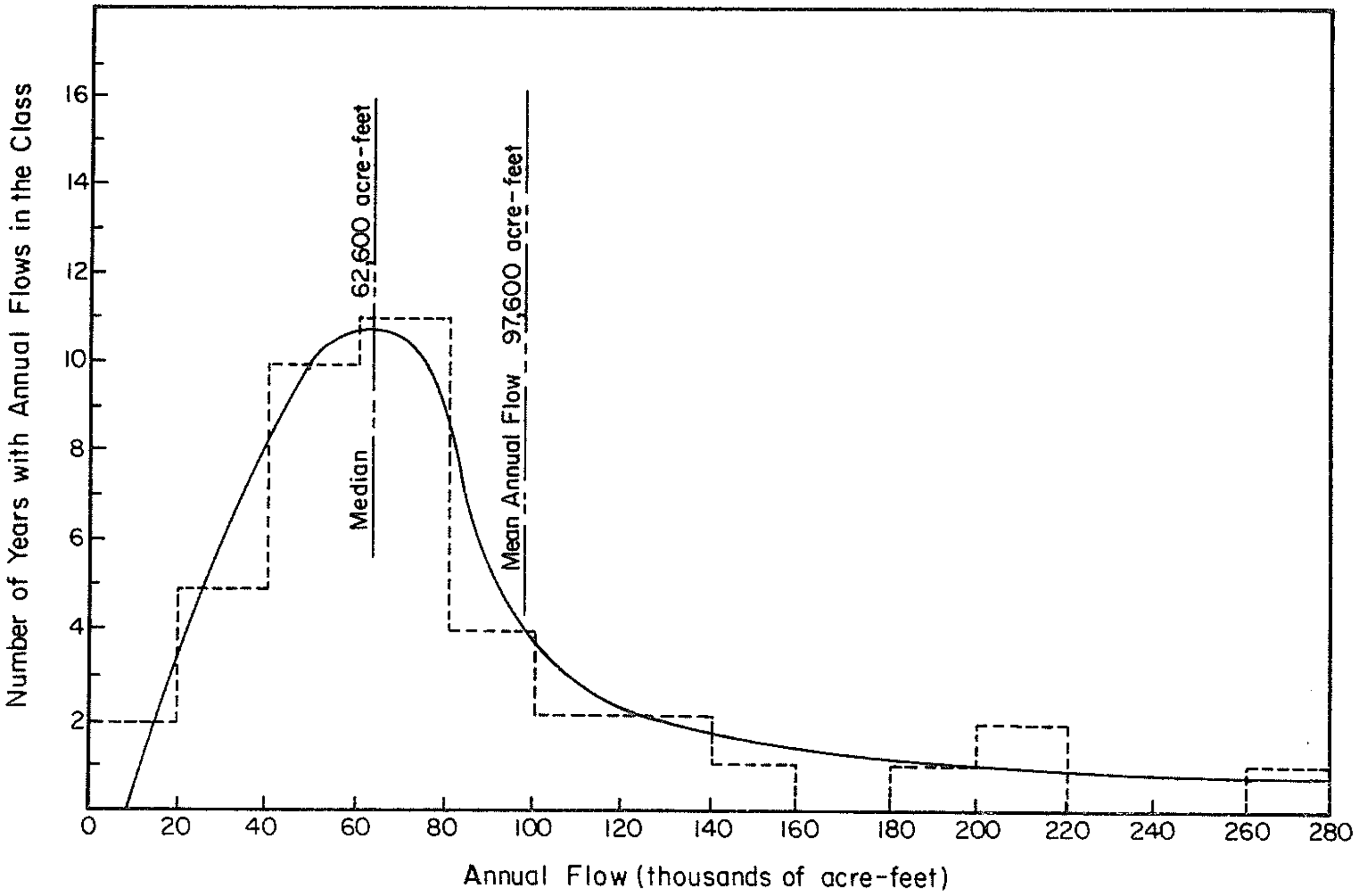

Figure 20. Bar graph and fitted distribution curve for annual flows into Los Esteros Reservoir, New Mexico, 1919-1961.

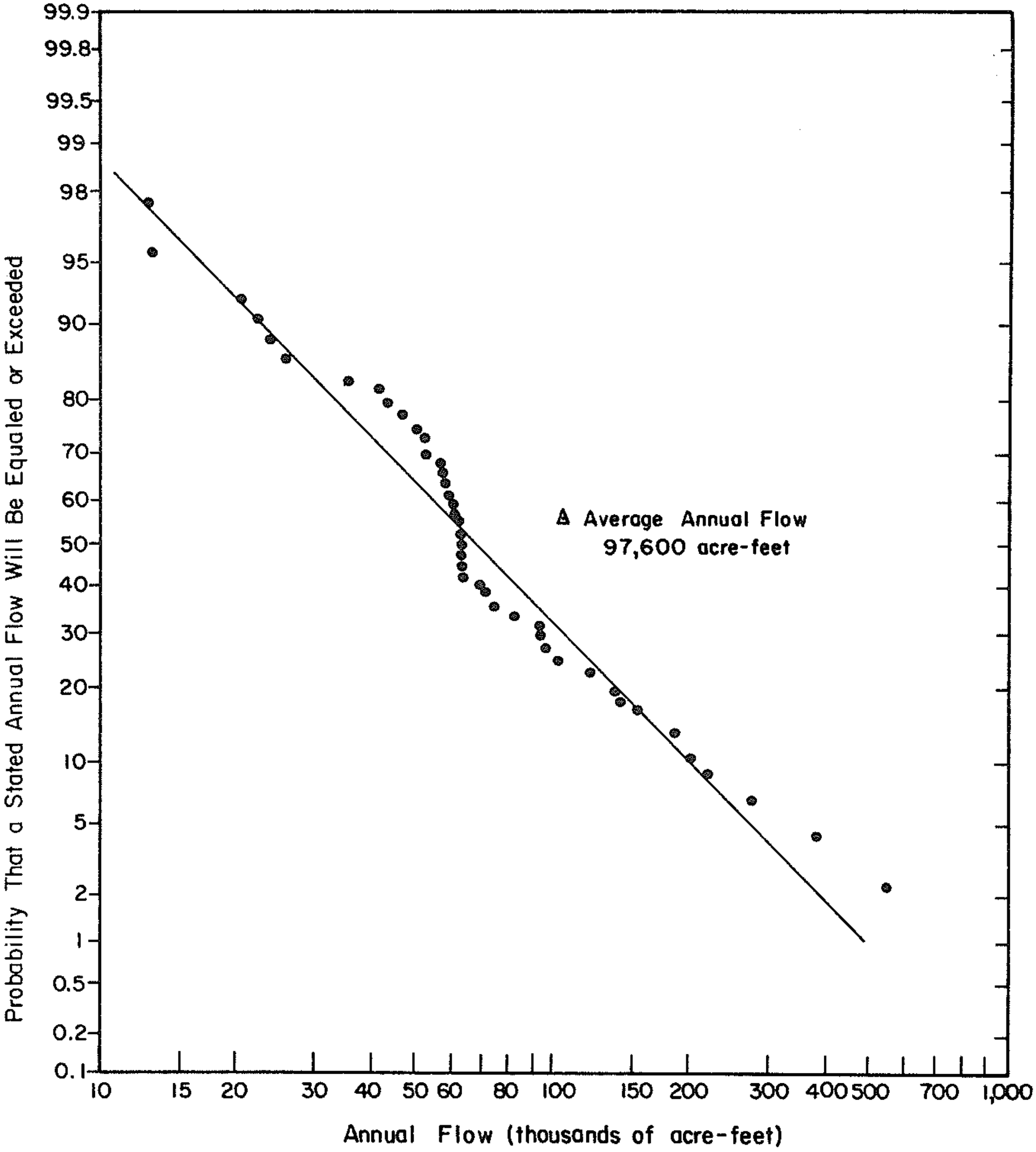

Figure 21 . Log-probability curve for historical annual discharge into Los Esteros Reservoir, New Mexico, 1919-1961.

Esteros. As is characteristic of western United States stream-flow records, the fitted frequency curve is skewed to the right, with the mean (97,000 acre-feet) set far to the right of the median (62,600 acre-feet) discharge. The log-probability graph shows considerable variation of points about the line of best-fit; this is borne out by the large arithmetic standard deviation of 100,525 acre-feet.

In their characterization of a log-normal distribution for flows in the Upper Rio Grande and Pecos, Lof and Hardison [29] found the average index of variability to be 0.14; this index is the standard deviation of the common logarithms of the annual yield. This roughly approximates the average of the index values found in this study--historical inflow into Los Esteros, 0.37; inflow between Los Esteros and Alamogordo, 0.084; historical inflow into Alamogordo, 0.12; Artesian inflow, 0.13; and flood inflow between Artesia and Lake McMillan, 0.30.

The typical method of generating synthetic hydrographs from non-normal distributions is to use higher moments of the data [18, p. 14] to transform the curve into a log-normal function. This standard approach was used in the early efforts to derive a simulation model, but problems developed when efforts were made to correlate the modified discharge at Los Esteros with the subsequent tributary inflows to the Pecos in the more than 250 miles to Lake McMillan. These deviations from the log-normal plot are demonstrated in figure 22, a log-probability graph of the inflow to Alamogordo Reservoir.

As a compromise, a distribution was selected that approximated not only the Los Esteros inflow, but also the other inputs to the system. The index of variability for the synthetic distribution is 0.144. Figure 23 is the generalized log-probability plot for the principal inflows and for the synthetic distribution generated. This graph was obtained by setting the geometric mean flow as 1.0 for each and plotting the log-probability line at a slope equal to the index of variability for each distribution. Values for the geometric standard deviations are given in table 32, which also probides a comparison of statistical parameters for the historic inflow in each reach with those of the synthetic distribution. Note that in most cases the mean values are quite comparable, although a difference between the recorded minimum and maximum values and those generated is evident. This comes about because of the truncation

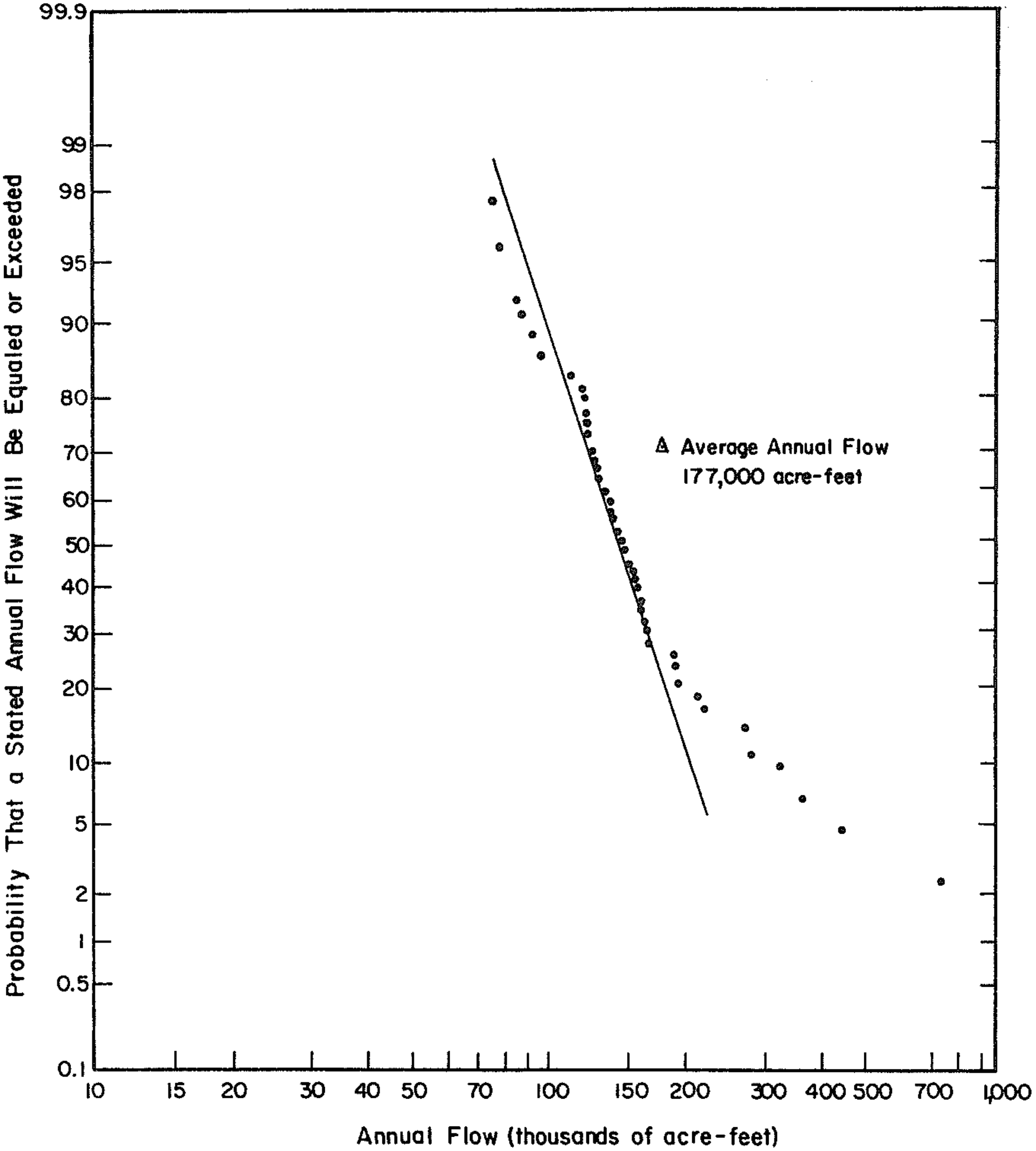

Figure 22 . Log-probability curve for historical annual flow into Alamogordo Reservoir, New Mexico, 1919-1961.

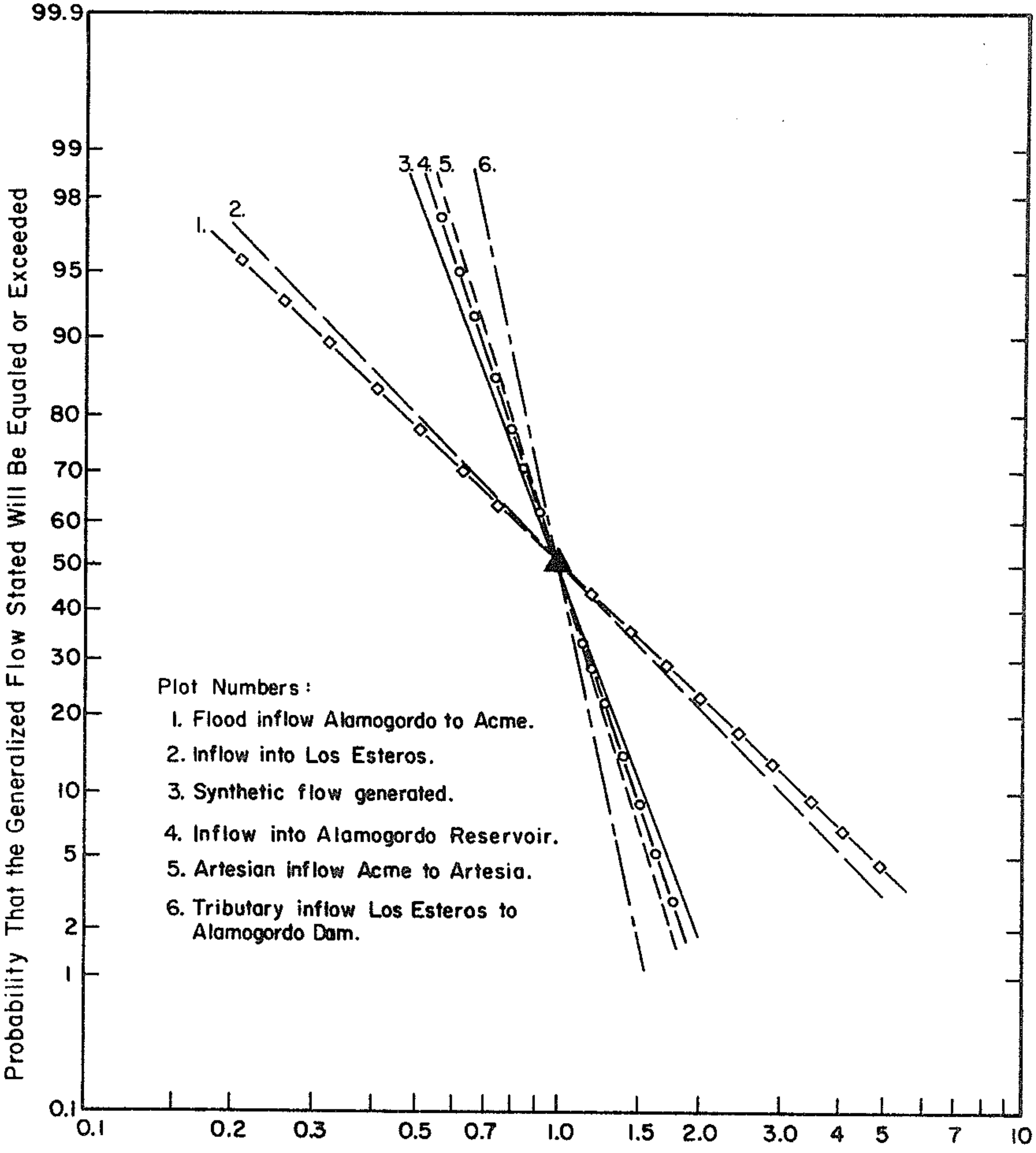

Figure 23. Generalized plot of the log-probability distributions for annual inflow into the Pecos River and the log-probability line for the synthetic record generated.

Table 32. Annual values[1] for historical flow parameters for gains to stream-system flow, 1919-1961 and values for synthetic flow data for a 100-year period, Pecos Basin, New Mexico.

Stream System Gains	Mean		Std. deviation		Median		Maximum		Minimum	
	Hist.[2]	Syn.[3]	Hist.	Syn.	Hist.	Syn.	Hist.	Syn.	Hist.	Syn.
Inflow into Los Esteros Reservoir	97.1	87.1	100.5 (arith)[4] 2.34 (geo.)[5]	1.39 (geo.)	63.3	77.0	539.6	497.5	12.6	27.0
Tributary Inflow Between Los Esteros Reservoir and Alamogordo Reservoir	80.1	79.2	24.2 (arith.) 1.21 (geo.)	1.39 (geo.)	71.8	78.0	190.8	127.6	52.9	72.1
Flood Inflow Alamogordo Reservoir to Artesia	90.6	83.4	119.5 (arith.) 24.5 (geo.)	1.39 (geo.)	60.4	75.0	746.9	472.1	10.3	26.5
Artesian Inflow Acme Gage to Artesia	45.3	44.5	16.9 (arith.) 1.84 (geo.)	1.39 (geo.)	43.0	43.5	110.9	90.0	22.4	37.8
Flood Inflow Artesia to McMillan Reservoir	18.4	17.4	18.1 (arith.) 2.0 (geo.)	1.39 (geo.)	14.4	16.0	94.8	73.2	1.1	9.2
Flood Inflow McMillan Reservoir to Brantley Reservoir	24.2	22.3	23.8 (arith.) 2.0 (geo.)	1.39 (geo.)	17.7	20.8	121.9	94.1	1.7	11.8
Flood Inflow Brantley Reservoir to Carlsbad	10.7	9.9	10.5 (arith.) 2.0 (geo.)	1.39 (geo.)	8.4	9.1	54.2	41.9	0.5	5.2
Flood Inflow Carlsbad to Angeles Gage	28.1	25.1	36.6 (arith.)	1.39 (geo.)	19.2	22.5	225.1	141.7	0.3	8.0

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[1] Values are in thousands of acre-feet.

[2] Hist. = indicate values for historical, recorded flows.

[3] Syn. = indicate values for synthetic flow data.

[4] arith. = arithmetic mean.

[5] geo. = geometric mean.

of the random selected flows at both the lower and upper ends of the distribution.

Method of Calculating Synthetic Flow

Synthetic flow was generated by approximating the historical frequency distribution of annual discharge at Los Esteros (figure 20). This skewed distribution exhibited three characteristics that were used to derive a synthetic distribution: (1) if two of the extreme low annual flows are disregarded, then the third lowest flow is equal to about one-fourth of the mean flow; (2) discharges equal to or greater than the mean flow do not occur 50 percent of the time, but occur nearly 25 percent of the time; and (3) the distribution curve from low flow to mean flow could be approximated by a parabola that would include 75 percent of the annual flows. The equation for this portion of the distribution is

$$Y = 1.0125 - 2.813\,(X - 0.6)^2 \qquad (8)$$

where $\underline{X}$ is the annual flow, with the mean flow at $\underline{X}$ equal to 1.0 and the low flow, $X = 0$. The part of the curve to the right of the mean (figure 20) is described by the equation

$$Y = 0.157/(X - 0.428)^{2.29} \qquad (9)$$

where values of $\underline{X}$ that were more than six times greater than the mean flow were halved until the random values selected met this criterion. This operation and the constraint of the low flows to one-fourth of the mean value has the tendency to truncate the distribution and, in effect, to make it somewhat less variable than the original distribution. This modification was readily accepted because it produced a distribution more like that of other inflows (figure 23).

A random-number generator was used to provide a number taken as the probability that the flow for any year in the synthetic sequence was equal to or less than the flow represented by the random number. Starting with any four-or five-digit number, synthetic flow sequences were generated for 100-year periods. Each starting number led to a different flow sequence and to a different mean value, although all came from the same distribution.

Except for the truncating effect, the synthetic distribution maintained most of the basic characteristics of the original historic sequence (see table 32). Figure 24 is a log-probability plot of a century of synthetic

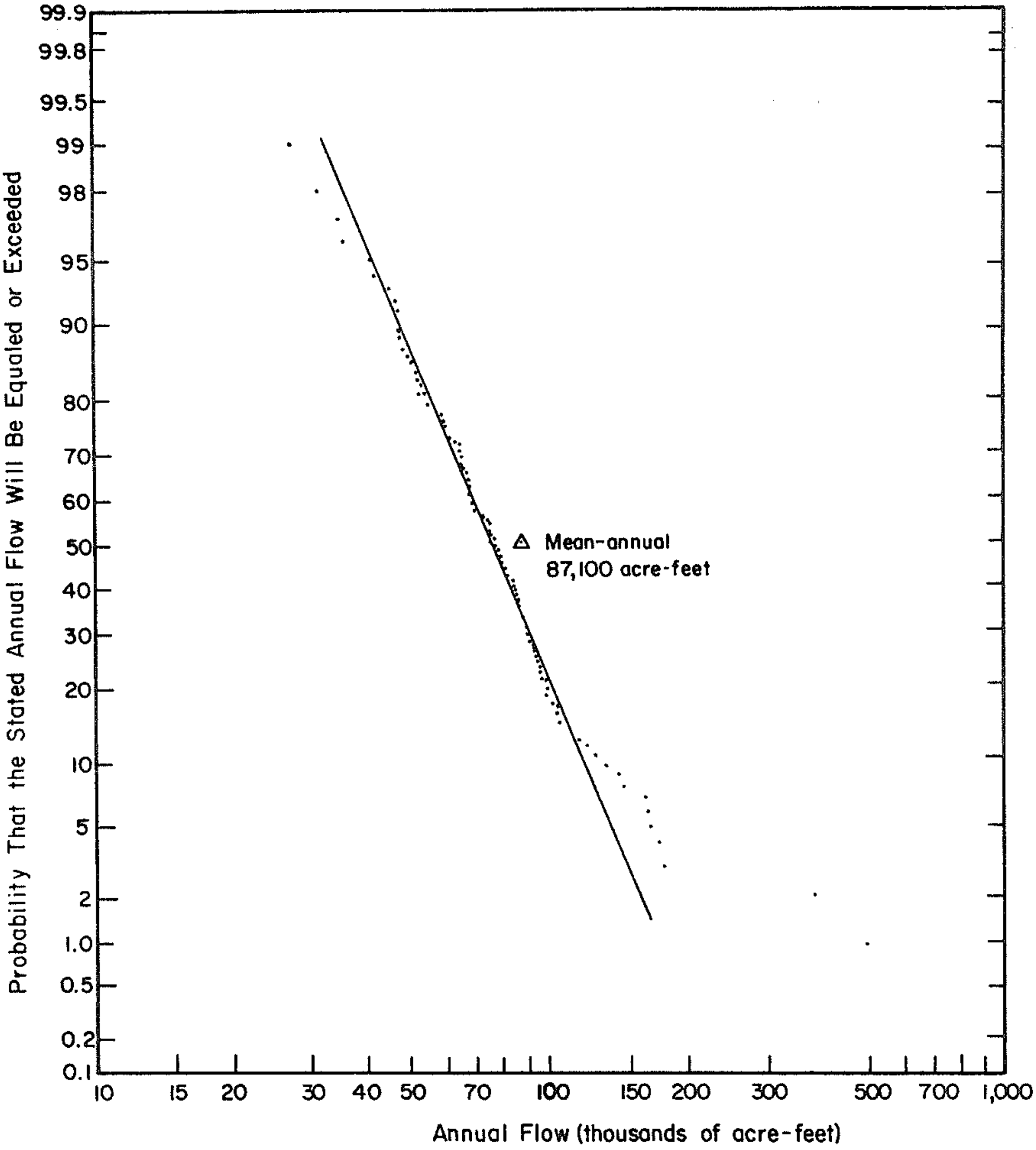

Figure 24. Log-probability curve for 100 years of synthetic annual flows at Los Esteros Reservoir, New Mexico.

flows (initial random number: 8911), with the mean value of 87,100 acre-feet set to the right of the median. The distribution also exhibits a tendency toward extreme values at both ends of the curve, much as do historic flows (compare figures 21 and 24). The sequence of synthetic flows looks very much like the original; the hydrograph of synthetic annual discharges in figure 25 is quite similar in appearance to the historic given in figure 17.

Do Distributions Belong to the Same Family?

The data of table 32, pictured in figures 24 and 25, are for 100 years of synthetic stream flow with the mean of 87,100 acre-feet. This is 10,000 acre-feet less than the historic mean inflow at Los Esteros. Noting this difference, one may question whether both come from the same parent distribution.

There are two reasons for believing that the synthetic record does adequately represent the historic. First, if an initial random number other than 8911 is used, a different sequence of flows is generated. Figure 26 is an arithmetic probability plot of the mean values of 10 different 100-year synthetic flow sequences. The average annual flow varies from a little more than 78,000 to more than 94,000 acre-feet. Clearly, all come from the same distribution. Secondly, a statistical ranking test [21] was performed to evaluate the probability that the historic record could not have come from this same family; on its basis, the hypothesis that both do come from the same parent distribution may be accepted at the 5 percent significance level.

Serial Correlation Studies

In developing the simulation model I considered the possibility that significant year-to-year serial correlation exists for the various system inflows. Such a relationship would be anticipated below each of the reservoirs, as water is carried over from year to year. There is also the relationship between ground water recharge and precipitation over a three-year period that Hantush [17] developed (see equations 1 and 2 in Chapter 4). Another indication of serial correlation is the equation for base flow at Artesia, developed by the Engineering Advisory Committee [14], which included precipitation for two consecutive years. Statistical tests do show serial correlation for the station below Alamogordo Dam (0.65), at Acme (0.60), and below Lake

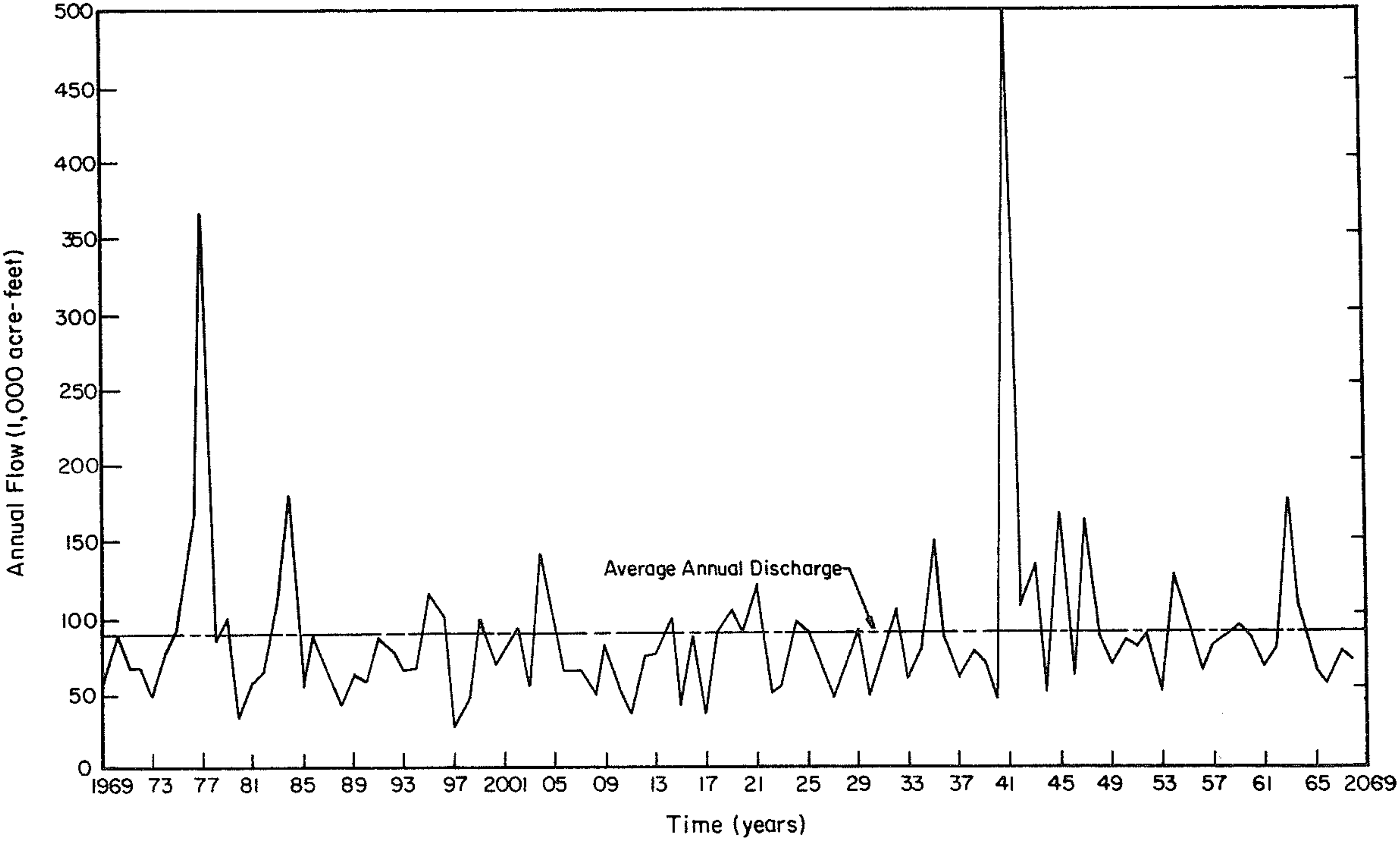

Figure 25 . Synthetic hydrograph time-flow sequence for 100 years (1969-2069) at Los Esteros Reservoir, New Mexico.

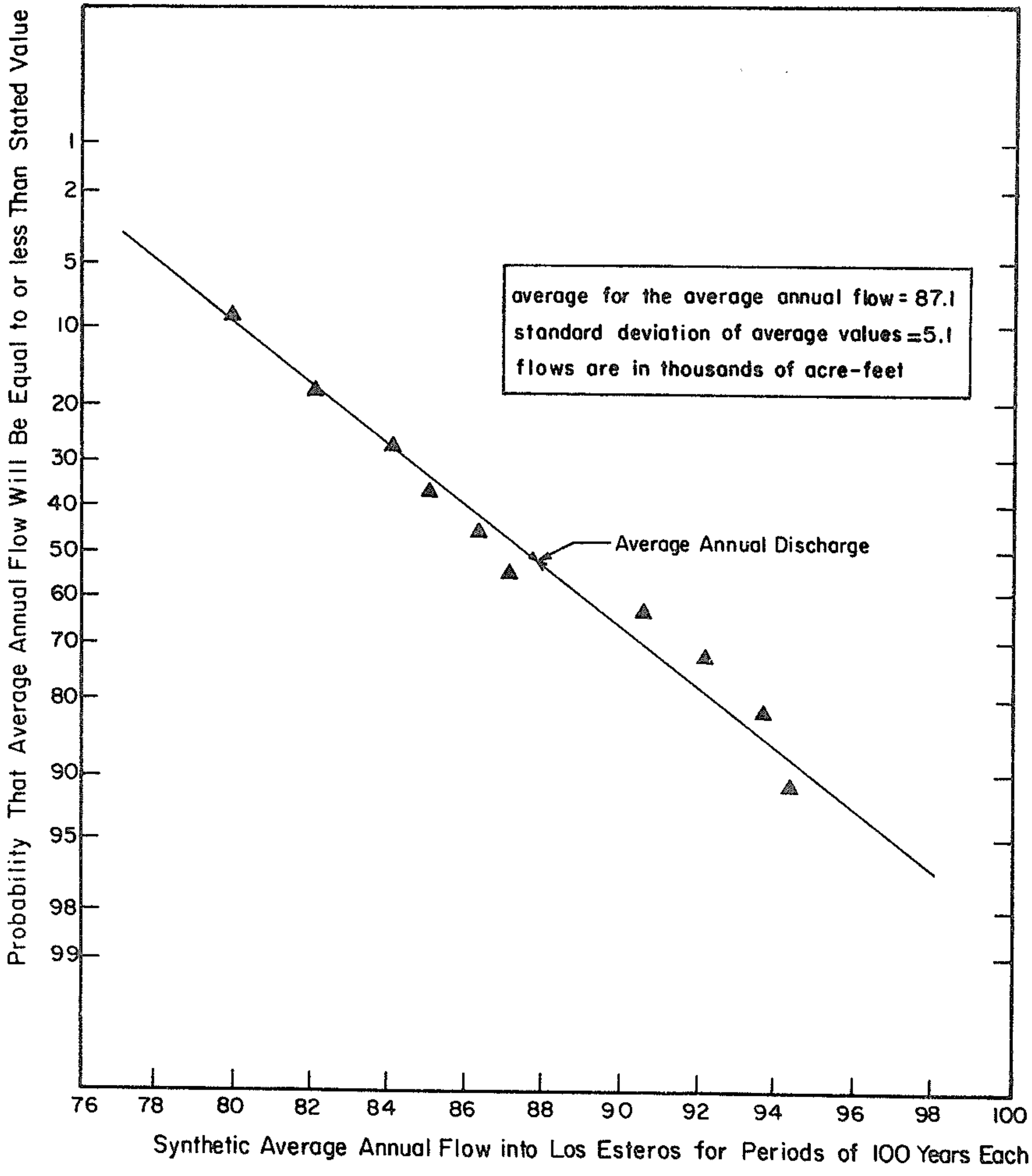

Figure 26. Variable water-supply studies, probability of generating a synthetic flow sequence for a 100 year period whose mean value is equal to or less than the stated value.

McMillan (0.65). Less, but still significant, correlation was found for the stations at Anton Chico (0.51), Santa Rosa (0.53), and Puerto de Luna (0.53). As there is almost no storage on the Pecos above Puerto de Luna, and statistical tests on precipitation records for middle-basin weather stations indicate no special serial correlation between years, this apparent serial relationship for stream discharge must be due to changes in use, changes in base flow and changes in ground water held in storage.

In some of the reservoir-routing studies undertaken, a component for serial correlation was included in the inflow to Los Esteros, and omitted in others. Its inclusion did not alter the results significantly; the correction had the tendency to smooth further the peaks, both high and low, in the system.

Reservoir-Routing Studies

Objectives

The purpose of these studies was to review reservoir design and operating criteria in order to select the "best policy" to be pursued. "The best policy" should lead to the largest average annual deliveries below Brantley Dam, with the fewest years with shortages. The objective function for the study was to obtain the design and operation of the system that would yield the most water below Brantley Dam for irrigation purposes. Selection of any policy would, of course, depend upon the physical and economic realism of the proposal.

Each of the policies studied was based on its effect on the supply released from Brantley Dam, the point chosen as the principal New Mexico diversion for the Carlsbad Irrigation District. Here a shortage is defined as an irrigation release of less than 142,800 acre-feet in a year. The identification of a lesser annual release as being a "shortage" is quite arbitrary and not totally realistic as the actual irrigation demand will depend on the rainfall received during the growing season. However, a specific value was selected to provide a means of testing the effectiveness of different reservoir designs and operating procedures.

Procedures

To conduct the proposed reservoir-routing studies it was necessary to work out relationships for the losses from the system. Table 33 lists the main losses, methods of calculating the historic record (based in most cases on the EAC study [14]), and derivation of data for the

Table 33. Description of methods of calculating historic and synthetic data for losses between Los Esteros and Brantley Reservoirs, Pecos Basin, New Mexico.

Source of Loss to System	Determination of Historic Record for 1947 Conditions	Derivation of Synthetic Data[1]
Reservoir Evaporation 1. Los Esteros 2. Alamogordo 3. McMillan 4. Brantley	Area-capacity curves with corrections for sediment deposition have been developed by the Bureau of Reclamation for these reservoirs. Net annual evaporation rates of 5.6 acre-feet per acre for Los Esteros and Alamogordo Reservoir and 6.0 acre-feet per acre for McMillan and Brantley Reservoirs have been used to find annual rates.	Equations for annual evaporation based on area-capacity curves are 1. $E_1=5.6x10^{-3}[1.6(V_1x10^3)^{0.7}]$ 2. $E_2=5.6x10^{-3}[10(V_2x10^3)^{0.55}]$ 3. $E_3=6x10^{-3}[280(V_3x10^3)^{0.3}]$ 4. $E_4=6x10^{-3}[0.495(V_4x10^3)^{0.64}]$ where _V_ is the end of year volume.
Ft. Sumner Diversion	District has right to 100 cfs from Pecos, March thru October and for two 8-day periods November to March, but this right is not satisfied due to low flows at times of need. The Engineering Advisory Committee (EAC) derived relationships between precipitation during irrigation season and percent of actual diversions of the district's water-right.	The average-annual depletion of 35,900 acre-feet was used. The maximum use was 45,900 acre-feet and the minimum 21,300. The median also falls essentially on the average indicating a uniform distribution.
Channel Losses Alamogordo Reservoir to Acme	Determined by plotting monthly inflow into reach versus monthly outflow for periods of no flood-flow to obtain the general relationship loss= 0.1 (inflow) + C where _C_ is a variable related to the season.	A modified annual relationship was used. Loss = 0.1(Flow in reach)+25.6
River Pumpers Acme to Artesia 7,150 acres irrigated	EAC studies of representative units, plus electricity use-records and precipitation records were used to obtain the relationship.	As use for irrigation is inversely proportional to precipitation, relationship with inflow into Los Esteros was used. Riv. P.=18.4-0.021(SFLOW) where SFLOW is the selected inflow into Los Esteros.
McMillan Delta Losses (more than 13,500 acres)	Bureau of Reclamation studies have resulted in a relationship between inflow and outflow for the reach so that loss-flow curves for both present and a cleared condition have been developed. Cleared condition losses were based in part on consumptive use estimates.	These curves have been generalized as follows: <u>Present conditions</u> DL=6.5+0.244(Flow in Reach) For flows up to 275,000 acre-feet DL=73.0 for greater flows <u>Cleared condition</u> DL=-10.0+0.196 (Flow) for flow below 240,000 DL=13+0.0985 (Flow) for flow 240,000 to 310,000 DL=43.5 for greater flows.

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[1] Flows are in thousands of acre-feet for all equations, _E_ is in thousands of acre-feet, _V_ is in units of thousands of acre-feet.

model. With inflow to Los Esteros a random-number generated value, with other inflows to the system calculated from the regression equation values given in table 31, and with losses determined in the manner described in table 33, the system components given in table 34 were calculated for each year in a 100-year sequence, subject to initial conditions and constraints also given in the table. These conditions are the basic limitations on operating policies. The limitations on maximum reservoir capacity do not reflect storage capacity retained to replace losses in initial capacity caused by sediment deposits and the temporary storage for flood-control purposes--storage for these purposes is not available for conservation of irrigation waters.

The basic program was run many times, with one of the constraints varied each time. The average values for the system components given in table 34 are for a generated synthetic flow (SFLOW) into Los Esteros that averages 87,000 acre-feet (initial random number 8911). All subsequent runs made in this part of the study on reservoir design and operating procedures used the same SFLOW. Serial-correlation correction is not incorporated into this set of calculations.

Comparison of the values of table 34 with the calculated historic flows of figure 19 for similar conditions indicates rather close simulation of the actual system by the model. Generated inflows to the system are about 5 to 10 percent below historical averages. This difference reflects the variations between the average of the synthetic flows and the historic flow.

Design and Operation of Los Esteros

Four different design or operating policies for the reservoir were studied: the amount of irrigation water storage to be provided; the minimum pool to be maintained; the maximum irrigation release; and the effects of evaporation on the downstream supply. The proposed irrigation storage to be provided by Los Esteros is based on the transfer of part of the Carlsbad Irrigation District's rights from Alamogordo to the new reservoir [46, p. A-27] and the inclusion of capacity for "unappropriated" flood waters [46, p. A-50] for a total irrigation-conservation pool of 200,000 acre-feet. The effect of increasing and decreasing the size of this pool from the basic conditions of 200,000 acre-feet was studied by re-running the simulation program, making different storage capacities available. Figure 27 is a

Table 34. Simulation model system components calculated for each year in a 100-year synthetic flow sequence, Pecos Basin, New Mexico.

	System Components Calculated For Each Year in 100-Year Sequence		
Reservoir	Item	Mean Annual Value (1,000 acre-feet)	Basic Conditions or Constraints; Operational Decision Rules
Los Esteros	Flow into the reservoir	87.1	Reservoir empty at t=0; maximum content 200,000 acre-feet; minimum content 10,000 acre-feet; maximum irrigation release per year 150,000 acre-feet.
	Evaporation	7.3	
	Spills	1.1	
	Irrigation release	78.5	
	Content at end of year	17.1	
	Flow below the dam	79.6	
Alamogordo	Tributary inflow	79.2	Initial volume at t=0, 10,000 acre-feet; maximum content 20,000 acre-feet; minimum content 7,000 acre-feet; maximum irrigation release 112,000 acre-feet.
	Total flow into reservoir	158.8	
	Evaporation	12.3	
	Spills	34.7	
	Irrigation release	111.7	
	Content at end of year	18.6	
	Flow below the dam	146.4	
McMillan	Ft. Sumner Diversion	35.9	Initial volume in storage at t=0 7,000 acre-feet; maximum volume 13,900 acre-feet; minimum volume held in storage 1,000 acre-feet; cleared delta conditions assumed.
	Irrigation return flow	19.0	
	Channel losses Alamogordo to Acme	38.6	
	Flood inflow Alamogordo to Artesia	83.4	
	Artesian inflow	44.5	
	Diversion by river pumpers	16.5	
	Flood inflow Artesia to McMillan	17.4	
	McMillan delta losses	29.0	
	Total flow into the reservoir	190.7	
	Evaporation	3.6	
	Seepage	30.4	
	Spill	0.0	
	Irrigation release	115.0	
	Content at end of year	1.0	
	Flow below the dam	187.1	
Brantley	Flood inflow McMillan to Brantley	22.3	Initial volume at 1,000 acre-feet; minimum storage 40,000 acre-feet; maximum volume 1,000 acre-feet; maximum irrigation release 142,800 acre-feet.
	Flow into the reservoir	209.4	
	Evaporation	13.5	
	Seepage	0.9	
	Spills	16.6	
	Irrigation release	135.0	
	Content at end of year	11.9	
	Flow below the dam	193.2	

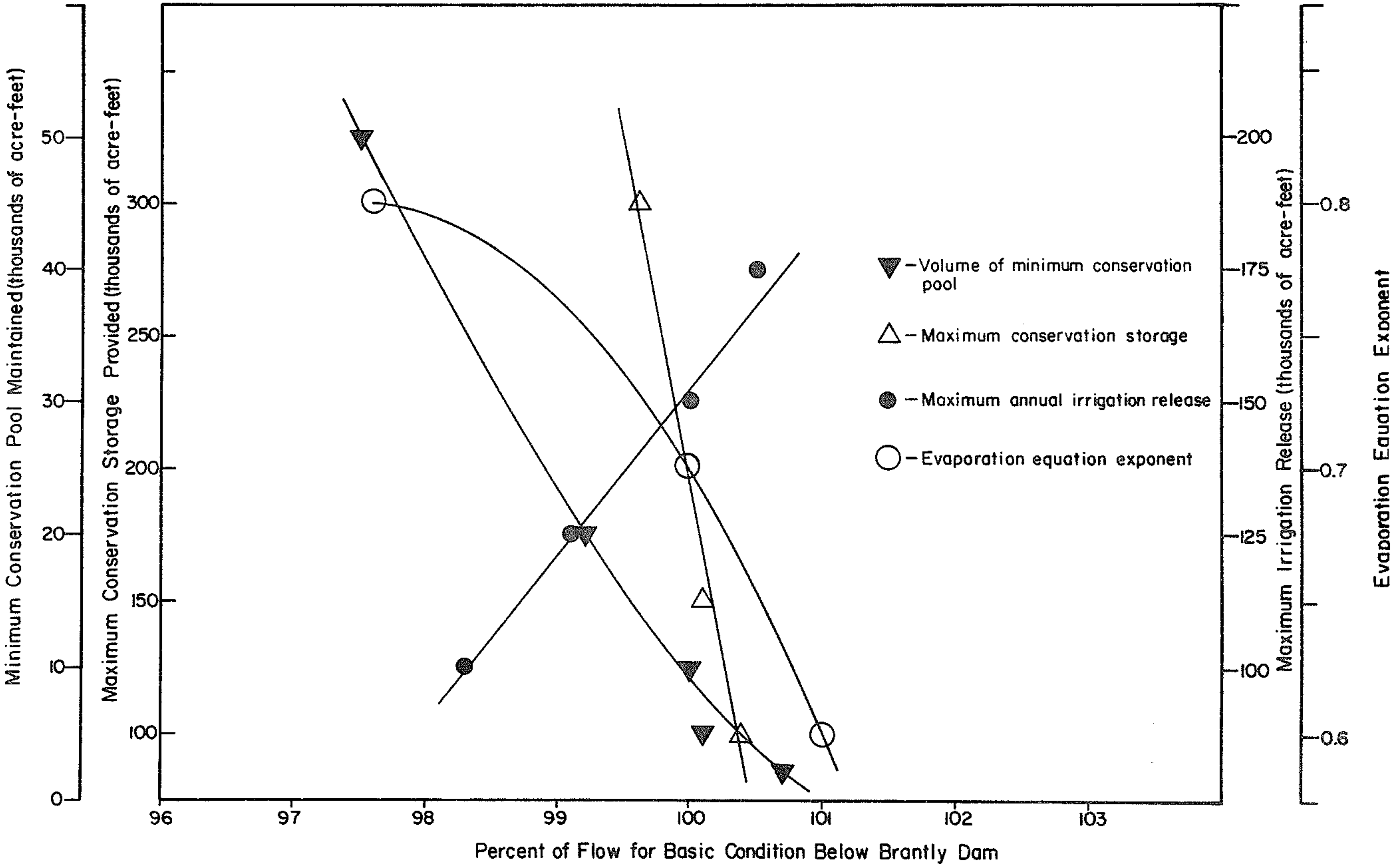

Figure 27. Effect of operation and design of Los Esteros Reservoir on the flow below Brantley Dam, Pecos Basin, New Mexico.

graphic analysis of the percentage of change in flow below Brantley Dam for these variations. One can see that these changes in maximum storage available at the reservoir have no great effect on yield. Each of the four capacities tried (100, 150, 200, and 300 thousand acre-feet) resulted in a similar number of irrigation shortages (36 to 37 times per 100 years), similar average annual irrigation yields (134.9 to 135.0 x 10^3 acre-feet), and similar average values for the flow below Brantley (194.4, 193.7, 193.2, and 192.4 x 10^3 acre-feet). This indicates that the need to provide conservation storage for irrigation waters much in excess of 100,000 acre-feet in Los Esteros should be seriously questioned. The average inflow into the storage is somewhat less than 100,000 acre-feet and the historic median is far less--63,300 acre-feet (table 32).

Maintenance of minimum conservation pools of 2, 5, 10, 20 and 50 thousand acre-feet was studied; figure 27 shows the results. The flow below Brantley (193.2 to 193.8 x 10^3 acre-feet) and the number of years with irrigation shortages (35 to 37) were reasonably close together for both 5,000 and 10,000 acre-feet minimum storage, but when the minimum storage was increased to 20 to 50 thousand acre-feet, the number of shortages increased to 40 and 50 times per 100 years, respectively, and the average water released dropped from 135,000 to 133,900 and 130,800 acre-feet, respectively. When a primary pool of 2,000 acre-feet is maintained, irrigation shortages drop to 32 times per 100 years, and average yearly irrigation release increases to 136,000 acre-feet. Effects of the amount of minimum storage maintained in Los Esteros are far more important in determining the amount of water available for use by the Carlsbad Irrigation District than is the maximum storage capacity provided in the reservoir.

It is necessary to have some sort of policy on the amount of water to be released from the reservoir each year, which will then affect the amount of annual residual carryover. If each of the annual inflows into the system is independent of the inflow for the preceding year and of that for the succeeding year, then a fixed policy as to the maximum amount of water that will be released from each reservoir on the system can be adopted. This procedure has been used although the basic premise has the inherient weakness that several correlations between yearly flows could alter an operating policy based on the assumption of independence. Unfortunately this element was not studied extensively. The effect on downstream yield of maximum irrigation releases of 100, 125, 150 and 175,000 acre-feet was studied, as reported in figure 27. The basic condition for the analysis was 150,000 acre-feet, with the effect of the other irrigation releases expressed as a percentage of the flow below the dam for a release of 150,000 acre-feet. Smaller maximum releases (125 and 100 x 10^3 acre-feet) result in a 1 to 2 percent decrease in the average annual discharge from Brantley, but, probably more important, they result in fewer years with irrigation shortages (35 and 33 per 100 years) and slightly larger average annual releases from the reservoir. The difference is that with a low (100,000 acre-feet) annual release from Los Esteros, fewer spills result at Brantley, so that the average annual volume spilled drops from 16,600 acre-feet for 150,000 to 12,200 acre-feet. The smaller the irrigation release, the better the use made of the storage available in Los Esteros--31 years where over-year storage occurs for a release of 100,000 acre-feet versus only 11 for a release of 150,000 acre-feet. It is interesting to note that even when policy sets the maximum irrigation release at 100,000 acre-feet, on only seven occasions in 100 years is the capacity of more than 100,000 acre-feet used, and only five times if the maximum release is set at 125,000 acre-feet per year.

The shape of Los Esteros Reservoir makes it acceptable from the standpoint of losses from evaporation when residual storage is kept below certain levels. Between the bottom of the reservoir and a capacity of 75,000 acre-feet, the volume increases exponentially with respect to the area (0.7 log V); between 75,000 and 125,000 acre-feet, the area-capacity curve approaches a straight line and at greater storage values the area increases at a greater rate than does the volume. Three different exponents (b) were used in the equation

$$E = a\ V^{b} \quad . \quad (10)$$

where $\underline{E}$ is the evaporation in acre-feet per year; $\underline{a}$ and $\underline{b}$ are values determined by reservoir shape; and $\underline{V}$ is the capacity of the end-of-year volume in storage in acre-feet. The effect of changing exponents on the water supply below Brantley is pictured in figure 27, where b = 0.7 is the basic condition. The change in average flow below Brantley is not marked, but the number of years with shortages in the releases from that reservoir is quite different for an exponent of 0.6--31 times per 100 years, versus 37 for b = 0.7. While it is not reasonable to suggest changing the shape of the reservoir, it is possible to set a policy against maintaining residual storage above 125,000 acre-feet, and preferably below 75,000 acre-feet. If the maximum irrigation release is fixed at 100,000 acre-feet per year, a storage capacity of more than 75,000 acre-feet would be needed only nine times in 100 years.

Design and Operation of Alamogordo Reservoir

The 1970 plans for additional storage on the Pecos called for the amount of Carlsbad Irrigation District water stored in Alamogordo Reservoir to be reduced to a maximum of 20,000 acre-feet. Using this as a basic condition,I considered the effect of making more storage capacity available in the reservoir. Figure 28 shows the change in yield below Brantley Dam when the maximum irrigation storage in Alamogordo is 20, 40, and 60 thousand acre-feet. Increasing the storage increases the number of years with shortages in release from 37 to 42 to 50 per 100 years for the three storage volumes, respectively. The increase also results in a smaller annual supply below Brantley Dam on the average because of greater losses. Flood control storage provided in Alamogordo Reservoir is not considered in this analysis and is in addition to that made available for irrigation.

I also studied the minimum storage maintained, considering three levels: 2, 7, and 10 thousand acre-feet, with the basic condition of 7,000 acre-feet. There is virtually no difference in downstream yield nor in number of years of short supply between the levels (figure 28). The reason for the apparent absence of response to changes in minimum volume is that the end-of-year storage almost always exceeds this minimum volume because of the greater effects of the amount of water released each year for irrigation.

Four different release levels were evaluated for their basic effect on downstream yields: 100, 112, 125, and 150 thousand acre-feet, with the basic condition of 112,000 acre-feet. By far the best procedure is to set releases at the largest of those studied: 150,000 acre-feet. The analysis indicates small but favorable increases in the flow below Brantley (figure 28), but more important is the reduction of years with shortages, from 37 for 112,000 acre-feet to 27 for 150,000. More severe, but far fewer, shortages occur; these severe shortages may however, be more costly to an irrigator than a series of small shortages. The change results because fewer spills go over Alamogordo under such an operating policy: only 22 times per 100 years, compared with 79 when the maximum irrigation release is 112,000 acre-feet. The end-of-year content of the reservoir

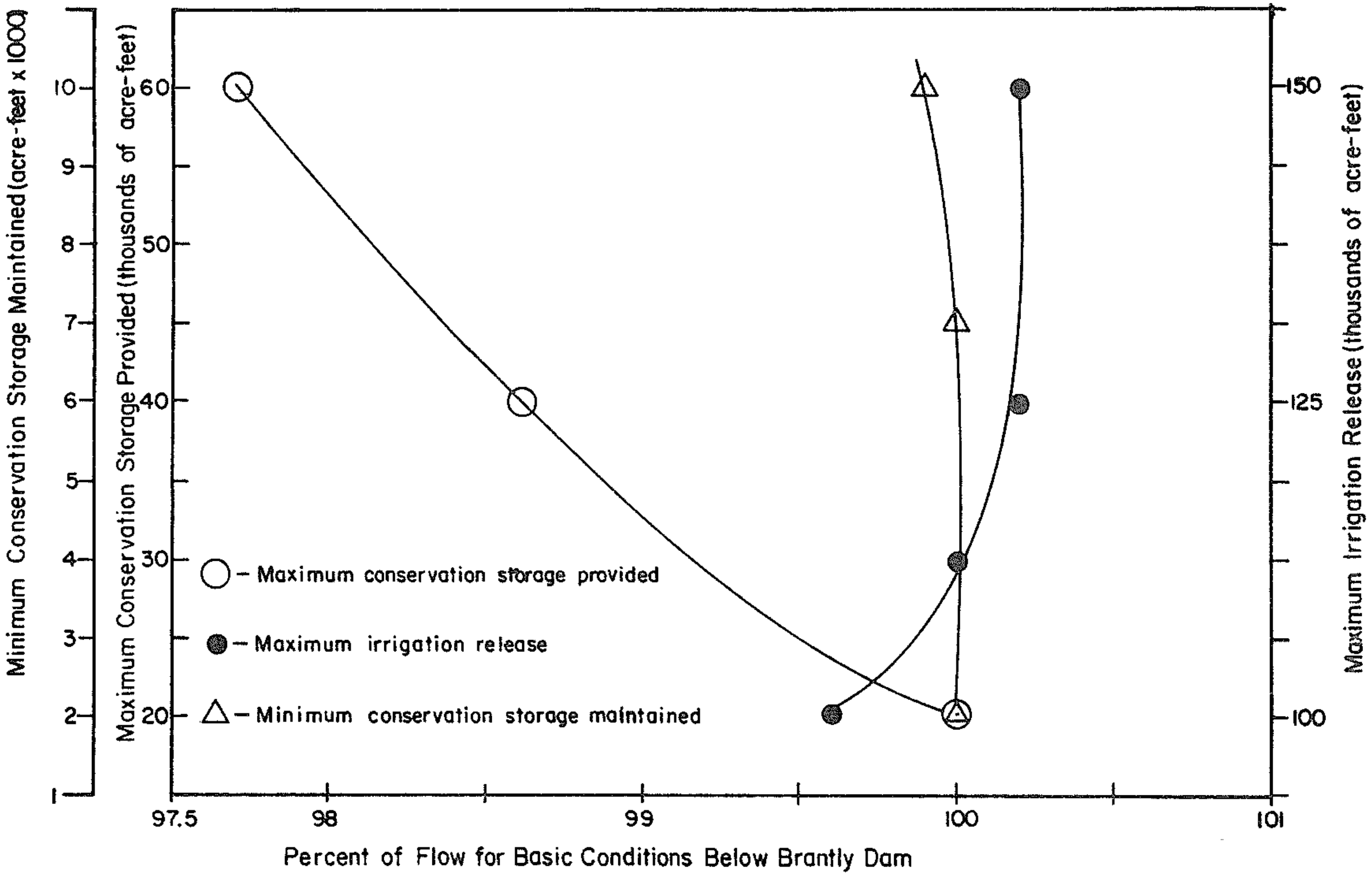

Figure 28 . Effect of changes in operation and design of Alamogordo Reservoir on the flow below Brantley Dam, Pecos Basin, New Mexico.

is drawn down to the minimum 46 times per 100 years if this operating policy is followed, making downstream yields somewhat responsive, but still not overly so, to changes in the minimum storage level maintained.

Channel and Delta Losses

Historically the losses in the reach from Alamogordo to Acme have averaged approximately 38,000 acre-feet, while those between Artesia and McMillan, the delta area, have been almost 50,000 acre-feet per year. The Bureau of Reclamation has proposed mechanical clearing programs to reduce water losses due to salt cedars, and a channel through the delta (Chapter 1). Figure 29 portrays effects of decreasing the losses on the supply below Brantley Dam. Changes in coefficients in the loss equations have far more influence on flow to the Carlsbad Irrigation District than do major changes in upstream reservoir volumes and operation.

The relationship used for channel losses between Acme and McMillan for the basic condition in the analytical studies is

$$Cl = 25.6 + 0.1\,(FLOW) \qquad (11)$$

where Cl is the yearly loss in thousands of acre-feet and FLOW is the yearly flow in the reach. The coefficient, 25.6, is made up of the sum of the monthly loss coefficients ranging from 0.3 for the winter months to 5.8 in June; the flow coefficient is 0.1 for all months [46, p. A-15].

Channel loss in this stretch may be reduced by channel alignment and lining. Analytical studies indicated improved yields below Brantley when the coefficient "a" (figure 29) is reduced from 25.6 to 5.0 (193,300 versus 203,600 acre-feet average annual flow). The number of years with shortages is dropped from 37 per 100 to only 14, with maximum shortage reduced from 50,000 to 30,000 acre-feet.

Reducing the coefficient "b" by 50 percent (figure 28) from 0.1 to 0.05 results in an increase in average flow below Brantley to 196,900 acre-feet; when reduced to 0.02, the number of shortages drops from 37 to 23 and the average yield approaches 200,000 acre-feet. Here again, major changes have occurred in the downstream supply.

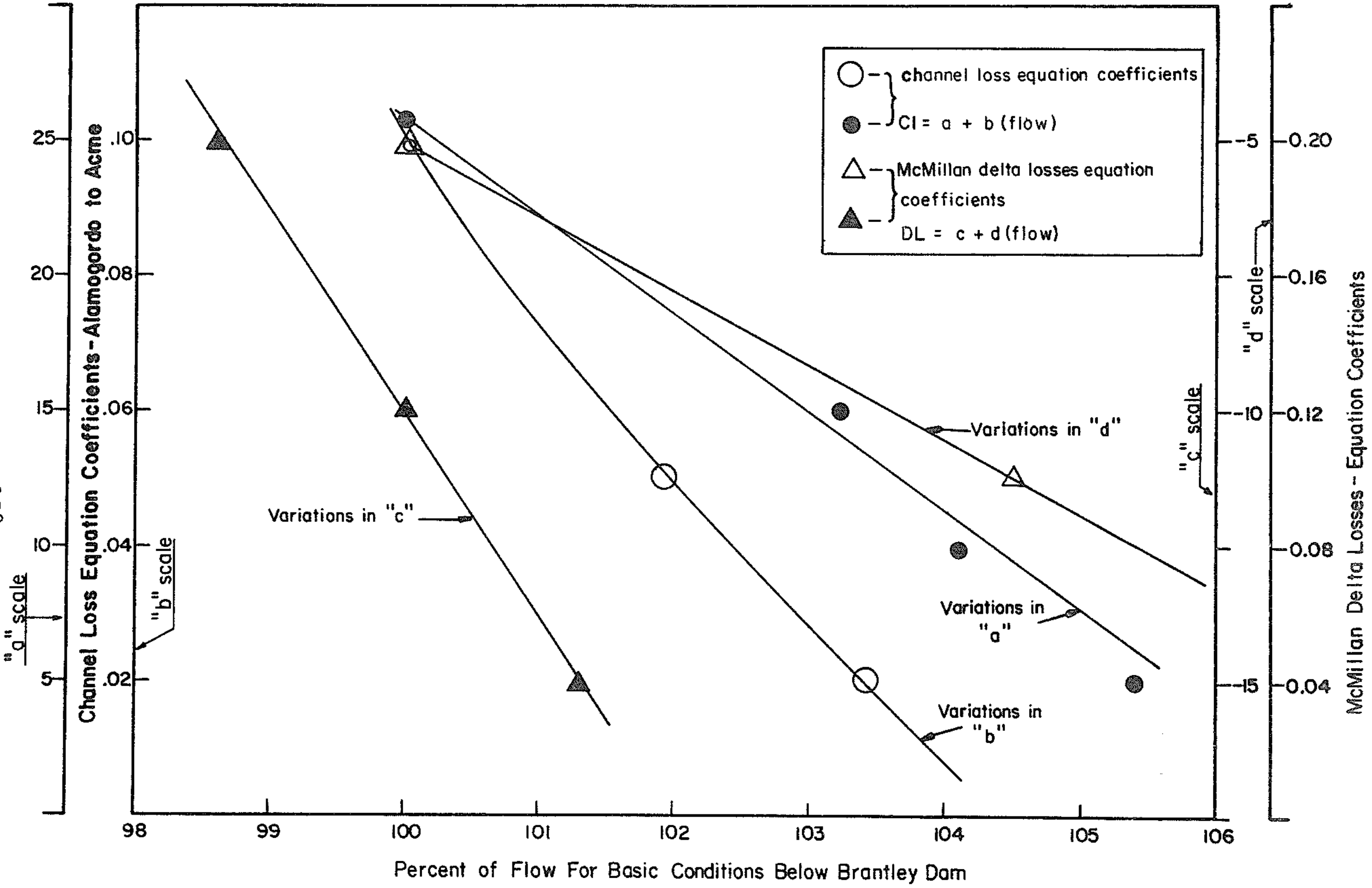

Figure 29. Changes in flow below Brantley Dam caused by changes in losses between Alamogordo Dam and McMillan Dam, Pecos Basin, New Mexico.

Delta losses present an even greater waste in the system. The relationship for losses in the uncleared condition--which is the existing situation in the delta--is

$$Dl = 6.5 + 0.244 \text{ (FLOW)} \qquad (12)$$

where Dl is the annual loss and FLOW is the annual discharge in thousands of acre-feet. The basic conditions used in the study were for the cleared condition where the coefficients, c and d (figure 29) became -10 and 0.196, respectively. Changing c from -10 to -15 reflects some, though minor, increase in downstream yield. Reducing the coefficient d had more effect: a 50 percent decrease to 0.1 allowed the average flow past Brantley to increase to 201,900 acre-feet and reduced the number of years with shortages from 37 to 18. Limiting the periods of flow through the reach to the winter months might be beneficial. If an adequate channel were constructed through the delta additional benefit could be realized.

Storage in Brantley Reservoir

Present plans for the reservoir [46] call for 40,000 acre-feet of active conservation storage, with winter but no over-year storage in McMillan. The simulation program was run with both smaller (20,000 acre-feet) and greater (60,000 and 80,000 acre-feet) amounts of storage provided. Figure 30 shows that flow past the dam (irrigation releases plus spills) increases when maximum storage capacity is reduced to 20,000 acre-feet, with little increase in the number of shortage years (38 versus 37 for the basic condition) and a very small decrease in the average annual irrigation release (134,900 versus 135,000) when compared to the basic condition. Provision of more than 40,000 does not improve the yield.

Effect of the minimum pool on yield was also studied and results of these computer runs are given in figure 30. The basic condition was taken to be a minimum storage of 1,000 acre-feet. Small variations (0.1 and 2.0 thousand acre-feet) brought minor changes in yield. When minimum storage is increased to 5,000 acre-feet the number of shortage years increases from 37 to 41, whereas serious changes in average annual irrigation release occur when the minimum is increased to 10,000 acre-feet (130,800 versus 135,000 for basic condition).

System Storage Requirements

Two specific requirements are placed on reservoir facilities: (1) to provide the storage needed to meet

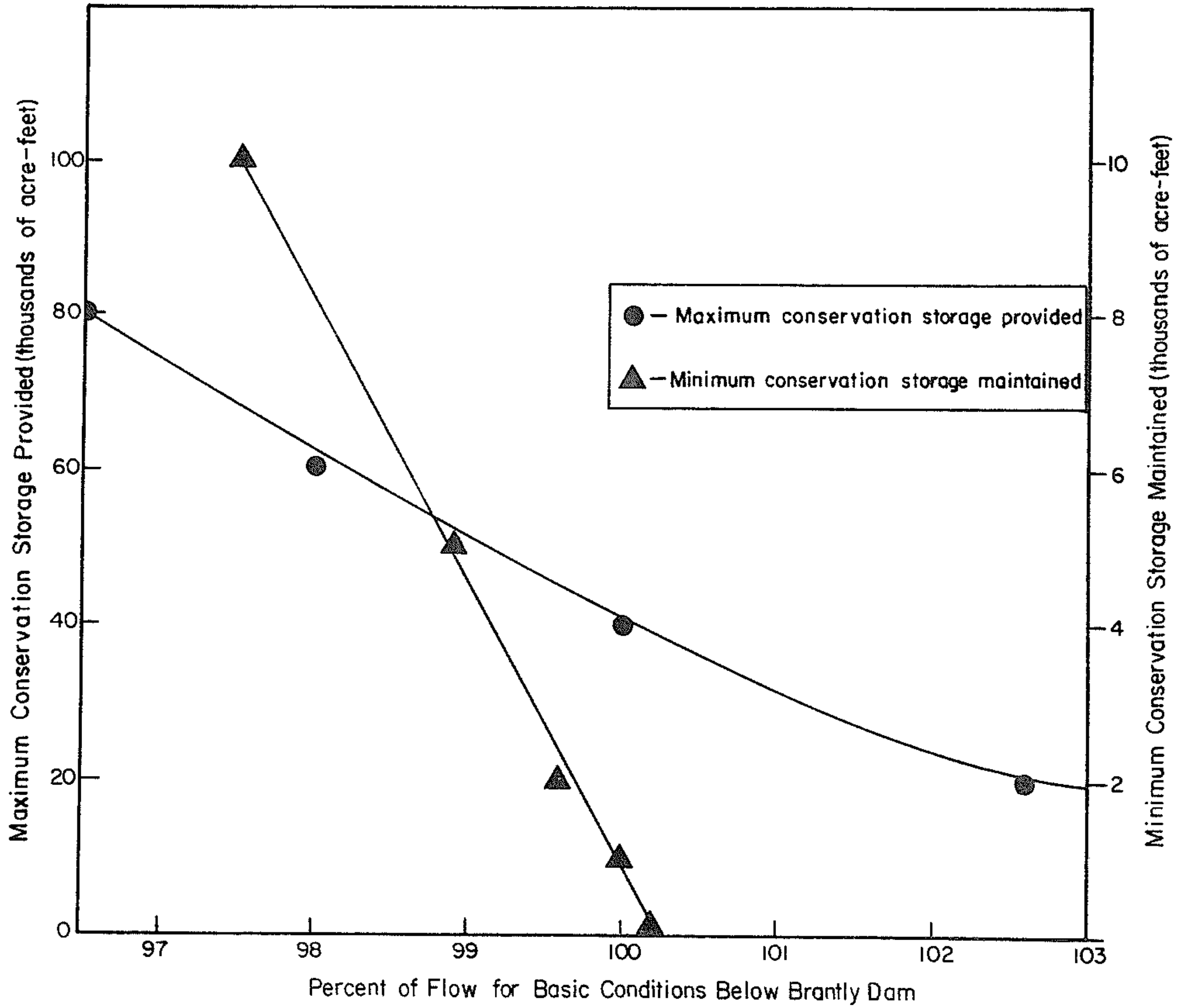

Figure 30. Changes in flow below Brantley Dam caused by changes in operation and design of Brantley Dam, Pecos Basin, New Mexico.

seasonal difference between supply and demand; and (2) long-term detention of water for one or more years, the over-year storage needed to balance yearly variations in the supply. Analytical studies have been conducted to evaluate the magnitude of the reservoir capacity required on the Pecos for these two purposes.

Over-Year Storage

Within limits, downstream yield is not greatly enhanced by increasing the storage available. Bureau of Reclamation routing studies indicate that, even if additional storage is provided by construction of Los Esteros, shortages will still occur 46 percent of the time, and average annual shortage to the Carlsbad Irrigation District will be 14 percent of demand [46, p. A-58]. The need for additional storage is questioned. When the conservation capacity of Brantley was varied from 40,000 to 80,000 acre-feet the number of times over-year storage was used only varied from 47 to 49 times per 100 years. Only when irrigation volume was reduced to 20,000 acre-feet did this number drop to 40 per 100 years--but the number of years where less than 142,000 acre-feet was released from the dam was essentially the same for all reservoir volumes tested (37-38 times per 100 years) and the average annual release was virtually the same for all (134,900 to 135,100 acre-feet).

Irrigation demand is made up of consumptive uses plus canal losses less effective precipitation. It can be shown that the historic irrigation demand is not constant, but has an arithmetic normal distribution with a mean value of 5.28 acre-feet per acre or about 132,000 acre-feet per year for 25,055 acres. Figure 31 shows that demand is less in those years with high flows (years of good precipitation) in the Pecos at Artesia. The dotted line on the illustration is the demand plus the losses in the McMillan delta. This line is approximately the same as the median line for historic flows at Artesia, the implication being that over-year storage is required about 50 percent of the time.

The equation for the relationship between demand and annual river flow at Artesia is

$$\text{DEMAND} = 225 \;/\; (\text{FLOW})^{0.1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (13)$$

based on the regression equation relationships between flow into Los Esteros and other system inflows (table 31)

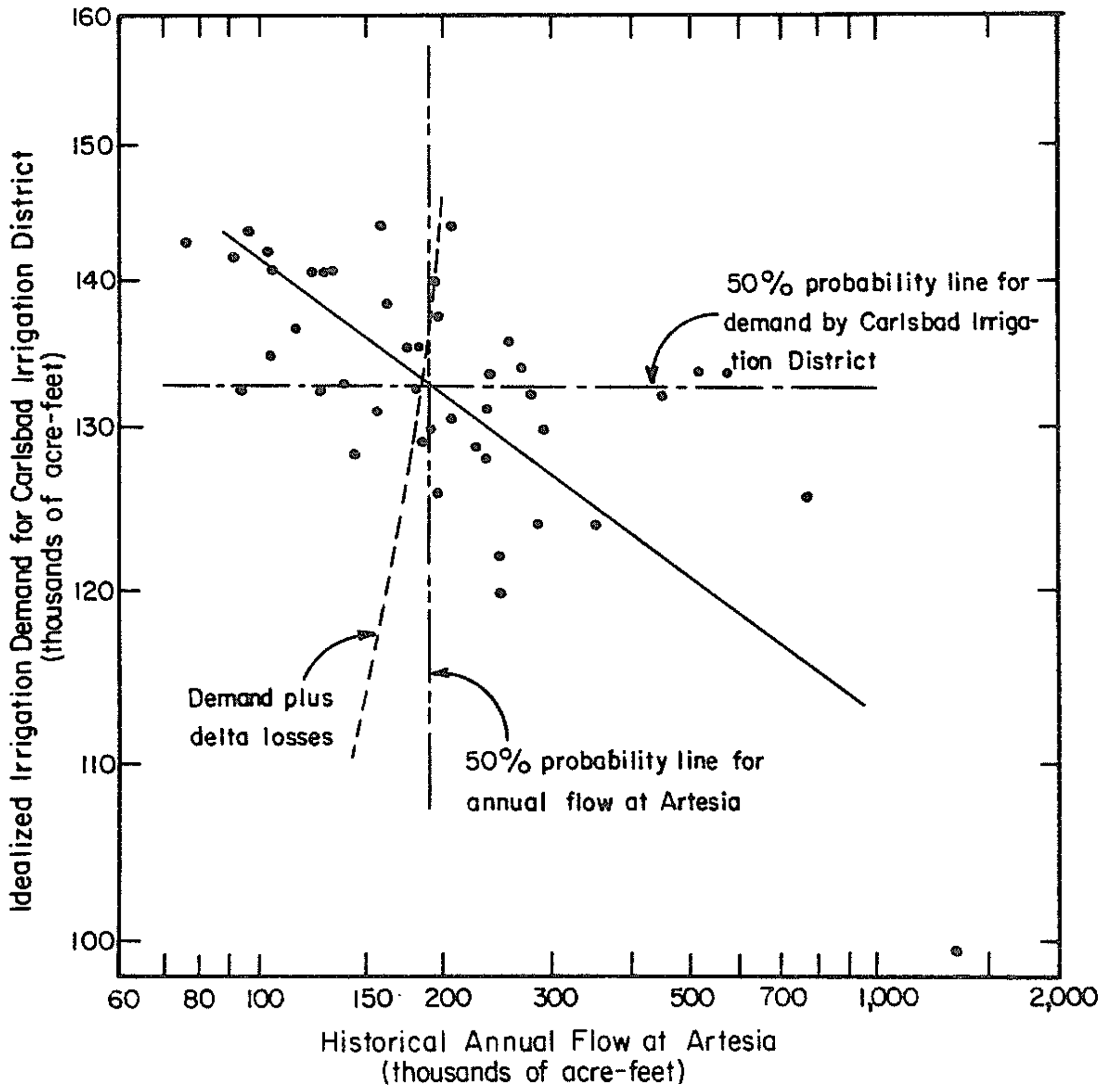

Figure 31 . Idealized irrigation demand for full supply to 25,055 acres in the Carlsbad Irrigation District vs. flow at Artesia, Pecos Basin, New Mexico.

and the mathematical expression for losses from the system (table 33), an equation has been derived for the volume of over-year storage needed in the reservoir system to meet demands. A relationship for years when releases from storage are necessary is

$$\Delta V = 225 \, [2.22 \, (SFLOW) + 43.9 - 0.9 \, (E_2)]^{-0.1}$$

$$-1.68 \, (SFLOW) - 26.7 + 0.68 \, (E_2) + E_3 . \; . \; . \; . \; . \quad (14)$$

where ΔV is the volume to be released from Brantley and Los Esteros; where no over-year storage is released from Alamogordo and E_2 is its evaporation loss; where E_3 is the evaporation from McMillan; and SFLOW is the synthetic inflow to Los Esteros. The equation is for uncleared-loss conditions in the McMillan delta.

It is impractical to provide over-year storage to meet all possible shortages. As a first approximation it is assumed that sufficient over-year storage should be made available to meet demands for low flows that are encountered five times per 100 years, such low flow being 40,400 acre-feet into Los Esteros. Equation 14 may be solved for storage required in Brantley for this value of SFLOW, by arbitrarily setting the volume retained over-year, in storage at Los Esteros at 100,000 acre-feet--making the long term average release 71,500 and the average evaporation from that reservoir 28,500 acre-feet. Average evaporation rates from Alamogordo and McMillan given in table 34 were assumed. For these conditions, the amount that must be released from Brantley is zero. No over-year storage need be provided to meet shortages that occur in any one year for flow conditions expected only 5 percent of the time. This argument has a severe weakness: under conventional operating rules it is unreasonable to believe that there will be 100,000 acre-feet of over-year storage (before evaporation losses are taken) held in Los Esteros during a year of very low flow. More likely, the water that could have been held in storage will have been released to meet demands during other years of less than the median flow. It should also be noted that providing additional storage capacity at Los Esteros does not change this situation. In the Bureau of Reclamation routing studies (table A-7, 46) there were 11 of 43 years in which 100,000 or more acre-feet was in Los Esteros at the end of a year and only times when this volume was 200,000 acre-feet.

Intra-Year Management Storage

Demand on the Pecos system does not correspond to the supply, neither temporally nor spatically. In addition to providing conservation storage on the system for years of low supply, intra-year or seasonal storage is needed to level out differences between supply and demand within any water year. Figure 32 provides bar graphs of the distribution of system inflows at various points. The peaks vary from May to October. Figure 32 is a monthly bar graph of supply and demand by the Carlsbad Irrigation District (CID) at McMillan Reservoir. Table 35 gives the monthly distribution of inflows as percent of the total supply, and the monthly percent distribution of net irrigation demands. Demand is a function of consumptive use requirements less effective precipitation. No demand was assigned to November, although historically the CID has used some water during all months of the year.

Figure 33 indicates the average months when withdrawals from storage are required--March, April, July, August, and December. Excess water is available during the remaining months. Using an average annual CID irrigation demand of 132,000 acre-feet, values for net management storage required each month were calculated, based on an empty reservoir at the end of August (table 35). These figures were then converted into average gross storage requirements in McMillan. The computations were based on a limit of 13,900 acre-feet of active storage available in the reservoir causing a need to draw more seasonal reserves from Alamogordo, with resultant channel and delta losses. The calculations indicate that, even for an average year, the management storage exceeds 22,000 acre-feet, but they fail to take into account three factors that will lead to greater demands for such intra-seasonal storage: (1) the considerable variations in the supply, particularly the flood inflows expected to provide September and October moisture (coefficient of variation for flood-flows is about 1.3); (2) the channel and delta losses, which are greatest during the summer months; and (3) the fact that demand is not constant but an inverse function of effective precipitation, being greater in dry years. The calculations in table 35 are for the average year when supply meets demands and no withdrawals from over-year storage are required. Considering the variability inherent in inflows, losses, and demands, the storage needed for satisfactory seasonal management is probably close to twice that calculated in table 35--or around 40,000 acre-feet. Monthly routing studies to accurately determine storage requirements are not included in this report, but

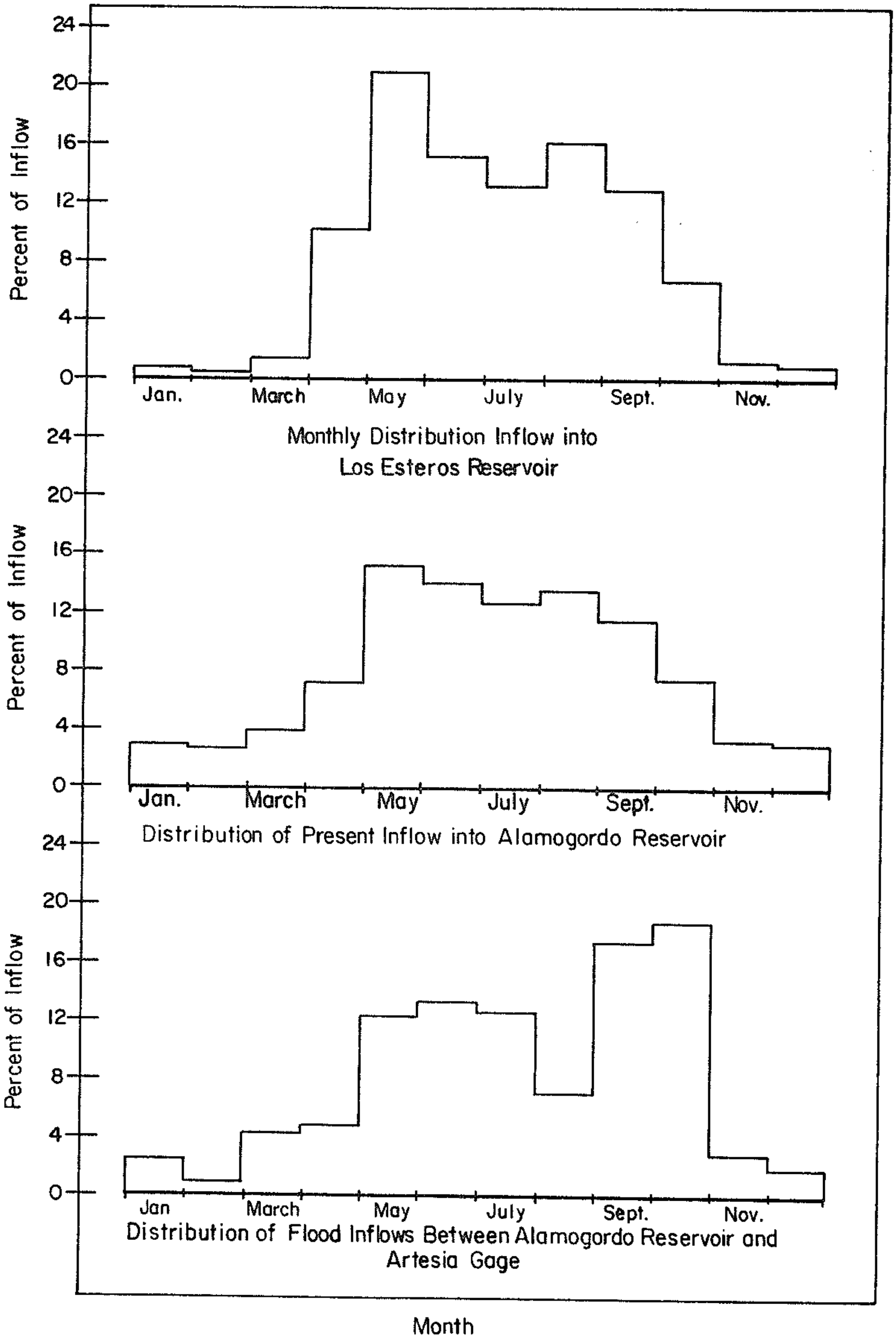

Figure 32 . Distribution of monthly flows as percent of mean annual flows for indicated stations, Pecos Basin, New Mexico.

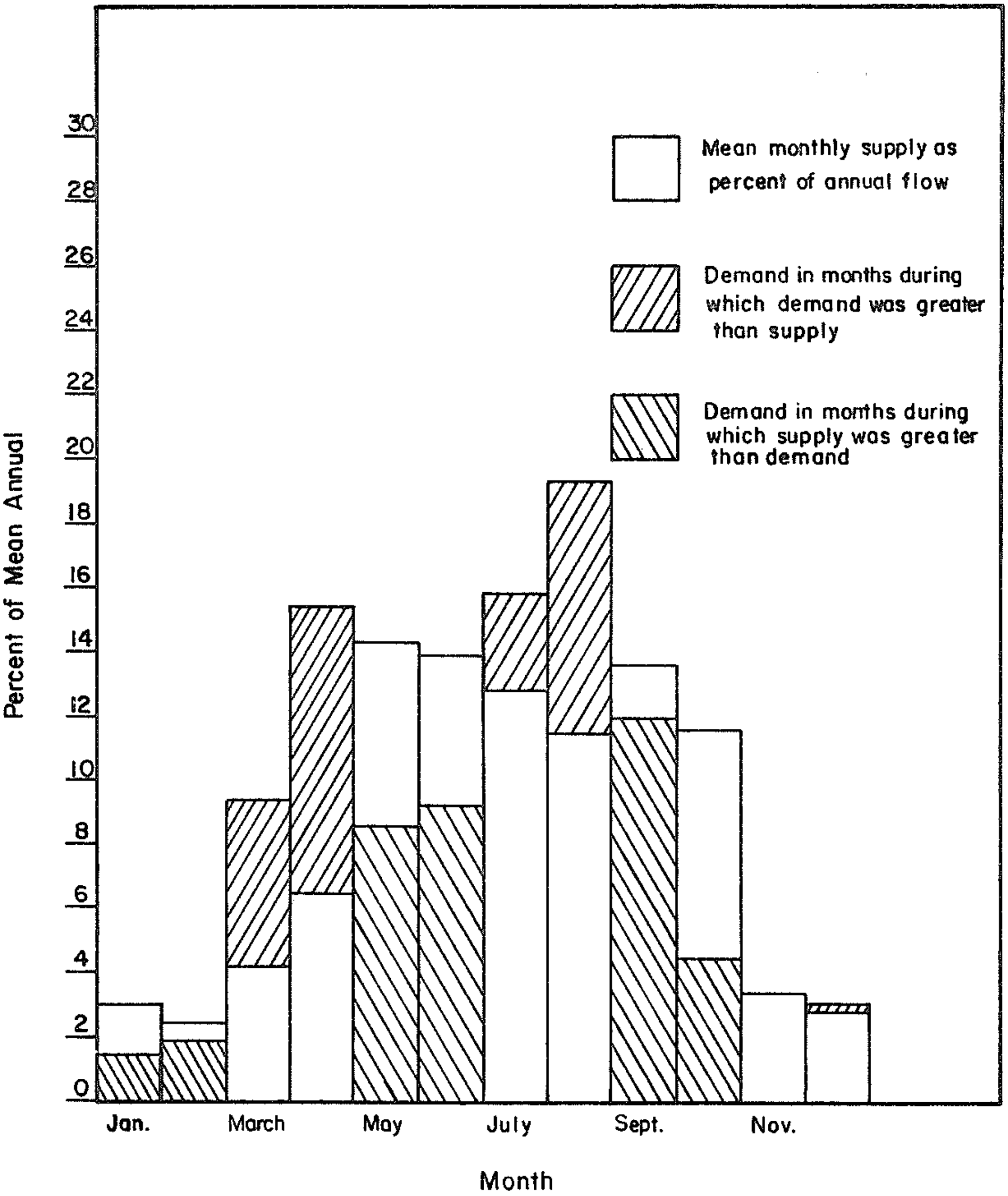

Figure 33 . Distributions of supply and demand for irrigation as percent of mean annual supply at McMillan Reservoir, Pecos Basin, New Mexico.

Table 35. Seasonal storage requirements, Alamogordo and McMillan Reservoirs, Pecos Basin, New Mexico.

Month	Monthly Distribution of Inflow: To Los Esteros Reservoir	To Alamogordo Reservoir	Flood Inflow Alamogordo To Artesia	Combined Distribution of Inflow	Monthly Distribution of Irrigation Demand	Net Management Storage Required: Percent of Mean Annual Demand	Thousands of Acre-feet x10^{-3}	Gross Management Storage Required[1]	Evaporation Loss on Gross Management Storage from Indicated Reservoir	Delta and Channel Losses on Management Storage
	(percent of mean annual)				(percent of mean annual)			(thousands of acre-feet)	(thousands of acre-feet)	(thousands of acre-feet)
Sept.	12.9	11.6	17.6	13.6	11.9	1.7	2.2	M[1]=4.8 A[1]= 0	M = 2.4 A = 0	0
Oct.	6.8	7.7	19.0	11.5	4.4	8.9	11.9	M =13.4 A = 0	M = 1.5 A = 0	0
Nov.	1.4	3.5	3.0	3.4	0.0	12.3	16.2	M =13.9 A = 5.0	M = 0.9 A = 0.2	1.2
Dec.	1.0	3.3	2.0	2.9	3.0	12.1	16.0	M =13.9 A = 4.1	M = 0.6 A = 0.1	0.9
Jan.	0.8	3.4	2.5	3.0	1.3	13.8	16.3	M =13.9 A = 7.1	M = 0.6 A = 0.2	1.6
Feb.	0.6	3.1	1.0	2.4	1.9	14.3	14.3	M =13.9 A = 8.4	M = 0.9 A = 0.3	1.9
Mar.	1.7	4.0	4.5	4.2	9.4	9.1	12.1	M =13.9 A = 1.8	M = 2.6 A = 0.3	0.3
Apr.	9.2	7.5	4.6	6.5	15.4	0.2	0.3	M = 1.5 A = 0	M = 1.1 A = 0	0
May	21.0	15.3	12.3	14.3	8.5	6.0	7.9	M =11.1 A = 0	M = 3.0 A = 0	0
June	15.2	14.1	13.4	13.9	9.1	10.8	14.3	M =13.9 A = 6.3	M = 3.5 A = 0.8	1.2
July	13.2	12.9	12.7	12.8	15.8	7.8	10.3	M =13.9 A = 0	M = 3.6 A = 0	0
Aug.	16.2	13.6	7.4	11.5	19.3	0.0	0	M = 1.7 A = 0	M = 1.5 A = 0	0

[1] M = indicates McMillan Reservoir.
A = indicates Alamogordo Reservoir.

are a part of the Bureau of Reclamation's historical analysis [46]. The fact that this study is not based on monthly flows and monthly demands seriously limits its applicability and makes some of the judgements on reservoir volume requirements accurate for average conditions only.

Variable Water-Supply Studies

The river-routing studies were based on an average annual synthetic flow (SFLOW) of 87,100 acre-feet into Los Esteros (the sequence being generated by the initial random number 8911), while the Bureau of Reclamation analyses [46] assume the historical inflow of 97,100 acre-feet--the average for the period 1919-1961. Statistical tests show that the hypothesis that both historical and SFLOW sequences could come from the same parent population may be accepted at the 5 percent significance level. The capacity to generate different flow sequences with different mean values, but from the same distribution, makes it possible to evaluate the function of the Pecos water supply system for conditions other than the historical flow. Bureau of Reclamation studies [46] on reservoir needs have been based on the record, which includes at least one very wet year (1941) with remarkably higher flows. The disparity between the historical median and the mean flows into Los Esteros (63,000 versus 97,000 acre-feet), although characteristic, indicates that the relatively few wet years have had a dominant effect.

In the studies reported in this section, 10 different flow sequences of 100 years each were generated. A "full water supply" is taken to be the sequence with an average annual SFLOW into Los Esteros of 94,300 acre-feet. This results in an average inflow of 174,400 acre-feet into Alamogordo (177,600 acre-feet historical) and a total average gross yield at Artesia of 328,200 (348,400 acre-feet historical). The effect of lesser average annual flows on operation of the system is considered. Operating conditions and policies for the studies were the same as those for tables 33 and 34, except that an uncleared McMillan delta situation was assumed and a serial correlation correction, 0.2, was used to modify the annual inflows into Los Esteros.

Operation of Los Esteros on Short Supply

Figures 34 and 35 indicate characteristic changes in performance of Los Esteros with less water available. When

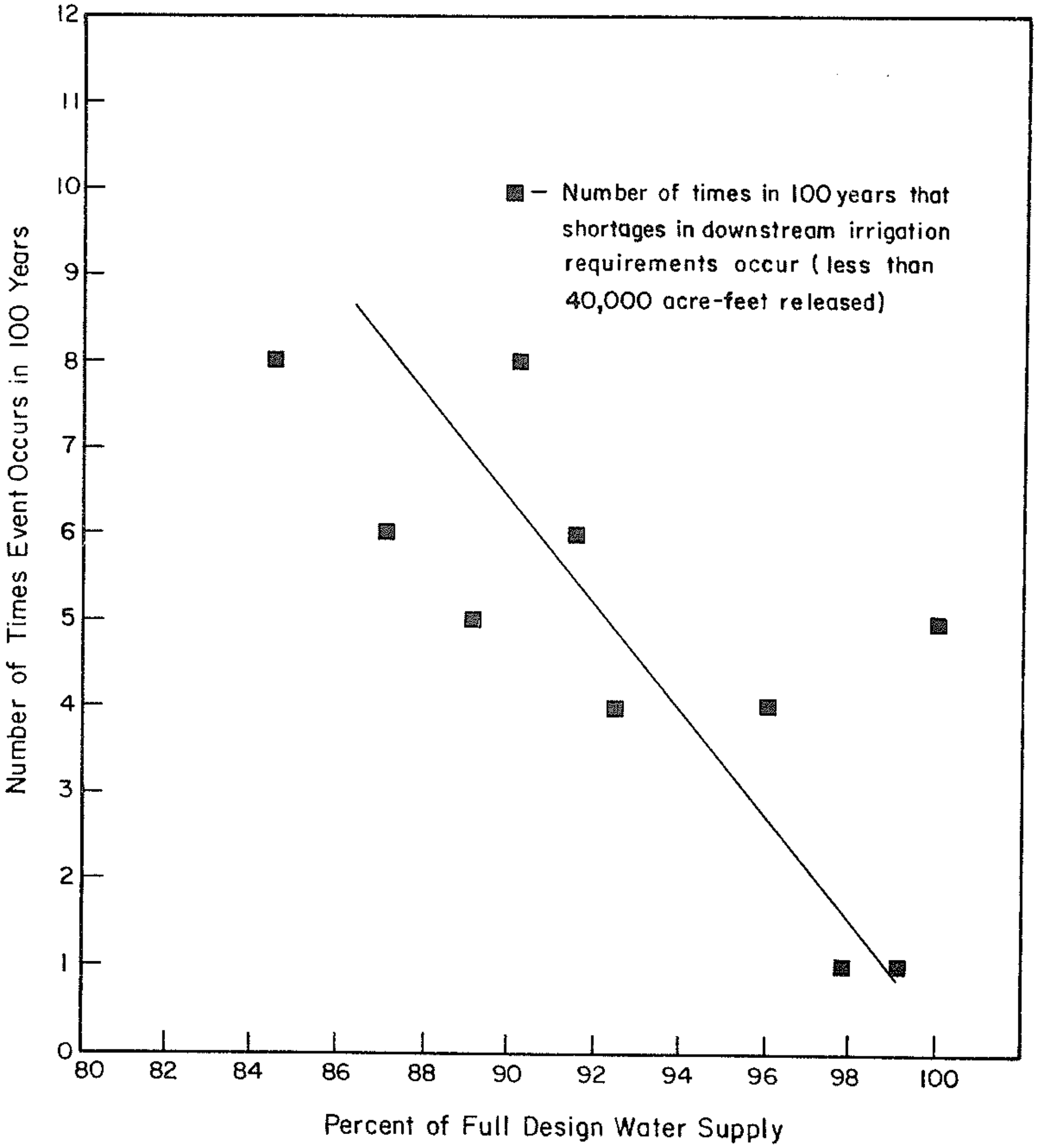

Figure 34. Variable water supply studies of Los Esteros Reservoir, Pecos Basin, New Mexico, showing number of times shortages occur per 100 years.

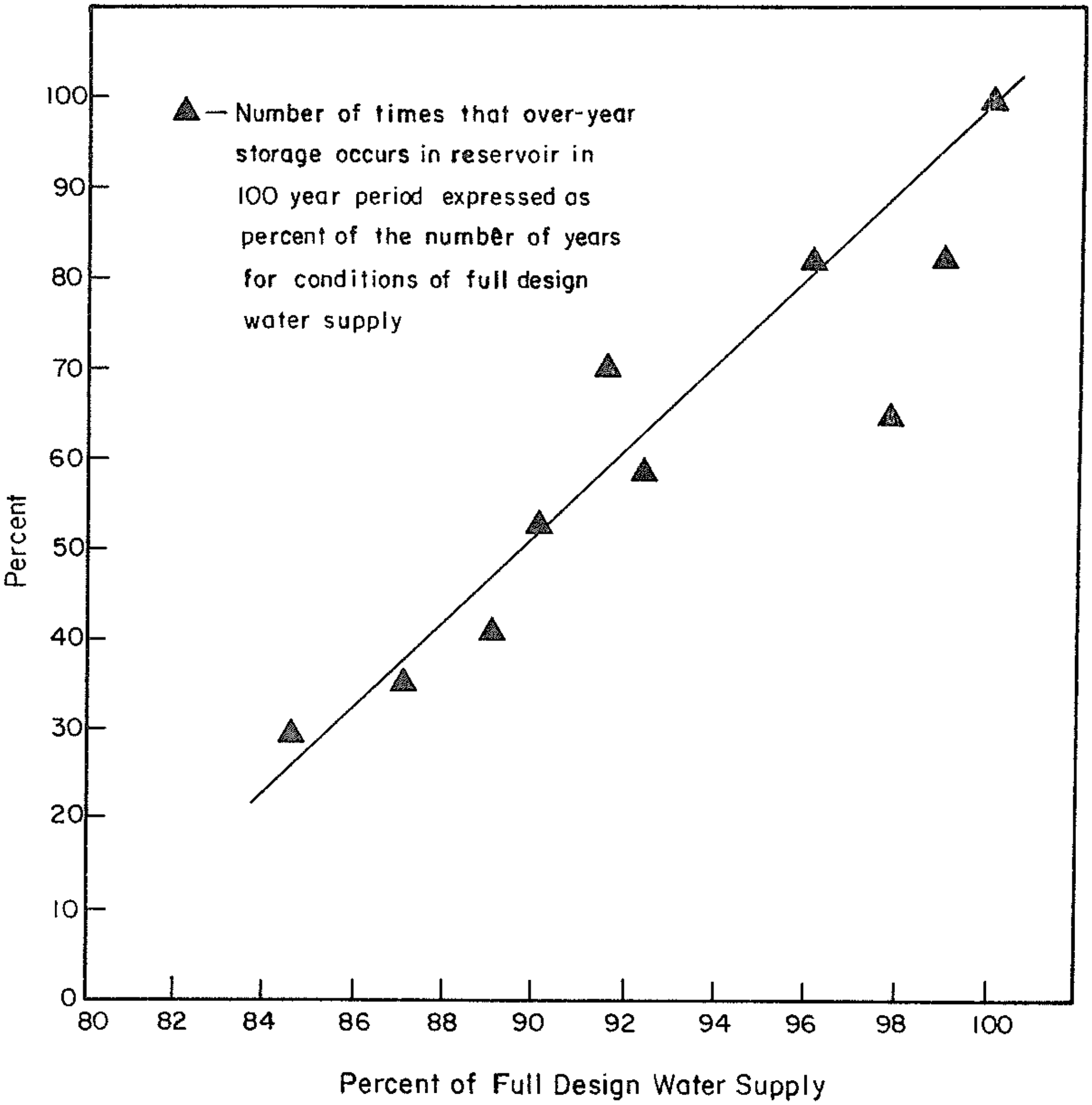

Figure 35. Variable water supply studies of Los Esteros Reservoir, Pecos Basin, New Mexico, showing number of times over-year storage occurs per 100 years.

a release of less than 40,000 acre-feet is taken to be a shortage, the number increases from one to two at 97 percent and 98 percent of full supply, to five or six per 100 years for 80 to 90 percent. The number of times shortages occur also depends on the sequence of inflows, as indicated by the fact that five such shortages occurred when the average inflow was 94,300 acre-feet per year (figure 34).

Short supply markedly affects the number of times over-year storage is needed: from 17 times per 100 years for full supply to nine times for a 10 percent reduction in supply (figure 35). The total amount of over-year storage for 100 years is reduced from 1,580,000 to 870,000 acre-feet, or about 50 percent less. If the average long-term supply is 10 percent less than 94,300 acre-feet per year, the feasibility of providing 200,000 acre-feet of conservation storage in Los Esteros can be questioned.

Operation of Alamogordo and Brantley on Short Supply

Figure 36 shows that a 10 percent reduction in average supply to Alamogordo will result in a 10 percent decrease in yield below the dam. Other factors remain essentially the same in the operation of the reservoir.

Because of channel evaporation and delta losses, a reduction of 10 percent in average supply will cause the flow into Brantley to be reduced to 82.5 percent of the yield under conditions of full supply (see figure 37). The total over-year storage for 100 years will be reduced from 1,188,000 acre-feet to 267,000, or about one-fourth of that stored under conditions of full supply. The number of times over-year storage occurs is reduced from 25 to 7. Here again, the value of providing over-year irrigation-conservation storage comes into question.

Intra-Basin Transfers

Both Lansford [26] and d'Arge [10] suggest the possibility of intra-basin transfers: that is, transferring part of the water now allocated to upper basin irrigation for use in the middle basin of the Pecos. The acreage reported under active cultivation varies: Lansford reports 17,050 acres tilled in 1966-67, while a U. S. Geological Survey study [39, p. 234] lists diversions above Alamogordo Dam for about 12,500 acres. The gains attained by water-right transfers would be higher net benefits returned per acre-foot diverted because of larger farming units, longer growing season,

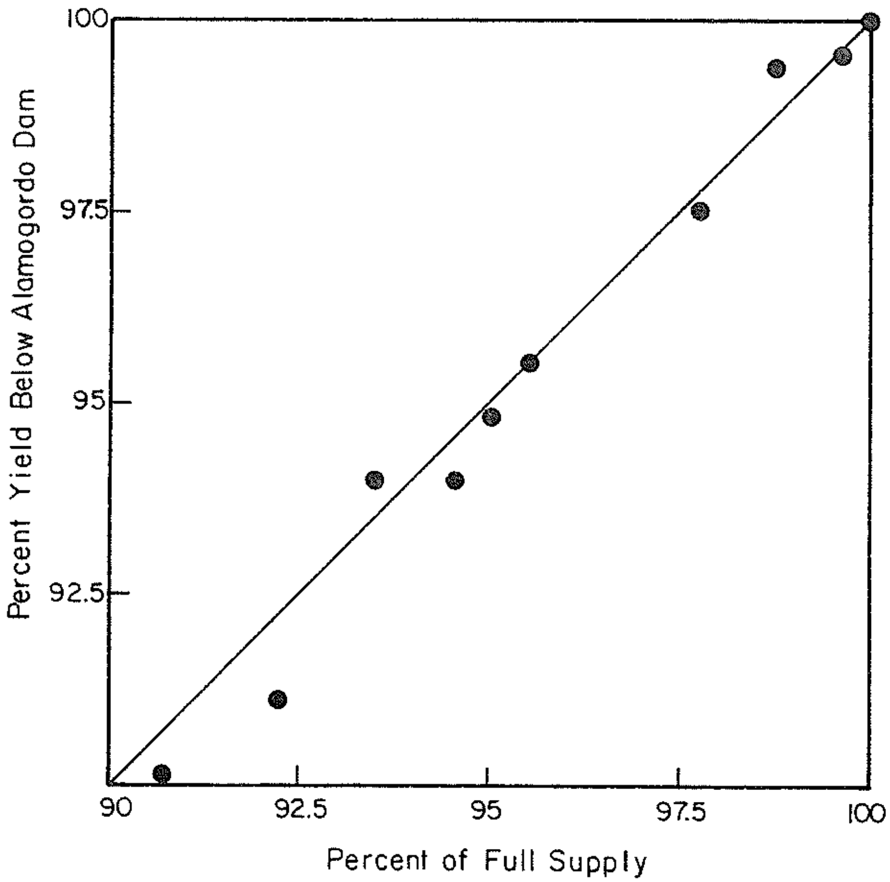

Figure 36 .Variable water supply study of Alamogordo Dam, Pecos Basin, New Mexico, showing yield as a function of supply.

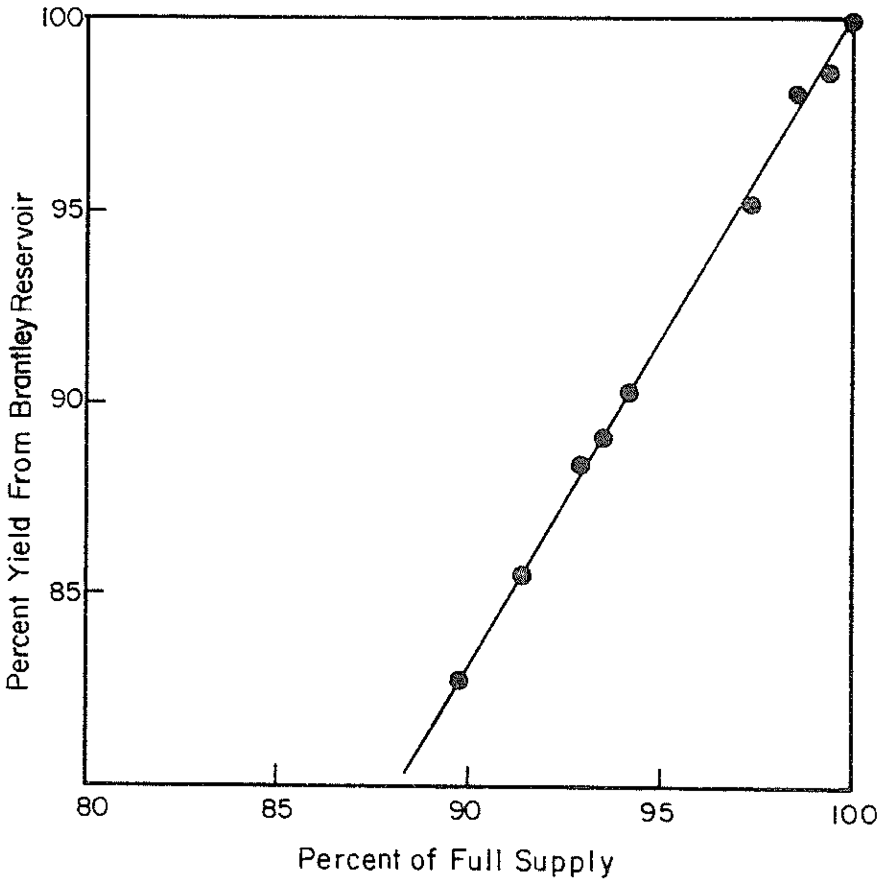

Figure 37 .Variable water supply study of Brantley Reservoir, Pecos Basin, New Mexico, showing yield as a function of supply.

and better soil quality. The disadvantages would be loss in both quality and quantity during transportation of the water downstream, and in regional income from use in the upper basin. The quantity losses would result from additional evaporation in the reservoirs on the system, as well as from dissipation in the channel and delta.

An increase in average inflow into Los Esteros resulting from the cessation of irrigation upstream, will enhance the likelihood that some of the incremental inflow will be retained over-year in the reservoir, causing additional evaporation losses. Under the operating rules used in the routing studies (table 34), an increase of 10,000 acre-feet in average annual flow into Los Esteros will add an additional eight years per 100 to the number of times that over-year storage occurs. The average additional evaporation loss is about 25,000 acre-feet each time over-year storage occurs. An average increase in annual inflow of 10,000 acre-feet will result in a loss of about 2,000 additional acre-feet due to evaporation. The routing studies showed no net change in evaporation from Alamogordo because of the operational criteria employed in the study. Operation of Brantley Reservoir with an additional 10,000 acre-feet inflow produced an additional over-year evaporation loss of about 4,000 acre-feet. These losses occurred under the particular operating rules of the routing study (table 34) and could be reduced by adopting more efficient policies. But it should be recognized that some additional evaporation losses will be incurred. Channel dissipation in the reach between Alamogordo and Acme of one-tenth of the flow, and the loss in the uncleared delta of 24.4 percent of the flow, must also be considered. A summation of all potential losses (table 33) indicates that for an additional average inflow of 10,000 acre-feet into Los Esteros per year, between one-half and two-thirds (depending on delta condition, sequence of flows, and operating policies adopted) will be lost to evaporation and nonbeneficial uses, so that net yield will be 330 to 500 acre-feet per thousand increase.

There will also be an attendant loss in quality at the point of use. The water used in the upper basin is of good quality. If not used in the upper basin, the quality of this unit of water will be poorer when used downstream. Allowing additional water to move downstream will not have a significant effect on the quality available to the Carlsbad Irrigation District, but the water transferred will depreciate from a total dissolved-solids content of just over 100 ppm to 2,500 ppm (table

A-2). Depending on quality of the lands withdrawn from production in the upper basin as compared with those cultivated in the middle basin, it is conceivable that a net loss in production potential could result because of the downstream transfer of water-rights.

The socio-economic significance of irrigation in the upper basin should not be discounted. While the cash returns to irrigated agriculture may seem small, the impact of farm operation on the individual families is of considerable consequences. In view of the water losses and quality losses that will be sustained and in view of the great need for sources of income generation in the upper Pecos, the basic concept of water transfer from this area to the middle basin appears to be totally without merit.

Quality Losses Between Anton Chico and Santa Rosa

The proposed construction of Los Esteros Dam approximately nine river miles above Santa Rosa carries with it a potentially critical problem: changes in hydraulic gradients due to storage levels maintained in the reservoir may result in increased ground water discharge in the vicinity of Santa Rosa that may cause additional deterioration in quality of the surface supply. The Bernal and San Andres formations underlie the reservoir and are exposed upstream in river channels and, at one site (River Ranch), within the reservoir conservation pool. Both contain gypsum and anhydrites that contaminate the ground waters passing through the beds.

In the 30-mile reach between the Anton Chico gaging station and the small farming community of Colonias, low flows of the Pecos (up to 40 cfs) are completely lost into these formations and the stream is dry for a 5-to-10-mile stretch. High flows are also significantly depleted. Colonias is roughly five miles upstream from the upper extremes of the proposed reservoir. A sequence of reaches of small gains and losses precedes the zone of significant loss that occurs in the 10-mile reach above Colonias. Only a small part of the water lost above Colonias is recovered again in the next 10 miles to River Ranch. The greater part moves southward through the San Andres formation from the Anton Chico-Colonias reach to the Santa Rosa-Puerto de Luna reach.

Stream-Flow Losses

The first specific studies on losses in the reach were made as early as 1910 and 1911. These efforts have been followed in more recent years (1954-1964) by seepage investigations made by the U. S. Geological Survey. Open-file memoranda in the State Engineer Office, written by Spiegel [41] and Fowler [12], provide good summaries of the available information, while the 1960 Corps of Engineers geological report [49] for Los Esteros gives additional details on the geologic structure of the reservoir site.

Spiegel developed a log-log envelope curve for the losses between Anton Chico and a point below Colonias by making a base-flow correction to the difference in daily flows at Anton Chico and Santa Rosa for selected days when inflows between the two gages did not influence the record. His curve was not a straight line and it set the outer limits on the loss relationship, rather than being fitted through the data to represent the most probable loss function. To establish a loss equation, I have taken the results of the Geological Survey seepage studies of 1961-1964, added them to Spiegel's data points, and fitted a straight line to the plot to obtain the expression

$$NL = 1.6\ A^{0.84} \quad . . . . (15)$$

where NL is the net loss in the reach in cfs and $\underline{A}$ is the mean daily discharge at Anton Chico in cfs.

Stream-flow records for Anton Chico are available [39], indicating the number of cfs-days in each of a number of flow-ranges during a 35-year record (1911, 1929-1959). This record has been plotted as figures A-3 and A-4. The total net loss into the San Andres and Bernal above Colonias was calculated for this period using equation 15. The cumulative amount of water temporarily depleted from the stream and returned after passing through the ground water structure is on the order of 1.78 million acre-feet. This is approximately one-half of the total discharge during the period.

Water Quality Deterioration

Water lost from the stream system suffers a significant quality depreciation in its transit through the San Andres and/or the Bernal formation. The quality at Anton Chico is excellent--less than 5 ppm chlorides, less than 20 ppm sulfates, and total dissolved solids on the order of 100 ppm--while at Santa Rosa the median concentrations of sulfates have increased by a factor of more than 10 and the dissolved solids are five times greater. There the quality at low flows is considerably poorer; the specific conductivity ranges from the median value of 670 millimhos to values in excess of 2,400.

Chemical analyses of samples collected as a part of the U. S. Geological Survey seepage studies show no change in quality below Anton Chico until after the water passes through the reach of major loss and into a gaining reach. Beginning about four miles below Colonias, the sulfate content and specific conductivity began to increase, reaching a maximum in the next seven miles to River Ranch. Only a small part of the lost flow is regained here, but a significant part of the quality deterioration occurs. Within this section of the river sulfates increased from 20-30 ppm to 230-850 ppm and specific conductivity went from 250-350 to 650-1600 micromhos. Variations in quality reflect different rates of flow. Some poor quality water, not related to that lost from the river into the San Andres above Colonias, enters the river in the River Ranch area from springs originating from a perched water-table in formations above the San Andres that are exposed in the valley wall above the level of the river. Degradation in quality should be expected to continue even after construction of Los Esteros Reservoir. After construction, some of the water presently recovered from the San Andres within the Colonias-River Ranch reach may by-pass the reservoir to the southwest and reappear in a more degraded condition in Santa Rosa area.

Beginning in a gaining reach four miles above the Santa Rosa gage a marked increase in chlorides (up to 90 ppm) and sulfates (an additional 500-700 ppm) occurs. This water may have been discharged from the San Andres through the Bernal, or may come from higher formations.

An estimate of the cost of lost productivity that results from this contamination may be obtained from figure 38, a plot of quality versus marginal benefits returned. Even if the water could be transported to the Carlsbad Irrigation District without further additions and concentrations of the dissolved solids load, the depreciation is still about $2.50 per acre-foot.

Possible Reservoir Effects

A possibly serious situation is the reversal of hydraulic gradients in the ground water system that may occur because of the storage of water in Los Esteros Reservoir. The San Andres formation underlies the

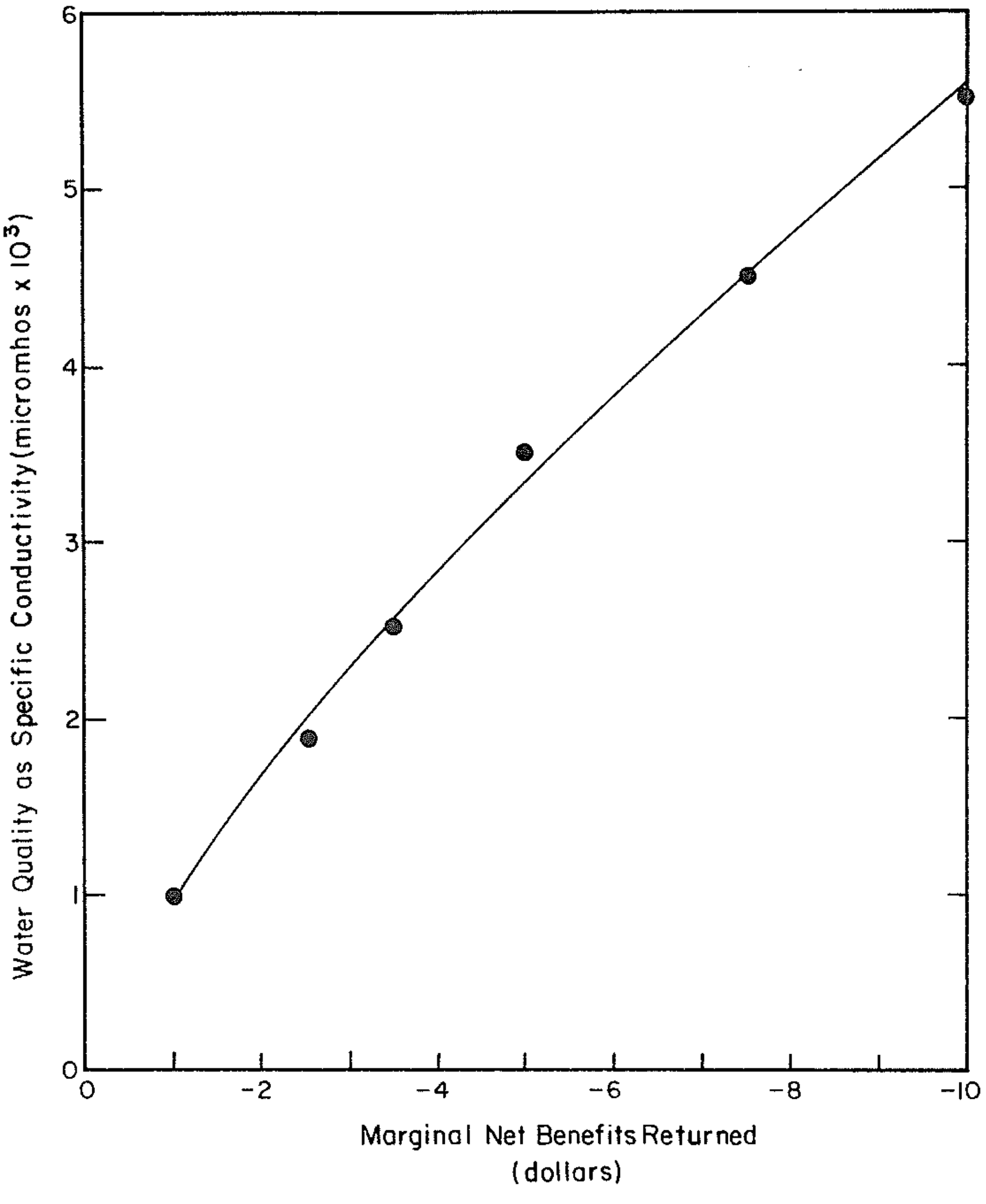

Figure 38. Water quality verses negative marginal net benefits returned for irrigation of Group I soils at three acre-feet per acre, with an optimal cropping pattern in the Roswell Artesian Basin, New Mexico.

reservoir and outcrops at River Ranch and again in the upper part of the flood-control pool. Spiegel [41] anticipated significant water losses from the reservoir at certain stages, with this water to be recovered in the vicinity of Santa Rosa, carrying with it additional salts and sulfates. The 1960 Crops of Engineers study [49], based on an extensive drilling program, considered that

> The presence of the upper water table and springs on both sides of the reservoir area, the slope of the water gradient being towards the river, and the massive sandstone beneath the reservoir area, is evidence that the reservoir would be comparatively water-tight. . . . Based on geological investigation and results of sub-surface and surface studies no evidence has been encountered indicating that reservoir seepage would be significant.

In spite of these reassurances, I believe that there are good reasons for serious concern. There are indications that the water table referred to in the Corps report [49] is a perched water table and that water may be lost into the San Andres despite higher water levels in formations above the San Andres. The U. S. Geological Survey seepage studies of the 1960s measured a small but definite increase in the flow of the Pecos roughly four miles above the gage at Santa Rosa, with a marked decline in quality.

The Crops of Engineers' investigations have included extensive core drilling directed at the conditions in the immediate reservoir site and in the uplands near and to the south of River Ranch. However, the problem of gorund water movement in the San Andres is one of regional flow from Colonias to Puerto de Luna and can only be resolved by a regional study. The regional studies that have been performed [12, 41] that pertain to the situation indicate that, because of the proposed dam, some flow from the reservoir area, through the San Andres, is likely to occur, with this water bieng discharged in the Santa Rosa area. Intensive water quality studies and tracer studies should be a part of a regional ground water investigation. A detailed regional study must be made before reliable statements can be made with respect to the effects of Los Esteros on ground water quality.

Chapter 9

SUMMARY AND POLICY STATEMENTS

Based on results of the mathematical simulation model of the surface water system of the Pecos River, New Mexico, a number of design-decision and operation policies have been developed. These suggested policies are supported by the analytical work reported in Chapters 7 and 8 and Appendix A, and summarized in the brief review presented with each policy. The assumptions and limitations embodied in the proposed statements may be found in the appropriate section of the preceding chapters. There is one general weakness in the model that should be kept in mind--the model is based on yearly and not monthly flows. The analytical results are most accurate in predicting average responces of the system and not the maximum nor minimum values that will attain under different operating policies and reservoir designs. Somewhat different conclusions might have been reached, had monthly routing studies been used.

System Storage Requirements

The amount of active conservation storage on the Pecos in New Mexico in 1947 (the date of the Pecos River Compact) was about 176,500 acre-feet. Since that time the effective capacity of the reservoirs on the system has decreased due to sediment inflows. The need for more flexible storage facilities and for additional flood control has prompted the proposal for construction of Los Esteros and Brantley dams.

Policy Statement

Storage facilities for the over-year retention of irrigation waters should be provided as follows: 100,000 acre-feet in Los Esteros and 20,000 acre-feet in Brantley. In addition, space should be made available for the intra-season management of the supply as follows: Alamogordo, 20,000 acre-feet; Brantley, 20,000 acre-feet; Avalon, 3,300 acre-feet. Minimum pools, in addition to the conservation storage, should be maintained for recreation and waterfowl propagation in each reservoir as follows: Los Esteros, 8,500 acre-feet; Alamogordo, 7,000 acre-feet; Brantley, 2,000 acre-feet; Avalon, 600 acre-feet; McMillan, 4,500 acre-feet (for winter storage only).

Arguments in Defense of the Policy

Analytical studies reported herein have shown that providing additional irrigation-conservation storage greater than those amounts recommended above does not significantly increase the yield to the Carlsbad Irrigation District and, if it is built into some reservoirs, it actually decreases the water supply available. Providing additional storage facilities above Carlsbad in the hope of recovering and using the unappropriated floodwaters of the system appears to be economically inefficient. Historical routing studies [46, p. A-10] indicate that these waters were available during only two periods in the 43-year record, amounting to an additional average annual supply of about 3,300 acre-feet, of which 45 percent was lost to evaporation before release from Los Esteros.

Studies on availability of unappropriated supply are based on the historical sequence of flows. It has been demonstrated that it is entirely possible, even likely, that smaller average annual yields will be generated on the system in the future. Lof and Hardison [29, table 10] indicate that only 87 percent of the gross flow of the Pecos, after losses, can be put to beneficial uses, with a 95 percent probability of adequacy. It is unreasonable to try to allocate the total long-term supply of the system; the supply is too variable for such planning.

The recommended minimum pools do not adversely affect the average downstream yield, and they would provide needed recreational and waterfowl facilities--beneficial uses that offer high returns in the value added to the water consumed. This recommendation is based on yearly routing studies. Had monthly routing studies been made a different conclusion might have been reached.

In accepting the policy recommendations on the amount of conservation storage needed, it should be remembered that the model employed is most likely to yield accurate results with respect to average system conditions anticipated and that it is not well suited to the prediction of system behavior during unusually wet or dry years nor for periods of high stream flow. However, I believe that the storage volumes suggested will be adequate if properly operated.

Reservoir Operating Policies

Specific operating policies should be adopted for the long-term management of the supply. The statements that follow are not intended as an optimum set, but only as an indicative guide to policies that should be employed.

Policy Statement

Maximum irrigation release from Los Esteros should approximate the average annual inflow into the reservoir--that is, between 90,000 and 100,000 acre-feet per year. With the exception of the minimum pool, minimal over-year storage should be maintained in Alamogordo, allowing annual releases to reach the maximum possible.

Irrigation releases from Brantley should be designed to meet current demands for irrigation water. Seasonal precipitation forecasts for the area and rainfall-probability predictions (Chapter 6) should be used to guide releases. In general, Brantley should be drawn down to about 20,000 acre-feet or less by September, with storage for the succeeding season to begin about that time.

In Defense of the Policy

It has been shown that the long-term, downstream yield is sensitive to maximum irrigation releases made from Los Esteros and Alamogordo. Los Esteros is designed for over-year storage, and release policy should reflect that type of operation, whereas Alamogordo is better suited for seasonal management.

Control of Channel and Delta Losses

Programs have been proposed (with some of these already underway) to control or limit the magnitude of channel losses between Alamogordo and Acme and in the McMillan delta area. Certain aspects of these programs offer limited long-term success.

Policy Statement

Cost-benefit studies should be initiated to evaluate the feasibility of a lined channel from Alamogordo into the upper end of McMillan. The delta channelization project should be initiated as soon as possible, although it should be noted that this project cannot be started until provision is made for replacement storage that will be lost in McMillan Reservoir.

In Defense of the Policy

Losses in the reaches between Alamogordo and Acme and in the delta now average about 60,000 acre-feet per year. Coupled with these is the further deterioration in quality of the remaining water. The combined effect of quality and quantity loss is on the order of $2.5 million per year in unrealized net benefits. In reality the total volume now being lost could not be salvaged, but considerable money could be invested to achieve even a 50 percent reduction. Mechanical control of salt cedars in the reach fails in three ways: (1) required annual maintenance is expensive; (2) game habitat is destroyed; (3) assurance of amount salvaged and consumers benefited is lacking. A lined channel may partly avoid some of these shortcomings. Water quality losses in this reach could possibly be reduced and sediment control structures could be included in a channel lining project. Loss of game habitat and recreational values would also be associated with a channel lining project.

Water Quality Deterioration Above Santa Rosa

Policy Statement

Feasibility studies for lining the river channel in the reach between the Anton Chico gage and River Ranch should be undertaken. Before constructing the dam, it should be made certain that seepage losses from Los Esteros into the San Andres are limited. An extensive regional water sampling and water-level measurement sutdy should be undertaken before Los Esteros Dam is built. These investigations should include tritium tracer studies on water lost from the river between Anton Chico and Colonias.

In Defense of the Policy

Deterioration of water quality in this reach can be expressed in terms of its dollar value. The change in quality that now occurs between Anton Chico and Santa Rosa costs downstream irrigation a minimum $2.50 for each acre-foot lost into the contaminating formations before its return to the stream. If average losses into the ground water system amount to 50,000 acre-feet per year, the economic loss would be $125,000 each year. A project representing a considerable capital investment could be constructed to control or limit this zone of contamination of the surface waters of the Pecos.

Part IV

CONCLUSIONS

Water resources of the Pecos River in New Mexico can be employed more efficiently, in that the quantity and quality of the waters of the system may be enhanced. Analytical studies detailed in this report indicate some of the ways that, if implemented, could provide for a better and larger supply.

Development of both surface supply and ground water simulation models may be usefull in future management. Admittedly neither of the models presented in this study is truely representational of the system, but both models may be easily modified to reflect different assumptions, constraints, and conditions, and they are quite flexible and can be used to assess specific problems of the Pecos.

There are four programs that should be initiated and sursued vigorously to improve the present systems water resources:

1. The level of pumping in the Roswell Artesian Basin should be reduced by retirement of necessary lands from production.

2. Channel and delta losses between Alamogordo and McMillan Dam should be reduced with projects to effect this reduction undertaken as soon as possible.

3. Deterioration of the quality of the surface supply in the reach from Anton Chico to Puerto de Luna should be reduced. A regional ground water quality and movement investigation should be undertaken to identify possible remedial programs for this reach of the Pecos with quality control measures to be a part of any new development work in the Santa Rosa area.

4. A salinity routing study should be undertaken to evaluate the combined effects of current and planned water development projects on the quality of the surface water supply of the Pecos.

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Appendix A

THE PHYSICAL SYSTEM OF THE PECOS BASIN

Hydrology

Historically, studies of the Pecos system have identified three principal reaches of the river: the upper and middle basins in New Mexico and the lower basin in Texas. The New Mexico-Texas state line crosses the upper reaches of Red Bluff Reservoir and provides a convenient demarkation point between the middle and lower basins. The dividing line between the middle and upper basins is Alamogordo Dam.

The U. S. Geological Survey [53] has divided the upper and middle basins into hydrologic units. Those of particular interest (see table A-1) are the upper basin and the sub-units of the middle basin that include the Fort Sumner area, the Roswell Artesian Basin, and the Carlsbad Irrigation District.

General Characteristics of the Stream System

The headwaters of the Pecos originate on the eastern slopes of the Sangre de Cristo Mountains in north central New Mexico. In a distance of 160 miles, elevations in the drainage area drop from 13,000 feet at South Truchas Peak to 4,300 feet above mean sea level at Alamogordo Dam. The reservoir is the downstream terminal point on the upper basin, an area that includes 4,390 square miles of contributing watershed. The runoff-contributing area above the confluence of the Pecos with the Gallinas includes 1,660 square miles, approximately one-third of this area being at an elevation of about 7,500 feet or higher. The stream course is on a steep grade, falling more than 5,000 feet in its first 30 miles. Above Pecos, New Mexico, the river would be classed as a mountain stream; below the town it flows through a series of narrow canyons separated by small valleys. Much of the mountain area is a part of the Santa Fe National Forest, with sections at the higher elevations set aside as part of the Pecos wilderness area.

The major tributaries in the upper basin may be divided into those heading in the Sangre de Cristo mountains, their flows being affected mostly by winter

Table A-1. Hydrologic units of the Pecos River system, New Mexico, included in the study.

Basin	U. S. Geological Survey Hydrologic Unit	Delineation of the Sub-Basin
Upper	3-1	Pecos River, its tributaries, and headwaters above the confluence of the Pecos with the Gallinas River below Anton Chico.
	3-2	Pecos River and its tributaries from the Gallinas downstream to the U. S. Geological Survey gaging station below Alamogordo Reservoir.
Middle		
Fort Sumner Area	3-4	Pecos River from Alamogordo Dam to its confluence with Arroyo de la Mora.
Roswell Area	3-7	Rio Hondo basin from its headwaters to its confluence with the Pecos.
	3-8	Pecos River from the Acme gage to Lake McMillan.
Carlsbad Area	3-9	Pecos River from below Lake McMillan to the state line.

moisture, and those arroyos in which flow is generated by thunderstorms and late-summer and early-fall moisture from the Gulf of Mexico. The period of sustained maximum flow of the headwaters, tributaries, and the Gallinas occurs in May, with 60 percent of the annual runoff during the months of snow-melt and spring rains.

The water yield from the mountain zone is a function of the snow pack, with elevation determining the average snowfall, which varies from 340 inches at 12,000 feet to 200 inches at 10,000 and 85 inches at 8,000 feet. The annual discharge contributed by snow accumulations depends upon several factors, one being water content of the snow just before melting. The April equivalent is a function of elevation, with mean annual value (in inches) varying from zero to one at 8,000 feet, nine at 10,000 and 25 at 12,000 [4]. Forest management will also markedly affect the yield and timing of snow melt. Good management procedures may lead to significant increases in downstream flow.

The headwater tributaries discharging into the Pecos above Anton Chico are Tecolote Creek, with 282 square miles of watershed, and Cow Creek, 128 miles square, draining the area north and east of the main channel and west of the Gallinas River watershed (figure 16). Two principal tributaries of the main stem are the Rio Valdez and the Rio Mora, both entering the river above the U. S. Geological Survey gaging station at Pecos, while others contribute below that point. Tecolote Creek joins the Pecos just upstream from Anton Chico. The gaging station there is located 314 river miles above the upper end of McMillan Reservoir (south line of section 19, T18S, R27E) and approximately 400 river miles above the state line. About 20 miles below the gage the Pecos is joined by the Gallinas, a major tributary (610 square miles) that provides the Las Vegas municipal supply and the Storrie Lake irrigation project, draining the area north of Las Vegas and the northeastern portion of the upper basin. Entering the Pecos two miles below Anton Chico is the Canon Blanco, a tributary that drains the high mesas in the western zone of the sub-basin, with branches heading near Rencona and near Clines Corners.

After the Pecos crosses Interstate 25 near San Joes, New Mexico, it flows east and then south along several very old farming communities whose irrigated lands lie in the valley floor. Santa Rosa, the first major town on the river's route, lies at the end of a canyon zone in a broad depression. Above it the valley area is quite narrow with occasional widening or benches where irrigated farming is possible.

The high mesas that flank the river as it leaves the mountainous area lead into broad, sloping plains that are deeply cut in places by the Pecos and its tributaries. The river runs in a southeastern direction as it crosses these plains, which also slope to the southeast at elevations ranging from 5,000 to 6,000 feet above mean sea level. In the reach between its confluence with the Gallinas to Alamogordo Dam, a distance of almost 100 river miles, the Pecos falls approximately 1,000 feet. Parts of the plains area on both the east and west flanks have interior drainage and do not contribute to the surface flow of the stream system, but do add to the ground water that discharges into the river. Surface flow in the reach just above Alamogordo is measured at the U. S. Geological Survey gaging station at Puerto de Luna, for which the contributing drainage area is 3,970 square miles. Two-thirds of the flow into the reservoir arrives during late spring and summer months and in September, with the maximum recorded runoff coming in the latter month. Tributaries to the flood flows into Alamogordo Reservoir are Pintado Creek (930 square miles), coming in from the west seven miles below Santa Rosa, and Alamogordo Creek, draining the area east of the reservoir and entering the lake.

The middle basin yields about one-half of the aggregate flow in the system from three-fourths of the drainage area. Its 15,000 square miles of contributing watershed include parts of 11 counties: DeBaca, Chaves, Eddy, Guadalupe, Torrance, Quay, Curry, Roosevelt, Lea, Otero, and Lincoln. Roughly one-fourth of the land area within the middle basin falls into the non-contributing category. Between Alamogordo Dam and the northern end of the Roswell Basin, Salt Creek and its tributaries, Gallo Creek, Padilla Creek, and Cienaga del Macho, carry the surface runoff from much of the area to the west. A large part of the water yield is underground. The area east of the Pecos in this reach is poorly drained, the only significant water courses being Taiban Creek that enters below Fort Sumner.

One hundred river miles below Alamogordo Dam the Pecos channel opens onto the Roswell Basin. Several tributaries enter the river along its 80-mile course through the broad valley. The most important of these streams head in the Sacramento Mountains to the west--Rio Hondo, Rio Felix, Rio Penasco, and Seven Rivers.

In the Carlsbad area the major drainage courses are Dark Canyon, Black River, and the Delaware River. Long Arroyo is the only important contributor from east of the river, entering near Hagerman.

Close to the junction of the Pecos with Seven Rivers the valley narrows to provide a suitable site for the proposed Brantley Dam and then widens again onto the irrigated lands below Carlsbad. Twenty miles below the city the river channel closes again near Malaga, afterward leading a short distance downstream to the state line at the upper end of Red Bluff Reservoir.

Summary of Stream-Flow Characteristics

Many recent publications of the State Engineer Office and U. S. Geological Survey have dealt with specific aspects of the hydrology of the Pecos River in New Mexico, the most useful being Flow Characteristics of New Mexico Streams [39], Characteristics of the Water Supply in New Mexico [15], and a paper by Heckler [19] that is specific to the Pecos. Table A-2 presents a summary of the stream flows recorded at the principal gaging stations on the main stem. One should be cautious in comparing these figures, as they occasionally represent different periods of record.

At many of the stations on the Pecos, the record of average daily flows and annual flows approach a log-normal distribution. Figure A-1 is a typical log-probability plot for two of the upper basin stations, with deviations from that distribution evident at both ends of the plot, indicating that both very dry and very wet years have been experienced. Lof and Hardison [29], who have characterized the distribution of the principal river systems in the United States, consider the flow in the Upper Rio Grande and Pecos Rivers to be a log-normal distribution. Runoff at both stations, for which data are shown in figure A-1, fails to correspond to log-normal distributions in many respects, particularly at the extremities of the plots.

Periods of prolonged low flow are common throughout the basin. Figure A-2 is a presentation of smooth distribution curves for daily flow at Anton Chico for three 10-year periods. The effect of the drought years is clearly shown when the data are plotted on log-probability paper in figure A-3.

Table A-2. Stream flow records at selected main stem station on the Pecos River in New Mexico.

Station	Contributing Drainage Area Square miles	Record Included	Average Discharge acre-feet per year
Santa Rosa	2,650	50 years 1912-24, 1928-66	105,000
Below Alamogordo Dam	4,390	1912-Ap1926 Aug1926-1936	170,900 (23 years prior to Alamogordo Dam)
Below Alamogordo Dam		1936-1966	158,500
Near Artesia	15,300	1905-08, 1909-1936	264,200 (30 years prior to Alamogordo Dam)
		1936-66	213,600
Below McMillan Dam	16,990	1906-07, 1939-40, 1947-66	74,570
At Carlsbad	18,100	1903-04, 1905-06, 1914-1915 1920-1936	184,600 (prior to Alamogordo Dam)
		1936-1966	133,200
At Red Bluff	19,540	1937-66	160,700

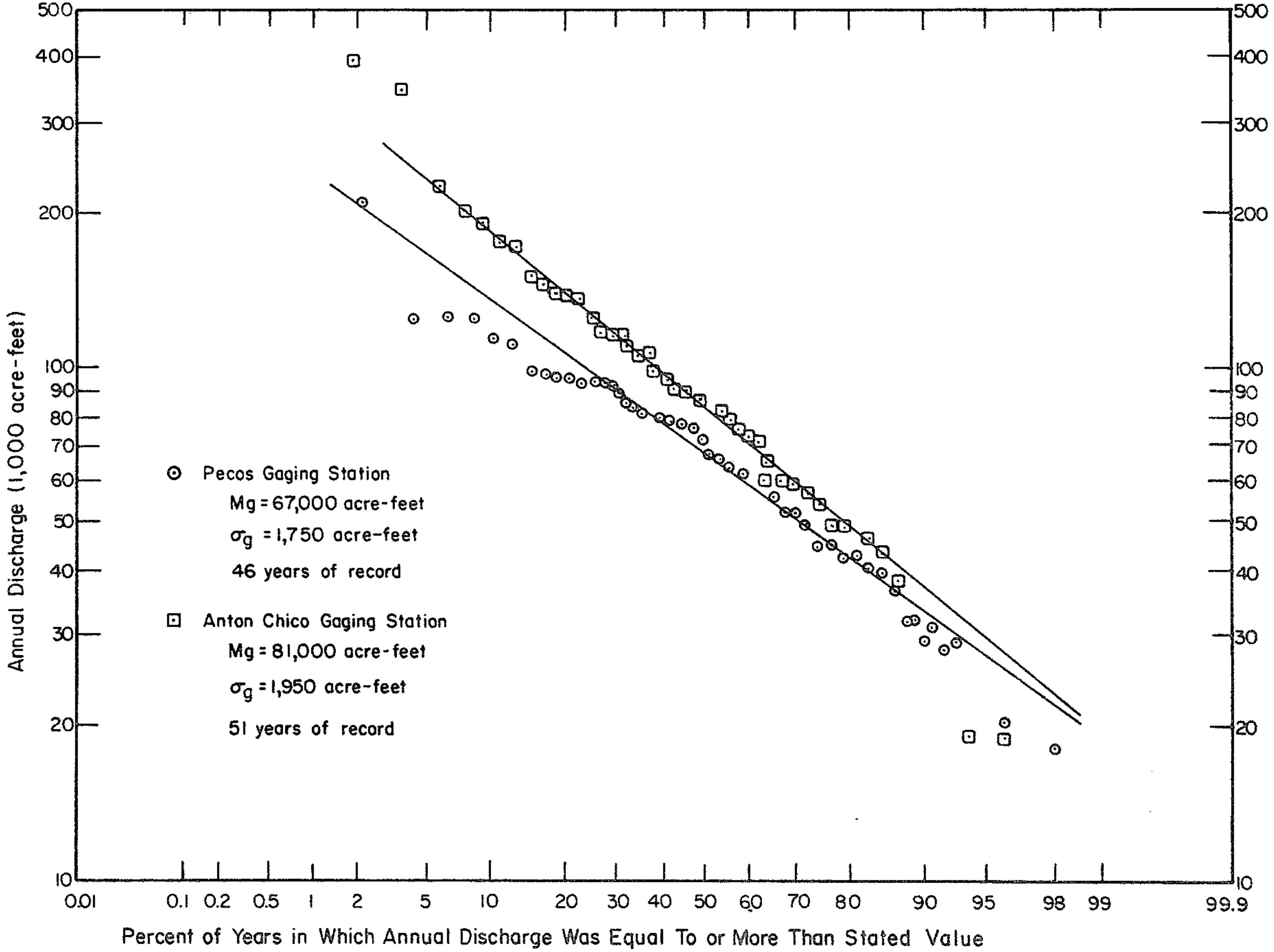

Figure A-1. Log-probability plot of annual flows, Pecos and Anton Chico gaging stations, Upper Pecos Basin, New Mexico.

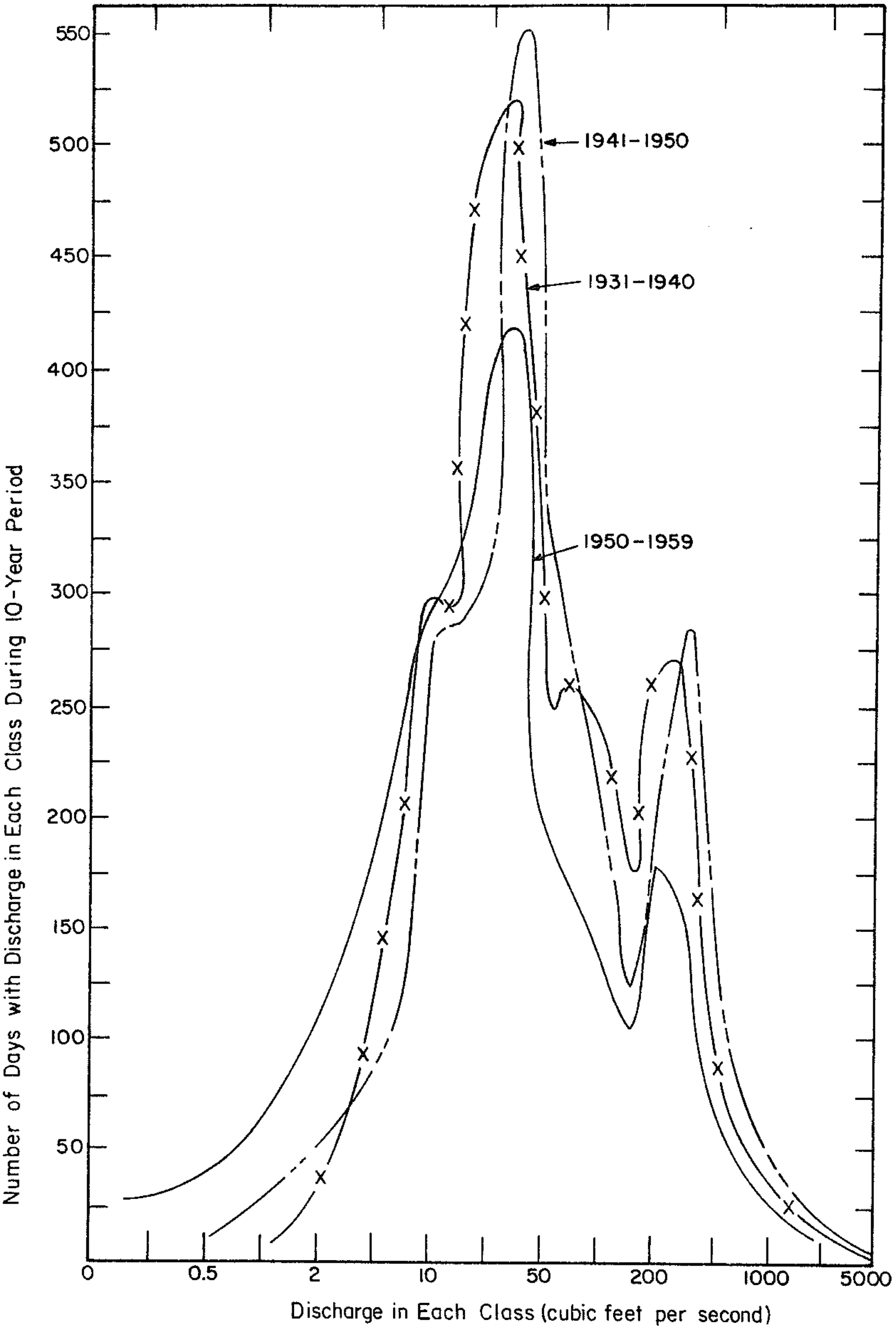

Figure A-2. Smoothed distribution curves of daily discharge rate for 10-year periods, Anton Chico gaging station, Upper Pecos River Basin, New Mexico.

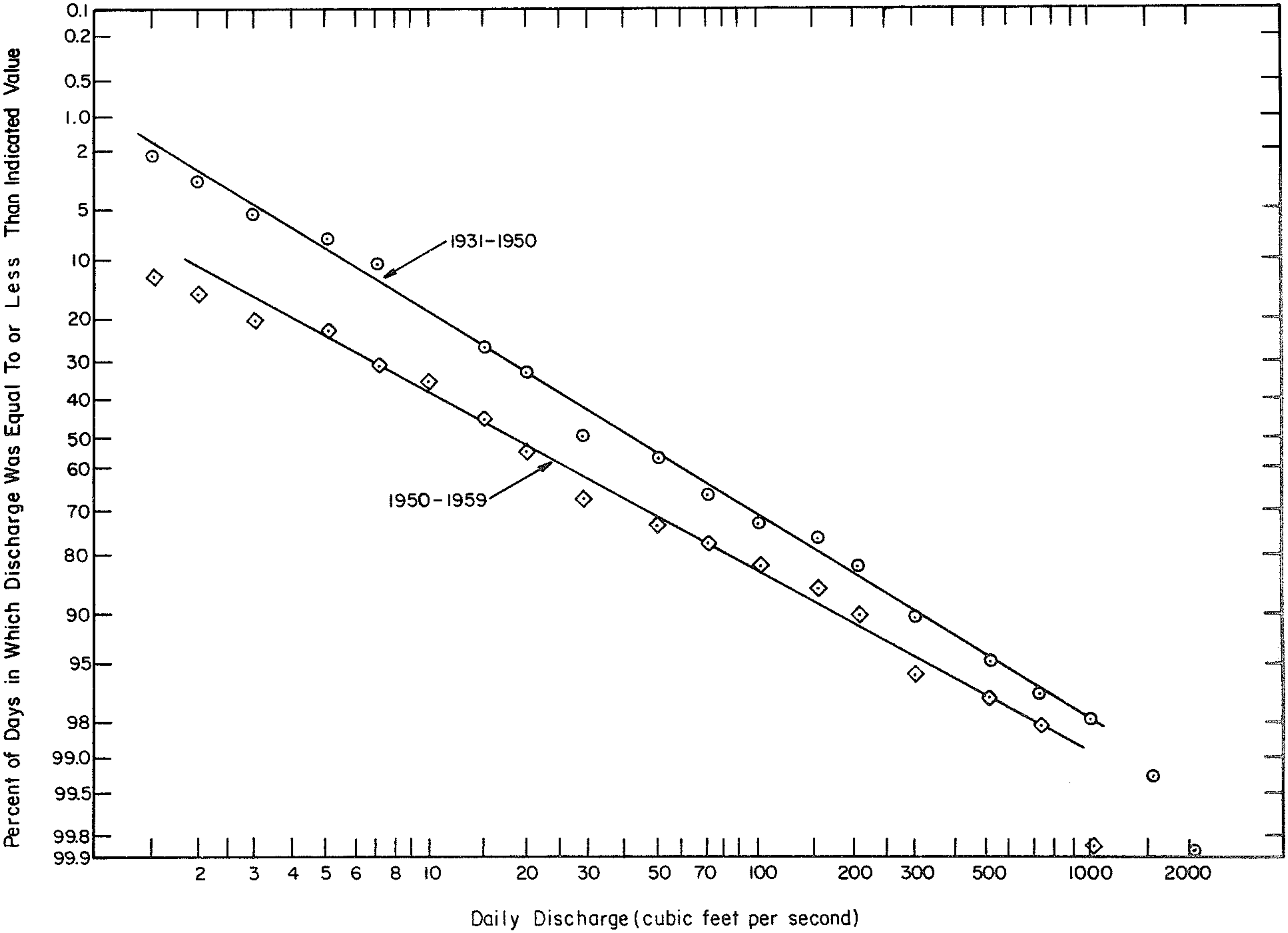

Figure A-3. Log-probability plot of distribution of daily flows during indicated 10-year period, Anton Chico gaging station, Upper Pecos River Basin, New Mexico.

Water Quality

Good records of surface water quality, principally those of the U. S. Geological Survey, are available for the river. Summaries and reviews of characteristics of the supply at various points along the river may be found in Heckler [19], Hale [15], findings of the 1942 Pecos River Joint Investigation [32], and in New Mexico water quality standards [37]. Lansford [26] selects quality as one of the determining factors in the economic classification of basin lands, while d'Arge [10] notes that constraints imposed by New Mexico stream standards [37] make quality as important to conserve as quantity in the basin. In his section of the Pecos Basin study, d'Arge found that "shadow prices for water quality, when transformed to quality units, were of the same magnitude as shadow prices for water quantity."

Dissolved Solids

The dissolved-solids content of the Pecos Basin supply is of considerable importance because irrigated agriculture represents the major beneficial use of water in the basin. For most chemical constituents in solution, the greater their concentration above a certain level the lower the productivity derived when the supply is used for irrigation. Figure 7 shows the relationship between net benefits from optimal cropping and varying water conductivity. A review of typical changes in net returns for various crops with changes in water quality is found in Part III.

Quality of the downstream supply is degraded by upstream use and tributary inflows of lesser quality. In general, irrigated farming results in the consumptive use, by evaporation and transpiration, of about two-thirds of the water diverted from the source of supply. Essentially all of the dissolved solids from the part of the supply that is consumed are transported back to the stream or ground water system by the remaining return flow.

Two general relationships hold for most of the ions that contribute to the dissolved-solids load of the Pecos: (1) increased concentration in the downstream direction and (2) diminution with increased volume of flow. Table A-3 gives the median concentration for selected dissolved materials for several stations, the median being defined as the concentration that may be expected to exist at least half of the time. The table should be used with

Table A-3. Summary of water quality characteristics at Pecos River gaging stations, New Mexico.

Pecos River Station and Period of Record Reviewed	Median Annual Discharge 1930-1960	Median Concentration	Daily Minimum	Daily Maximum	Median Value Specific Conductivity at 25°C	Median Concentration of Chlorides	Median Concentration of Sulfates
	(cubic feet per second)	(ppm)	(ppm)	(ppm)	(micromhos)	(ppm)	(ppm)
Anton Chico 1940-1941	111	129 (wt. avg. 1941)	96	185	--	less than 5	less than 20
Santa Rosa 1930-1940	92	542 (wt. avg. 1930-1940)	174	2,320	670 (wt. avg. 1930-1940)	10 (wt. avg. 1930-1940)	259 (wt. avg. 1930-1940)
Puerto de Luna 1939-1940, 1948-1960	--	2,500 (1953-1959)	220	2,740	--	135 (1953-1959)	1,510 (1951-1959)
Below Alamogordo Dam 1937-1965	180	1,450 (1960-1965)	435	2,730	1,790 (1960-1965)	74 (1960-1965)	872 (1960-1965)
Acme 1937-1965	--	2,330 (1960-1965)	459	19,870	3,660 (1960-1965)	442 (1960-1965)	1,430 (1960-1965)
Artesia 1937-1965	245	4,850 (1960-1965)	461	16,300	7,210 (1960-1965)	1,470 (1960-1965)	1,800 (1960-1965)
Below Mc-Millan Dam 1953-1965	--	--	4,930 (monthly)	6,070 (monthly)	--	--	--
Carlsbad 1937-1960	102	2,580 (1960-1965)	360	3,810	3,610 (1960-1965)	525 (1960-1965)	1,170 (1960-1965)
Malaga 1937-1965	133	6,550 (1960-1965)	384	9,100	9,510 (1960-1965)	2,280 (1960-1965)	1,960 (1960-1965)
Red Bluff 1937-1965	--	10,500 (1960-1965)	450	22,800	15,100 (1960-1965)	4,500 (1960-1965)	2,170 (1960-1965)

care, as entries represent different periods of record; some of the values show periodic or, in one case, monthly samples rather than flow-weighted daily samples. Summaries for longer periods of record may yield different values for some constitutents for some stations. A discharge weighted average will give far different values than will a time weighted average in some cases. The discharge weighted average for Puerto de Luna for dissolved solids for the period 1954-1959 is only 1470 ppm as compared to a median daily concentration of 2,500 ppm. From this table it will be noted that a significant degradation takes place from station to station in the downstream direction, with some improvement in the larger impoundments on the system--that is, below Alamogordo and McMillan reservoirs. The values for minimum and maximum dissolved-solids concentrations for below McMillan are quite similar, probably because they represent monthly samples. The water quality at Carlsbad is not indicative of that received by the Carlsbad Irrigation District as water for the project is diverted above the sample point at Carlsbad. The analysis for this station represent high flows in the Pecos and spring-flow quality.

Not all of this depreciation in quality is the result of upstream use. Very poor-quality water, discharging from the ground water sources, enters the river at several points in sufficient quantity to cause the quality of the surface supply to be significantly altered. A discussion of the magnitude and quality of these ground water system discharges in the reach from Anton Chico to Alamogordo Reservoir appears in Chapter 8.

Figure A-4 is representative of a situation found at most of the quality-sampling stations on the Pecos: that is, that a good relationship exists between flow and the concentration of particular dissolved constituents. For figure A-4 the sampling station is the Pecos near Acme, New Mexico, and the parameter is total dissolved solids. The relationship has the general form

$$C = a\,Q^{-b} \text{. . . . .} \quad (16)$$

where $\underline{C}$ is the concentration in ppm; $\underline{Q}$ is the discharge in cubic feet per second; and $\underline{a}$ and $\underline{b}$ are regression-equation coefficients. Equations of this type were used in establishing the New Mexico standards for dissolved constituents [37].

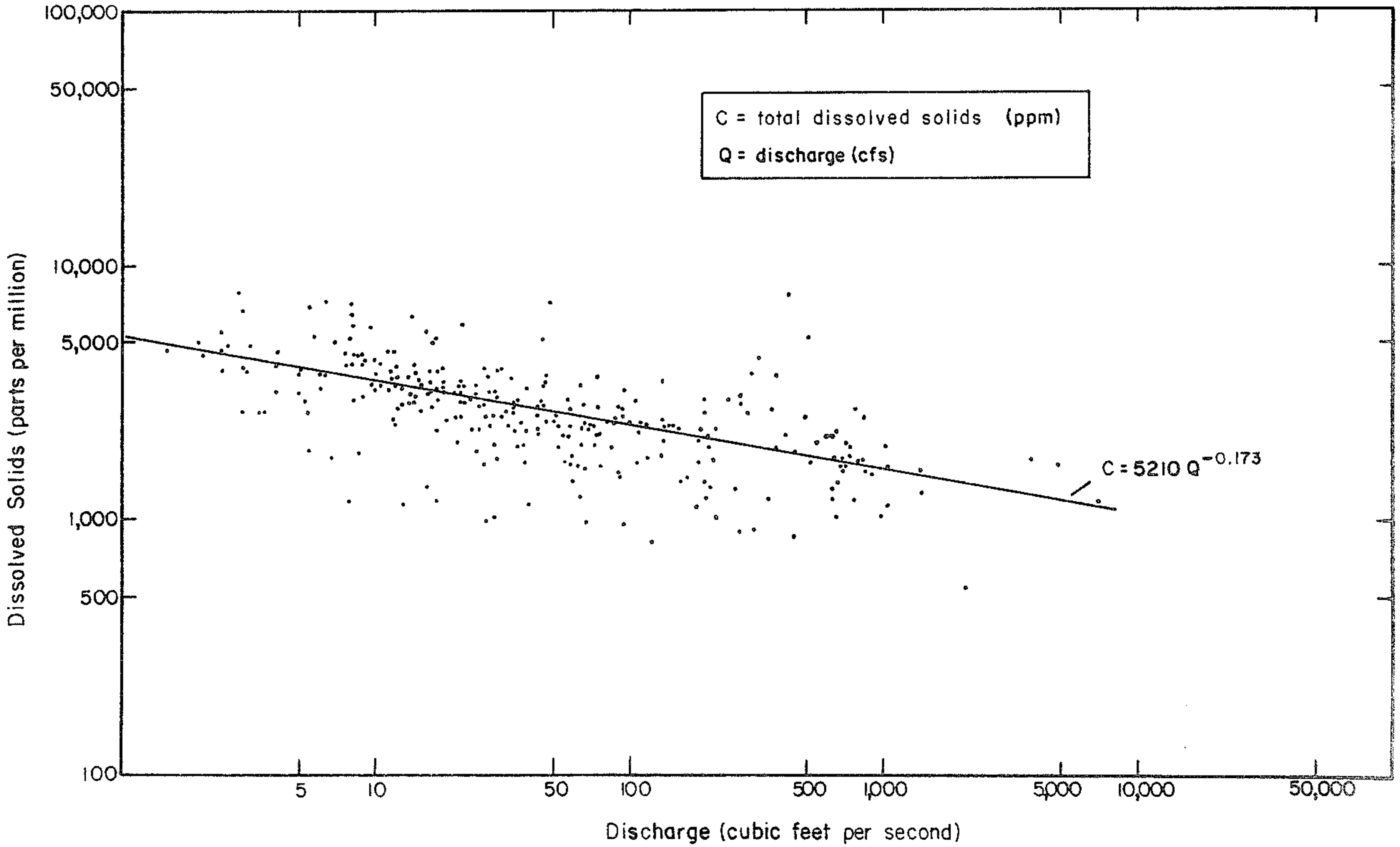

Figure A-4. Chloride concentration verses discharge for Pecos River near Acme, New Mexico, July 1960–June 1965.

Sediment Load

The load carried by the Pecos results in decreased reservoir capacities and in deposition of sediment in ditches, canals and channels. The total sediment load of the stream system has two components: the suspended materials, and the bed load or material that is transported along the bottom of the stream, particularly at periods of high flow.

The yield from the upper basin offers a significant quality problem. Between 1950 and 1959 the average suspended-solids load was 2.6 million tons per year at Puerto de Luna [15, table 9], with the maximum daily load for the period at 1.5 million tons. In comparison, values for the Artesia gaging station are 0.74×10^6 tons per year with a maximum day of 0.18×10^6 tons. During the 1950s the Rio Hondo,as measured at Diamond A Ranch, produced an average of 40 tons of sediment per acre-foot of discharge, and the Rio Penasco about 30 tons. In the same period the average suspended-solids load varied from over 600 tons per year per square mile of drainage basin at Puerto de Luna to less than 100 tons at Artesia.

There are many deposition points in the Pecos that are of interest: (1) the reach between Anton Chico and Colonias where the flow is lost underground, with the sediment temporarily dropped in the channel to be carried downstream during flood peaks; (2) the upper reaches of the Alamogordo Reservoir, which retain about 10 percent of the 1,600 acre-feet that are deposited annually in the reservoir; and (3) the McMillan delta area where, historically, much of the sediment of this reach of the Pecos has been deposited [46, p. A-37]. The average annual inflow of sediment in Lake McMillan has been about 400 acre-feet, based on a compacted weight of 76 pounds per cubic foot. The capacity of Alamogordo Reservoir has decreased from the original 1937 volume of 157,000 acre-feet to less than 111,000 acre-feet by 1964, whereas Lake McMillan has lost more than half its original capacity of 90,000 acre-feet, with much additional deposition occurring in the delta above the reservoir.

The rate and amount of sediment inflow into reservoirs on the system are quite variable, a function of volume of flow, channel width and slope, velocity of flow, size of drainage area, character of surface soils, season, and nature of the watershed in terms of topography, plant cover, and use. The degree of abuse of the area is probably the determining factor in the sediment yield, but the amount of transported load is a function of many factors, including the particle-size distribution. An example of the variability of the deposition in a Pecos-system reservoir is found in table A-4 for the inflow of silt into Lake McMillan during various periods since its construction.

For the 22-year period (1910-1932) included in table A-4, the average rate of sediment deposition in Lake McMillan was approximately 800 acre-feet per year, with the influx decreasing since construction of Alamogordo Reservoir in 1937. Because of changes in the watershed and in river control structures, an average figure should be used only with considerable caution. The continual build-up of stream-borne material in the delta area above McMillan has probably been a major contributing factor in the decline in rate of sediment inflow into the lake.

Characteristically, the larger, heavier particles drop out first, with the finer clay particles being carried further into the reservoir proper. Sediment particle-size studies for the Artesia station show that over 50 percent of the weight is made up of suspended particles smaller than 0.004 millimeter and only 5 percent is due to particles larger than 0.1, while 50 percent of the weight of bed-load material is composed of particles larger than 0.1 millimeter. Only 15 percent of the total sediment at this station may be classified as sand with the remainder being clay and silt.

During periods of above-average flow the weight of suspended solids transported by the Pecos is a function of the discharge of the river. The greater the flow, the larger the magnitude of the suspended sediment load. A general relationship between these variables takes the form

$$SS = K\,Q^n \qquad (17)$$

where SS is the suspended sediment in tons per day; $\underline{Q}$ is the mean daily discharge in cubic feet per second; and $\underline{K}$ and $\underline{n}$ are taken to be constants for a particular station over a given range of discharge. The value of $\underline{n}$ is a function of the flow, decreasing with an increase in the discharge. For the Pecos near Artesia, over the flow range from 2,000 to 20,000 cfs, the value of $\underline{n}$ is close to 1.0, with $\underline{K}$ at a value in the neighborhood of 20 [46, figure A-3]. The value of the exponent $\underline{n}$ increases to 1.5 to 2.0 when the flow range is between 200 and 1,000 cfs. Flow-duration curves for this particular

Table A-4. Variation in rate of sediment inflow into Lake McMillan, Pecos Basin, New Mexico.

Period	Length of Period	Total Deposited Sediment During Period	Approximate Flow into Reservoir During Period	Silt Deposited per Acre-Foot of Flow into the Reservoirs	Average Sediment Deposited Per Year
	(years)	(1,000 acre-feet)	(millions of acre-feet)	(acre-feet)	(acre-feet)
1910-1915	4.6	13.4	1.26	10.6×10^{-3}	2,920
1915-1925	10.0	3.5	3.17	1.1×10^{-3}	350
1925-1932	7.0	1.5	1.62	0.9×10^{-3}	215

station indicate that 50 percent of the time the daily discharge is below 100 cfs, with flows in the range of 200 to 1,000 cfs occurring less than 20 percent of the time. Major flood flows of 2,000 to 20,000 cfs can be expected to occur less than 2 percent of the time. A similar function may be used to relate bed load to discharge, with the values for *n* for the Pecos near Artesia being about 1.5 in the flow range between 10^2 and 10^4 cfs [46, p. A-34].

Basin Weather and Climate

Two detailed sources of information on the climatic characteristics of the basin are Frank Houghton's paper [23] which deals specifically with that area, and the more general textbook by Yi-Fu Tuan, *et al*. [45]. Much of the information in this section comes from these two reports.

The climate of the Pecos Basin can best be described as moderate in temperature, sub-humid to semiarid, with an abundance of dry, clear days. The lower elevations of the area are among the warmest in the state, with a mild, irregular temperature gradient rising from north to south. The gradual up-slope of the land from southeast to northwest is a determining influence on the regional climate. The north is higher, cooler,and somewhat greener than the south, mainly because of lower evapotranspiration but also because of its greater rainfall.

Diurnal, seasonal, and areal variations and contrasts in climate are apparent. Relatively rapid changes in temperature, with marked extremes both daily and annually, are due to the dry, clear atmosphere. Characteristic of a continental climate clear distinction between seasons is usually apparent throughout most parts of the basin. The climate is quite dissimilar from one life zone to another, particularly with changes in topography and elevation, which produce noticeable changes in vegetation. Factors most affecting the climate of a given part of the basin are distance from the Gulf of Mexico, latitude, and elevation of the station, as well as areal variations in topography nearby with distance from the Gulf probably the least important of these factors. Table A-5 is a compilation of the significant and characteristic variations in precipitation, temperature, and air-mass movement in the Pecos watershed of New Mexico. Table A-6 is a summary of the historic record for a number of stations for characteristic climatic parameters.

Table A-5. Trends and variations in climatic characteristics in the Pecos Basin, New Mexico[1].

Characteristic Variation	Monthly and Seasonal Variation
Precipitation	Median monthly values are usually less than arithmetic-mean values; the greater the mean monthly value, the greater the variation in general. Standard deviation for summer greater than for winter months, but coefficient of variation is less. June traditionally a period of less moisture than either May or July. November and February normally driest months; July and August, wettest; May is usually start of rainy season. Precipitation during late spring, summer, and early fall is from Gulf of Mexico, as moist air masses move into basin. Flood-producing rains often experienced during this period. Summer storms have greatest intensity soon after precipitation begins, with convective storms exhibiting high local intensity for short periods. Frontal storms cover larger areas with less intensity and longer duration. Intense 24-hour rains most likely to occur in early spring or early fall months with few intense rainfalls occurring November to March. Moisture tracks in basin originate from almost all directions, but are principally from Gulf of Mexico air masses, particularly in spring and summer. Fall and early winter storms from Pacific are usually relatively dry because of influence of western mountain barriers.
Temperature and Air Movement	Average monthly temperature is less variable between years than similar values for precipitation. Winter minimum temperatures at high elevations (10,000 feet) may be modified by area temperature inversions, which also occur in winter weather in valleys or down-slope areas. July is warmest month, January coldest in general, late summer months warmer than earlier. Nighttime temperature in spring and fall shows gradual drop if gentle westerly wind blows; sudden change may occur if winds shift to northeast. Daily

Table A-5. Trends and variations in climatic characteristics in the Pecos Basin, New Mexico continued.

Characteristic Variation	Monthly and Seasonal Variation
Temperature and Air Movement	temperature range is greatest in spring and fall months. Polar maritime air from northwest is occasionally cool and dry; westerly spring winds on clear nights are generally mild, although strong regional winds occur. Winds from southeast produce thunderstorms in summer; May to September tropical maritime air masses are subject to orographic lifting. Tropical continental winds in late spring and early summer may lead to warm days, due to hot, dry air.
	Annual Variation
Precipitation	Greatest annual rainfall, 62.5 inches, occurred at White Tail in Sacramento Mountains in 1941. Median annual precipitation is less than arithmetic-mean annual value at most stations. Annual precipitation is highly variable: coefficient of variation for Carlsbad is 0.45; for Santa Rosa, 0.41; and for Las Vegas, 0.34.
Temperature and Air Movement	Mean annual temperatures are strongly related to the elevation (see text).
	Topographic and Geographic Variation
Precipitation	At elevations above 7,000 feet, two-thirds or less of annual precipitation occurs in May to September; below that height more than two-thirds of annual fall is in this period. Areas of highest precipitation usually coincide with areas of high elevation: north of Santa Rosa at elevations above 7,000 feet, 20 to 35 inches per year; 14 to 20 below 7,000 feet; south of city at elevations above 7,000, 20 to 30 inches; below 7,000 feet, 12 to 16 inches per year.

Table A-5. Trends and variations in climatic characteristics in the Pecos Basin, New Mexico continued.

Characteristic Variation	Topographic and Geographic Variation
Precipitation	Orographic effects of elevation on precipitation are quire variable; seasonal variations are often more significant. May precipitation not strongly related to elevation with July rain more closely related to elevation. Storm intensity appears to be related to elevation and topography, but variations are too great to generalize on the connection (see text). Intensities at or near abrupt topographic barriers are likely to be higher than in the area in general.
Temperature and Air Movement	Factors determining temperature are latitude, topography, and elevation. Potential evapotranspiration (PE) increases from north to south: the PE for Dilia in Guadalupe County is approximately one foot less per year than the value for Carlsbad, but about 0.7 foot more than that expected in Tererro in San Miguel County. For north-south mountain alignments, the west flanks of the range are warmer and consequently drier. The farther air masses move overland from their sources, the less moisture per unit volume, in general. Temperature inversions and air mass drainage are found on gently sloping alluvial fans at base of mountains. Air masses are raised by terrain; this and other factors may result in temperature and moisture content condensation occurring causing low cloudiness and occasionally fog and drizzle. This effect is most pronounced with a southerly flow; low clouds almost always appear when winds persist from southeast for many days.
	Trends and Cycles
Precipitation	Variation in long-term frequency of storms appears in records of adjoining climatological areas. A peak year for precipitation

Table A-5. Trends and variations in climatic characteristics in the Pecos Basin, New Mexico continued.

Characteristic Variation	Trends and Cycles
Precipitation	throughout the area was 1941; 1956 climaxed a dry period that started in 1943. Pollen and tree-ring studies indicate historical periods of fluctuation in precipitation.
Temperature and Air Movement	Local-area conditions are more important in determining temperature variations than are trends or cycles. Warmer and cooler cycles are apparent in long-term records; periods of lower than usual rainfall coincide with periods of higher summer temperature for the Bell Ranch station east of the basin. January temperature for various stations appears to cycle in similar fashion and more synchronously than do averages for July.

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[1] Much of the information for this table is taken from Tuan, *et al*. [45].

Table A-6. Climatic characteristics at selected stations in the Pecos Basin, New Mexico[1].

Station and Period of Record Reviewed	Elevation	Highest Daily Temperature	Lowest Daily Temperature	Mean Annual Temperature	Average Freeze Free Period	Average Annual Precipitation	May Through September Precipitation as Percent of Mean Annual	Mean Number Days per Year With 0.1 Inch or More Precipitation	Mean Number Days per Year With 0.5 Inch or More Precipitation	Mean Annual Snow Fall	Drainage System Within The Basin
	(feet above msl)	(°F)	(°F)	(°F)	(days)	(inches)				(inches)	
Cowles 1894-1950 1954-1965	8,100	July 90	February -27	42	87	24	67	57	14	85	Main stem of the Pecos River above Pecos, New Mexico.
Tererro 1946-1961	7,500	July 94	February -35	43	95	18	67	40	10	53	
Pecos Ranger Station 1916-1920 1923-1968	6,900	July 99	February -22	49	127	16	63	38	7	46	
Rencona 1924-1964	7,000	July 99	February -25	48	136	15	67	38	6	43	Western high mesa--Canyon Blanco Drainage
Palma 1944-1968	6,532					14	71	41	14	38	
Las Vegas 1887-1968	6,470	June 100	February -31	49	155	17	69	36	8	36	Northeast Mountain slopes and eastern plains, Gallinas River drainage
Ribera 1915-1920 1924-1965	6,100					13	77	29	5	31	
Villanueva 1940-1968	5,800					14	86	39	12	20	Main stem of the Pecos River above Anton Chico and below the Pecos River station
Dilia 1941-1960	5,140	July 103	February -21	54	163	13	69	32	6	24	
Santa Rosa 1908-1968	4,620	June 108	February -18	58	188	14	70	31	9	14	Main stem of Pecos River below Anton Chico and above Alamogordo Dam
Alamogordo Dam 1937-1968	4,350	June 106	February -13	59	209	13	71	25	7	6	
Roswell 1931-1960	3,600	June-July 110	February -29	60	196	12	67	22	4	10	Lower part of middle basin
Artesia 1910-1968	3,375	June 116	February -35	61	208	11	67	23	3	9	
Carlsbad 1931-1960	3,120	July 111	February -17	63	212	12	66	22	5	3	

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[1] As the period of record for the various climatological parameters is variable, figures are rounded to the nearest integer. In most cases entries reflect the published period of record that was reviewed.

There are marked differences in temperature and precipitation patterns and ranges between the mountainous headwater zones and the high plains of the upper basin. The high plains have weather more typical of southeastern New Mexico, influenced principally by tropical maritime air masses from the Gulf of Mexico. Summer thunderstorms there often result from solar heating augmented by orographic lifting of these masses as they flow upward and to the north and west of the open areas of the valley to the south.

Variability is one of the chief characteristics of the rainfall in the drainage basin. The average annual precipitation at Las Vegas has fluctuated from 9 to 32 inches, with a standard deviation of 6 inches. The coefficient of variation for winter moisture is 0.55, while for summer it is only 0.32 [45]. The unpredictability of winter rain is indicated by the difference between coefficients for summer and winter at Carlsbad: 0.46 to 0.70. The coefficient of variation for annual precipitation increases in the downstream direction: Las Vegas, 0.34; Santa Rosa, 0.41; Roswell, 0.43; and Carlsbad, 0.45 [45].

The marked influence of elevation is reflected in the record of many of the climatic characteristics. For example, the mean number of days in the freeze-free period changes rapidly with elevation. Even at Dilia, in the middle of the upper basin, only during June through September do temperatures remain above 32°F, dropping below freezing in early May and October. The growing season is very short in the mountains with less than 100 days, but is over 200 at the lower elevations in the middle basin.

Although there are examples of good correlation between precipitation and elevation, there are other dominant aspects, particularly topography and geographic locations. Generalized relationships between rainfall intensity and elevation are difficult to draw, even though they appear to exist. Complicating factors in the basin are geographic location, rate of rise of the terrain, and the return-period (frequency) considered.

The rate at which water is lost to evaporation and transpiration is of considerable importance in management of the basin's supply. In the Bureau of Reclamation's Brantley study the average net evaporation rates were set at 5.6 feet per year for Los Esteros and Alamogordo reservoirs and 6.0 for McMillan, Brantley, Avalon, and

Red Bluff. The Engineering Advisory Committee for the Pecos River Commission has derived equations for these reservoirs that relate evaporation to percent of daylight hours, temperature, and humidity [46, p. A-4]. Tuan, et al. [45, pp. 112-142] provide values for basin locations for potential evapotranspiration (PE), the combined evaporation from the soil surface and transpiration from plants, when the water supply in the ground is unlimited. Tuan [45, p. 125] also presents values for the average annual moisture deficit for these locations, which may be taken as an estimate of the water needed for unrestricted plant growth that is not provided by precipitation.

Pertinent Geological Characteristics

Many of the basin's problems derive from its hydrogeology. Geological Survey reports are available for most of the counties and Maddox's 1965 summary on the availability and quality of ground water offers a short review of the current situation [30]. Three areas in which the geology is of particular interest with respect to proposed changes in surface water management are (1) the reach from Anton Chico to Santa Rosa, which will include the planned Los Esteros Reservoir; (2) the reach from Alamogordo Dam to Acme; and (3) the proposed site of Brantley Dam above Carlsbad. The geology in the Roswell Artesian Basin is briefly reviewed in Chapter 8. The description of the reach from the Puerto de Luna to the Acme gage is taken from the 1942 Pecos River Joint Investigation [33], while the pertinent dam-site geology is based on the work of E. R. Cox, summarized in [38, pp. 222-223].

Headwaters to Santa Rosa

The headwater valley of the Pecos is formed by two southerly tending hills of erosion-resistant, pre-Cambrian rock, the terminal parts of the southern Rocky Mountains with the western ridge running to a point north of the village of Pecos (figure 16). On the eastern ridge, pre-Cambrian stone surfaces along tributaries that enter from the east. Overlying this material and outcropping over much of the mountain area is the Magdalena group, a thick sequence of sandstone to shale to a predominating limestone.

As the river leaves the steep upper reaches it flows south along the base of the Glorieta Mesa, the dominant surface feature south along Interstate 25 and west of the stream. Irregularity of the pre-Cambrian rocks makes the thickness of the Magdalena formation quite variable. At several points along the highway between the village of Rowe and Las Vegas, the Sangre de Cristo formation may be seen. It overlies the Magdalena, ranges from 600 to 1,000 feet in thickness, and consists of alternating beds of shale and coarse sandstone. Outcrops occur in the mountain foothills in the lower slopes of the escarpments that form the northern limits of the Glorieta Mesa. The Sangre de Cristo formation blends into the Yeso, a siltstone and sandstone of variable thickness--400 feet where it is exposed on the north slope of Glorieta Mesa. The San Andres formation rests on the Yeso, with the Glorieta sandstone as the base of the San Andres--150 to 200 feet of mesa caprock. The limestone unit may be found over a considerable area on the mesa, up to 20 to 30 feet thick in places. The Bernal formation, equivalent of the chalk bluff farther downstream, is the upper member of the San Andres; as shale and siltstone, it may be seen in the hogback ridges west of Las Vegas and on the east and west sides of Glorieta Mesa. The very thick (1,000 to 1,200 feet) Dockum group follows next, with its base the Santa Rosa sandstone. There is relatively little ground water available for development in the basin above Anton Chico.

The sequence of geological formations that overlie the pre-Cambrian rocks of the foothills zone continues sloping to the southeast, with a regional dip of one to two degrees. To the west and south of the river the Santa Rosa sandstone covers much of the surface of these high plains, except where it has been cut away by erosion in the drainage system. In the Pecos channel and in the sides and walls of major tributaries above Santa Rosa, the siltstone and sandstone of the Bernal formation, and often the San Andres limestone, are exposed. Outcroppings of the latter are more frequent in the upstream section of the reach. The occurence of these beds is important for two reasons. The Bernal and the top of the San Andres formations contain gypsum beds that are related to deterioration of quality of the ground water in this section. Solution processes in the gypsum-bearing limestone have resulted in collapse features that are common to the area.

Along the Pecos channel in the vicinity of the proposed Los Esteros Dam site, the red beds of the Triassic Dockum group are the dominant feature. The following description of the hydrogeologic conditions in the reservoir area is taken from a project report by the U. S. Corps of Engineers [49].

> Underlying the sandstones and shales of this [the Dockum] group are Permian sandstones, shales, limestones, anhydrite, gypsum, and salt. The presence of considerable thicknesses of these predominantly soluble strata below the Triassic red beds is responsible for the semi-karst topography along the Pecos Valley. Sinks, closed basins, swales, and springs are common. The low flow of the river disappears in the vicinity of Colonias into a cavernous limestone and reappears a few miles downstream near the head of the flood control pool of the reservoir as a series of springs....
>
> ...Permian series rocks of the carboniferous system are represented in the reservoir area by outcrops of the Bernal formation and by the San Andres formation as found in core drill holes...
>
> ...The Bernal formation outcrops in the river valley from the upper end of the reservoir area to a point just below the Walker (River) Ranch. It consists of siltstone, shale, thin beds of white to gray sandstones, and lentils of gypsum or anhydrite. The thickness of individual beds varies considerably and any one bed pinches out when traced over a moderate distance.... The San Andres formation has been divided into two members, the limestone member above and the Glorieta member below.... The limestone member, as found in core holes, is a light-gray, dense, thin-to-thick-bedded, brecciated and at time cavernous limestone and dolomitic limestone with small and large lenses and veinlets of anhydrite and gypsum which show intraformational corrugations. Local contortions are generally explained as forces caused by recrystallization of anhydrite to gypsum with the addition of water and consequent increase in volume mass of 40 percent. It does not outcrop in the reservoir area, but it does near Colonias where the Pecos River loses its entire flow at low stages. There are numerous springs and seeps along each side of the river to the upper end of the Walker Ranch which could be lost water regained. Another possibility is that it might be new water from the west, but with springs in and on both sides of the river, this is remote.

Virtually all of the water lost from the river in the reach near Colonias returns before approaching the Puerta de Luna gaging station, but with an attendant loss in quality.

Puerto de Luna to the Acme Gage

The following description of the geology of the Pecos Basin between Pintada Canyon, just upstream from Puerto de Luna, and Salt Creek, which enters near the Acme gaging station, is taken, with minor modifications, from the Pecos River Joint Investigation [33].

> The rocks underlying the section of the Pecos Basin between Pintada Canyon and Salt Creek have a low regional dip to the east that is interrupted only by . . .occasional local warps and domes . . . a secondary feature produced by solution and subsidence. From east to west across the basin the Yeso, San Andres, Chalf Bluff, and Santa Rosa formations and the upper part of the Dockum Group are successively exposed in broad north-south belts . . . West of Fort Sumner and southwest of Santa Rosa a broad outlier of the Ogallala formation overlies the Santa Rosa sandstone and the upper beds of the San Andres formation.
>
> The important water-bearing formations in this section are the San Andres formation in the outcrop area consists of a lower unit of sandstone (Glorieta sandstone) 90 to 300 feet thick and an upper unit 700 to 900 feet thick made up predominantly of gypsum and gypsiferous limestone. East of the Pecos River about 30 percent of the upper section grades into salt. The Chalk Bluff formation is about 1,000 feet thick in this section and is made up largely of sandstone and red beds but contains numerous thin beds of gypsum (or anhydrite) and a few beds of limestone. East of the Pecos River the Chalf Bluff formation, like the San Andres, contains numerous beds of salt. The Santa Rosa sandstone is largely red and gry sandstone but contains numerous shale partings and beds . . . is 200 to 350 feet thick. The Ogallala formation . . . has a reported thickness of 200 to 300 feet and consists of sand, gravel, conglomerate, and clay.

Brantley Dam Site

The following description is from *A Decade of Progress* [38, pp. 222-223]:

> . . . the Cox study verified the existence of cavernous underground conduits between McMillan Reservoir and Major Johnson Springs. But it also indicated that, immediately upstream from the

springs, the composition of the underlying Seven Rivers formation changed from predominating soluble evaporite salts to a denser, less porous carbonate rock. This formation surfaced just below the springs; and upon encountering the less permeable underground barrier, the water was forced to the surface, to discharge through the springs. Further tests indicated that a short distance downstream from the springs this denser formation was more than 100 feet underground. Overlying it were porous rocks which seemed to explain the recurrence of leaky conditions at Lake Avalon. . . .

In terms of a possibly water-tight site for new surface storage, the potential significance of seemingly impermeable rock surfacing at Major Johnson Springs was immediately apparent.