[redacted]
C-1

PB-241 844

HYDROLOGIC ANALYSIS OF THE MOJAVE RIVER, CALIFORNIA USING A MATHEMATICAL MODEL

Timothy J. Durbin, et al

Geological Survey
Menlo Park, California

November 1974

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

KEEP UP TO DATE

Between the time you ordered this report—which is only one of the hundreds of thousands in the NTIS information collection available to you—and the time you are reading this message, several *new* reports relevant to your interests probably have entered the collection.

Subscribe to the **Weekly Government Abstracts** series that will bring you summaries of new reports *as soon as they are received by NTIS* from the originators of the research. The WGA's are an NTIS weekly newsletter service covering the most recent research findings in 25 areas of industrial, technological, and sociological interest—invaluable information for executives and professionals who must keep up to date.

The executive and professional information service provided by NTIS in the **Weekly Government Abstracts** newsletters will give you thorough and comprehensive coverage of government-conducted or sponsored research activities. And you'll get this important information within two weeks of the time it's released by originating agencies.

WGA newsletters are computer produced and electronically photocomposed to slash the time gap between the release of a report and its availability. You can learn about technical innovations immediately—and use them in the most meaningful and productive ways possible for your organization. Please request NTIS-PR-205/PCW for more information.

The weekly newsletter series will keep you current. But *learn what you have missed in the past* by ordering a computer **NTISearch** of all the research reports in your area of interest, dating as far back as 1964, if you wish. Please request NTIS-PR-186/PCN for more information.

WRITE: Managing Editor
5285 Port Royal Road
Springfield, VA 22161

Keep Up To Date With SRIM

SRIM (Selected Research in Microfiche) provides you with regular, automatic distribution of the complete texts of NTIS research reports *only* in the subject areas you select. SRIM covers almost all Government research reports by subject area and/or the originating Federal or local government agency. You may subscribe by any category or subcategory of our WGA **(Weekly Government Abstracts)** or **Government Reports Announcements and Index** categories, or to the reports issued by a particular agency such as the Department of Defense, Federal Energy Administration, or Environmental Protection Agency. Other options that will give you greater selectivity are available on request.

The cost of SRIM service is only 45¢ domestic (60¢ foreign) for each complete microfiched report. Your SRIM service begins as soon as your order is received and processed and you will receive biweekly shipments thereafter. If you wish, your service will be backdated to furnish you microfiche of reports issued earlier.

Because of contractual arrangements with several Special Technology Groups, not all NTIS reports are distributed in the SRIM program. You will receive a notice in your microfiche shipments identifying the exceptionally priced reports not available through SRIM.

A deposit account with NTIS is required before this service can be initiated. If you have specific questions concerning this service, please call (703) 451-1558, or write NTIS, attention SRIM Product Manager.

This information product distributed by

NTIS U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

PB 241 844

BIBLIOGRAPHIC DATA SHEET	1. Report No. USGS/WRD-75/028	

4. Title and Subtitle
HYDROLOGIC ANALYSIS OF THE MOJAVE RIVER, CALIFORNIA USING A MATHEMATICAL MODEL (Final report)

5. Report Date
November 1974

6.

7. Author(s)
T. J. Durbin and W. F. Hardt

8. Performing Organization Rept. No. USGS/WRI-17-74

9. Performing Organization Name and Address
U.S. Geological Survey, Water Resources Division
345 Middlefield Road
Menlo Park, Calif. 94025

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address
Same as 9 above

13. Type of Report & Period Covered
Final report

14.

15. Supplementary Notes
Prepared in cooperation with the Mojave Water Agency

16. Abstracts

The Mojave Water Agency is considering using the normally dry Mojave River as a natural conduit system to convey imported water about 60 miles downstream to Barstow. The imported water would be used to replenish aquifers now being overpumped. From 1930 to 1972 only 18 floods at The Forks (headwaters of the Mojave River basin) produced flow at Barstow. A mathematical model was developed that simulates the flow characteristics down the initially dry channel and evaluates the potential of the channel to move water to Barstow. Results of simulation by modeling indicate that the channel of the Mojave River can be used to efficiently convey imported water to Barstow only when the absorption capacity of the channel has been reduced by an antecedent flood. An electric analog model was also utilized to predict water-level effects from potential recharge to the underground west of Barstow. The appendix in the report develops the derivation of the surface-water mathematical model.

17. Key Words and Document Analysis. 17a. Descriptors

*Mathematical model, *Mathematics, *Water conveyance, Stream-groundwater relations, Infiltration, Floods, Electric analog model, Recharge water distribution, Imported water, Downstream, California, Stream gages, Streamflow

17b. Identifiers/Open-Ended Terms

Mojave River, Open-channel hydraulics, The Forks, Barstow, Model derivation

17c. COSATI Field/Group

PRICES SUBJECT TO CHANGE

18. Availability Statement
No restriction on distribution

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page)
UNCLASSIFIED

21. No. of Pages

i

HYDROLOGIC ANALYSIS OF THE MOJAVE RIVER, CALIFORNIA

USING A MATHEMATICAL MODEL

By Timothy J. Durbin and William F. Hardt

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 17-74

Prepared in cooperation with the

Mojave Water Agency

November 1974

UNITED STATES DEPARTMENT OF THE INTERIOR

Rogers C. B. Morton, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

For additional information write to:

District Chief
Water Resources Division
U.S. Geological Survey
345 Middlefield Road
Menlo Park, Calif. 94025

CONTENTS

APPENDIX

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Factors for converting English units to the International System of Units (SI) are given below to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric (SI)*
acre-ft (acre-foot)	1.233×10^{-3}	hm^3 (cubic hectometre)
ft (foot)	3.048×10^{-1}	m (metre)
ft/mi (foot per mile)	1.890×10^{-1}	m/km (metre per kilometre)
ft^2/s (square foot per second)	0.0929	m^2/s (square metre per second)
ft^3/s (cubic foot per second)	2.832×10^{-2}	m^3/s (cubic metre per second)
mi (mile)	1.609	km (kilometre)
mi^2 (square mile)	2.590	km^2 (square kilometre)

HYDROLOGIC ANALYSIS OF THE MOJAVE RIVER, CALIFORNIA

USING A MATHEMATICAL MODEL

By Timothy J. Durbin and William F. Hardt

ABSTRACT

The channel of the Mojave River in California is normally dry and is highly permeable over much of its length, and large quantities of water from natural floodflows in the channel infiltrate through the channel bed to the underlying ground-water body. From 1930 to 1972 only 18 floods at The Forks produced flow at Barstow, 55 miles (88 kilometres) downstream from The Forks. Peak discharges at Barstow from these floods ranged from 180 cubic feet per second (5 cubic metres per second) in 1967 to 64,300 cubic feet per second (1,820 cubic metres per second) in 1938. Total stream infiltration, primarily as ground-water recharge, ranged from 3,600 acre-feet (4.40 cubic hectometres) in 1935 to 50,400 acre-feet (62.1 cubic hectometres) in 1969 between The Forks and Victorville and from about 7,000 acre-feet (8.61 cubic hectometres) in 1935 to 128,000 acre-feet (158 cubic hectometres) in 1969 between Victorville and Barstow.

The Mojave Water Agency is considering the use of the channel of the river to convey water imported from northern California through Silverwood Reservoir (5 miles or 8 kilometres upstream from The Forks) downstream to the Barstow area. The imported water would be used to replenish aquifers underlying the Barstow area. A mathematical model was developed that simulates the advance of discharge down the initially dry channel of the Mojave River, and the model was used to evaluate the potential of the channel to move imported water downstream to Barstow.

Results of simulation by modeling indicate that the channel of the Mojave River can be used to efficiently convey imported water to Barstow only when the absorption capacity of the channel has been reduced by an antecedent flood. The volume of imported water that can reach Barstow depends on the volume and duration of the antecedent flood, on the volume of imported water released from Silverwood Reservoir, and on the rate at which imported water is released. A release of 20,000 acre-feet (24.6 cubic hectometres) of imported water may produce at Barstow a maximum volume of imported water of 2,500, 8,000, 11,000, or 15,000 acre-feet (3.08, 9.86, 13.6, or 18.4 cubic hectometres) for a release rate of 500, 750, 1,000, or 2,000 cubic feet per second (14.2, 21.2, 28.3, or 56.8 cubic metres per second).

For planning purposes in evaluating some of the hydraulic effects of recharge on the aquifer, a simulation of the aquifer near the Barstow area using an electrical analog model showed that a combination of no pumping and a yearly recharge of 5,000 acre-feet (6.17 cubic hectometres) for 10 years could raise ground-water levels at least 10 feet (3 metres) over an area of about 10 square miles (25 square kilometres). To obtain the water-level changes due to the combined effects of pumping and recharge, the above water-level changes should be superimposed on the separate effects of pumping.

INTRODUCTION

Part of the Mojave River basin (fig. 1) is an area of southern California that is experiencing rapid economic growth, and the demand for ground water by the present residential, commercial, and industrial water users significantly exceeds the local supply (Hardt, 1971). In an effort to deal with this problem, the Mojave Water Agency, which is charged with managing the water supply in much of the basin, is planning to import and distribute water from northern California and is undertaking intensive management of the ground-water resources including artificial recharge into the ground-water reservoir.

Water shortages will intensify in the Barstow area earlier than other areas of the basin (Hardt, 1971), and the Mojave Water Agency anticipates the need to replenish the aquifers with imported water. Imported water will be delivered to the agency at turnouts at various locations along the aqueduct that conveys the imported water, including a location adjacent to Silverwood Reservoir. The reservoir is located on the West Fork Mojave River about 60 mi (97 km) upstream from Barstow. This report was prepared to aid the Agency in planning and presents the results of a study of the potential use of the normally dry channel of the Mojave River to convey the imported water from Silverwood Reservoir downstream to Barstow; and the predicted rise in water levels due to potential artificial recharge between Hodge and Barstow.

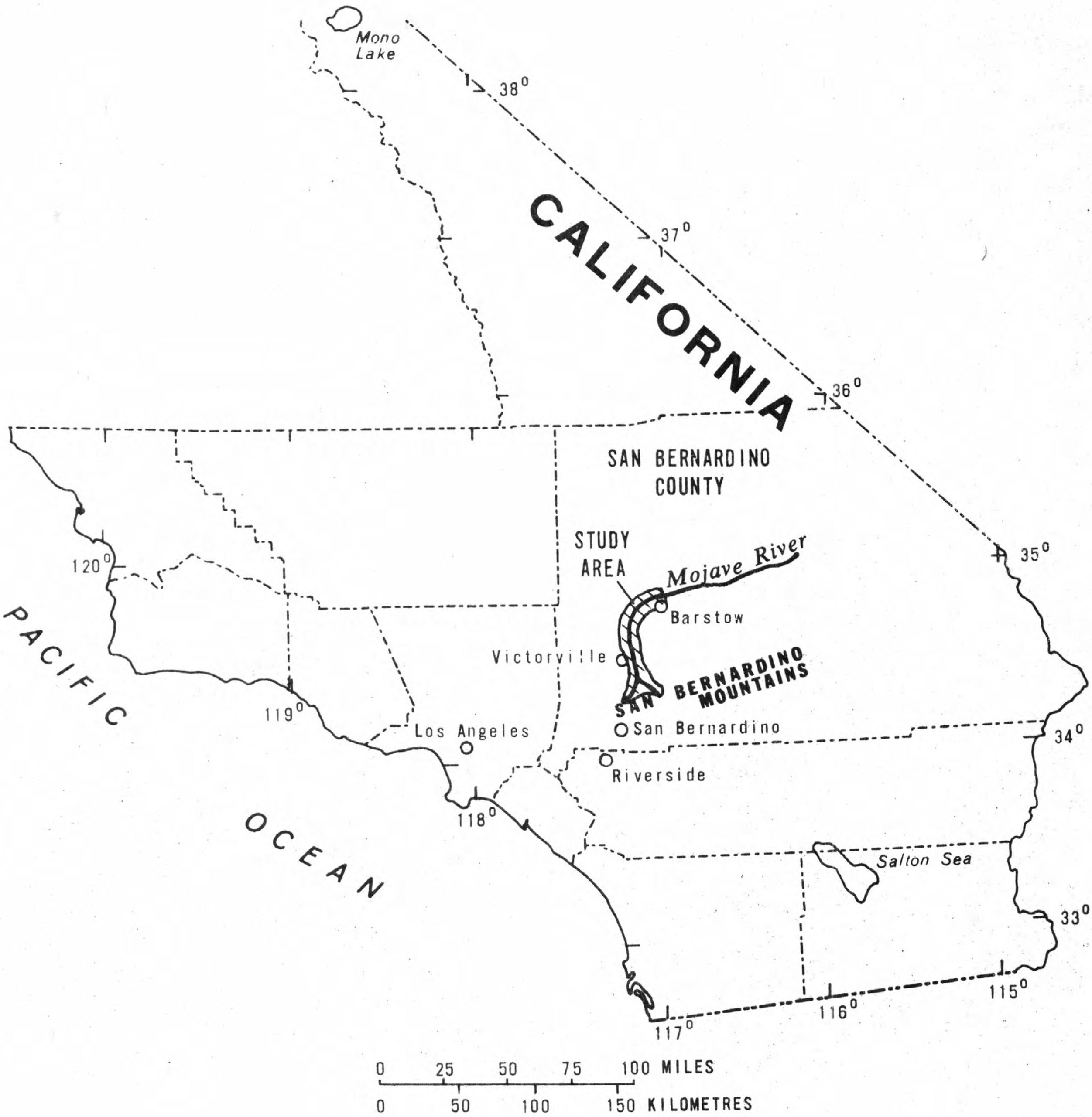


FIGURE 1.--Index map.

Location and General Features of the Study Reach

The channel of the Mojave River between The Forks, where the river debouches from the San Bernardino Mountains, and Barstow is of primary interest to the study (fig. 2). This reach of the river--a distance of about 55 mi (88 km)--crosses the broad alluvial surface of the Mojave River basin and is the main source of recharge to the aquifers underlying the basin. Deep Creek and the West Fork Mojave River drain the San Bernardino Mountains and join at The Forks to form the Mojave River. The Mojave River then flows 18 mi (29 km) from The Forks to Victorville and then 37 mi (60 km) from Victorville to Barstow.

The sandy channel of the river is highly permeable over much of its length, and large quantities of water are lost from the channel because of infiltration through the channel bed. For example, from 1931 to 1972 only 28 percent of the flow that entered the channel at The Forks reached Barstow.

The channel has a sand bed and is underlain by alluvial deposits that consist principally of sand and gravel but include boulders and lenses of silt and clay. Ground water occurs in the alluvium about at the level of the channel bed in a 15-mi (29-km) reach near Victorville. However, in other areas the depth to the water table underlying the channel bed is as much as 50 ft (15 m).

The Mojave River channel is entrenched in the alluvial deposits. The main channel generally ranges from about 100 to 600 ft (30 to 180 m) in width and is sufficiently large to contain most flows. Large floods have caused some flooding and damage along the adjacent lowlands. On February 25, 1969, the river overflowed its bank about 3 mi (4.8 km) north of Hodge, and some flow passed north of the main channel at Barstow (Hardt, 1969, p. 9).

A study of all discharge measurements that were made from 1930 to 1972 at the gaging stations between The Forks and Barstow shows a correlation between river width and discharge (fig. 3). The gaging stations at Deep Creek, West Fork Mojave River (until 1971), and Victorville are in constricted reaches of the river, and the channel width ranges from about 75 to 125 ft (23 to 38 m). The channel constriction at Victorville is not part of the upstream constriction at the gaging stations at Deep Creek and West Fork Mojave River. At Barstow the channel is in a broad part of the valley, and at bankfull stage the channel is about 300 ft (91 m) wide. Much of the river channel between The Forks and Barstow is not unduly constricted, and widths during bankfull stages of 200-300 ft (61-91 m) are common.

The natural streamflow of the Mojave River has been modified by the construction of two dams above the study reach. In 1971 the U.S. Army Corps of Engineers completed The Forks Dam, a flood-control structure located below the confluence of Deep Creek and the West Fork of the Mojave River. The outlet structure is a tunnel about at channel level. The tunnel is ungated and has a maximum capacity of about 25,000 ft^3/s (708 m^3/s) at the maximum reservoir storage capacity of 300,000 acre-ft (370 hm^3).

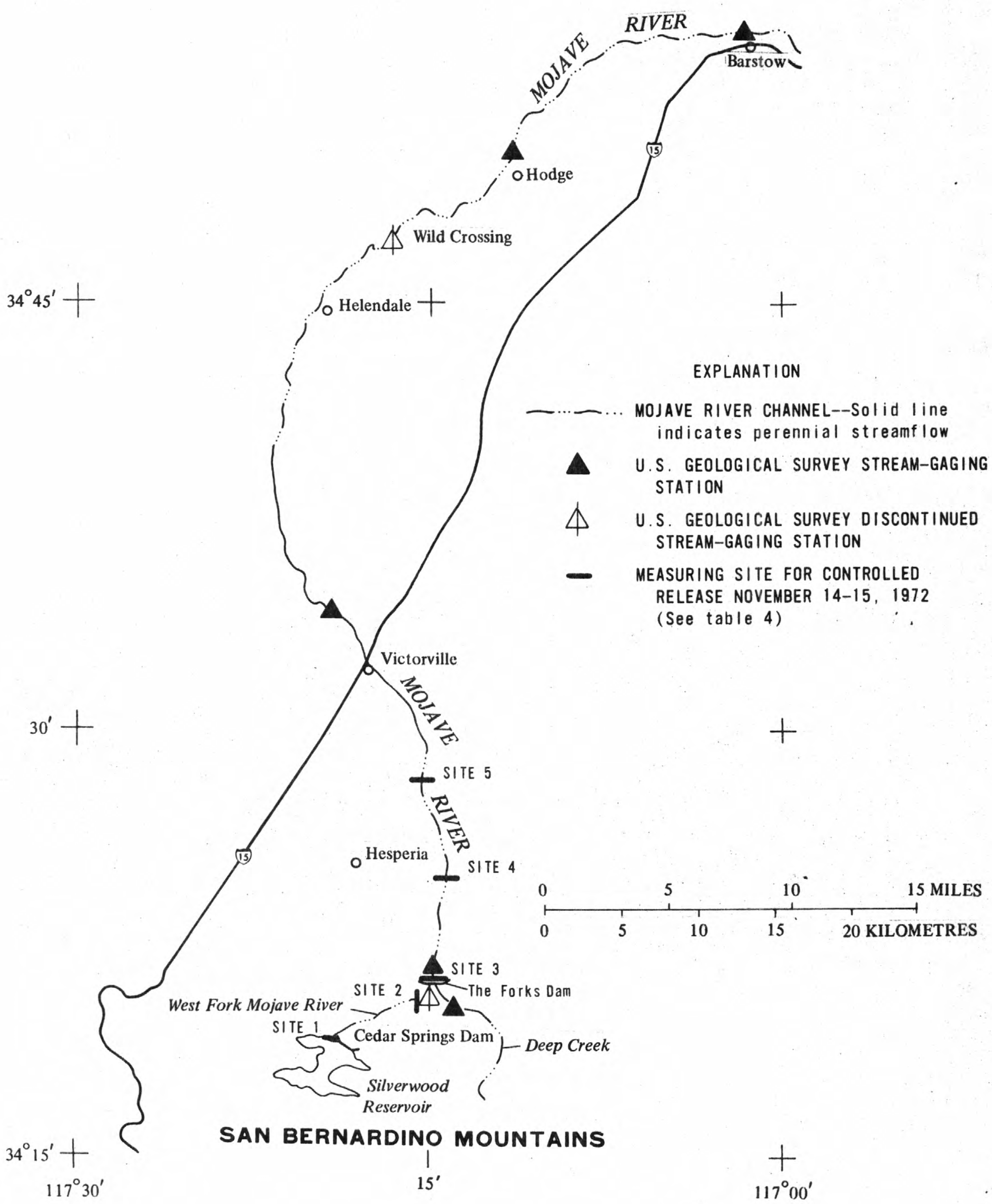


FIGURE 2.--Mojave River features.

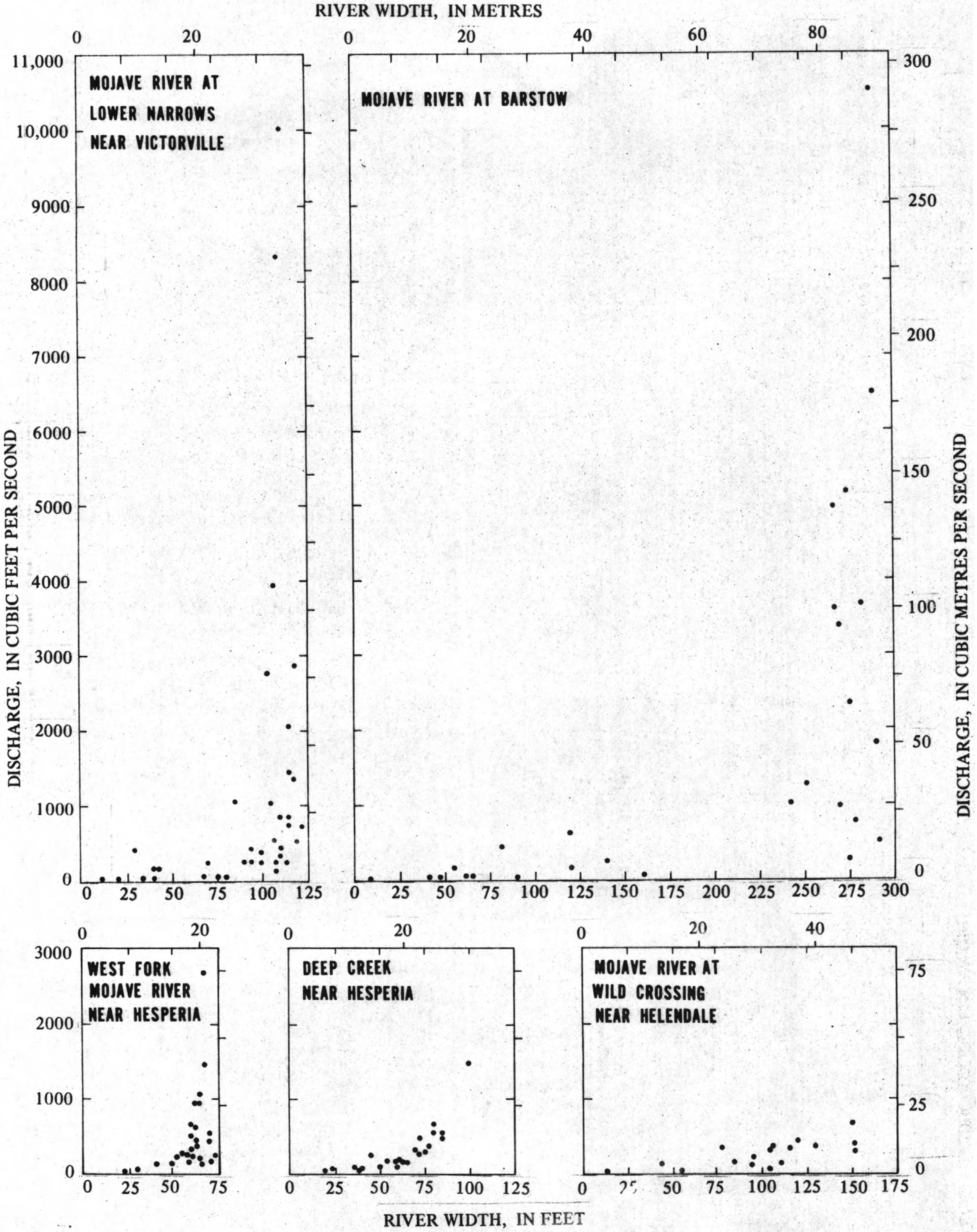


FIGURE 3.--Correlation of river width and discharge.

In 1972 the California Department of Water Resources completed the Cedar Springs Dam and Silverwood Reservoir on the West Fork Mojave River 5 mi (8 km) upstream from The Forks Dam. This facility is an integral part of the California aqueduct system used for conveying water from northern California. It regulates flow to the San Bernardino-Riverside area. Part of the imported water that is to be received by the Agency from the State will be released into the West Fork Mojave River adjacent to this reservoir.

The Mojave River basin has been the subject of many geologic and hydrologic studies, and detailed descriptions of the geologic and hydrologic features of the basin can be found in recent Geological Survey reports by Miller (1969) and Hardt (1969, 1971). Other reports are listed in the selected references at the end of this report.

Scope and Methods

The primary objective of this study was to evaluate the mechanics of flow in the Mojave River channel with respect to the ability of the channel to move water downstream. Secondary objectives were (a) to estimate the response of ground-water levels in the Barstow area to the recharge of imported water and (b) to estimate the effects of The Forks Dam on the natural streamflow in the Mojave River. Specifically, the scope of the study included the following:

1. The characteristics of natural flow in the Mojave River were analyzed, based on historic records which provide a base for anticipating future conditions.

2. The infiltration losses from historic floods in the reach of the river between The Forks and Barstow were estimated.

3. Water was released under controlled conditions into the channel from Silverwood Reservoir in order to study infiltration processes.

4. A mathematical model that imitates the river system was developed in order to simulate the Mojave River. The model was used to establish the conditions under which imported water can be efficiently conveyed down the Mojave River channel to Barstow. In addition, the model was used to study the effect of The Forks Dam on streamflow in the river.

5. An existing electric analog ground-water model (Hardt, 1971) was used to predict the response of ground-water levels to the recharge of imported water at two locations west of Barstow.

Acknowledgments

This report was prepared by the U.S. Geological Survey in cooperation with the Mojave Water Agency. Technical advice on selected aspects of the study was given by Roger E. Smith, Southwest Watershed Research Center, U.S. Agricultural Research Service, Tucson, Ariz., and Saul E. Rantz, U.S. Geological Survey. The U.S. Geological Survey, Phoenix, Ariz., performed the interrogation runs on the electric analog ground-water model.

FLOW CHARACTERISTICS OF THE MOJAVE RIVER

The flow of the Mojave River is measured at The Forks, Victorville, and Barstow. These stations are respectively 18 mi (29 km), 43 mi (69 km), and 55 mi (88 km) downstream from The Forks. Prior to September 1971, streamflow at The Forks was measured by the combined discharge at two gaging stations, Deep Creek and West Fork Mojave River. Now, the flow at The Forks is measured

TABLE 1.--*Selected floods in the Mojave*

Flood number	Date	Flow duration (days)		The Forks		
		The Forks	Barstow	Range in flow[1] (ft^3/s)	Average flow[1] (ft^3/s)	Total flow (acre-ft)
1	Feb. 7, 1932 - May 14, 1932	98	96	131-7,480	445	86,500
2	Apr. 8, 1935 - Apr. 21, 1935	14	10	152-1,646	423	11,700
3	Feb. 6, 1937 - May 28, 1937	112	111	108-6,140	689	153,100
4	Feb. 27, 1938 - May 18, 1938	81	79	150-19,000	1,170	187,600
5	Feb. 20, 1941 - May 25, 1941	95	94	130-2,822	703	132,500
6	Jan. 21, 1943 - May 6, 1943	106	104	129-13,850	675	142,000
7	Feb. 21, 1944 - May 11, 1944	81	79	138-3,424	425	68,300
8	Feb. 1, 1945 - May 4, 1945	93	92	69-3,820	286	52,800
9	Mar. 30, 1946 - Apr. 25, 1946	27	26	89-4,570	540	28,900
10	Dec. 24, 1946 - Jan. 15, 1947	23	20	81-1,254	306	13,900
11	Mar. 12, 1952 - May 8, 1952	58	50	215-2,387	495	57,000
12	Mar. 16, 1958 - Apr. 24, 1958	40	29	357-4,310	1,130	89,500
13	Feb. 8, 1962 - Feb. 16, 1962	9	1	421-5,490	1,850	33,000
14	Nov. 22, 1965 - Nov. 30, 1965	9	3	183-7,710	2,300	41,100
15	Dec. 29, 1965 - Jan. 6, 1966	9	3	221-11,550	2,200	39,200
16	Dec. 3, 1966 - Dec. 13, 1966	11	3	100-12,860	1,870	40,800
17	Mar. 10, 1967 - June 6, 1967	89	33	102-1,638	364	64,300
18	Jan. 20, 1969 - May 11, 1969	112	89	310-24,400	1,460	325,000

[1]Based on daily records.

at The Forks Dam. The Hodge station was moved from Wild Crossing (7 mi or 11 km upstream) in 1970. Streamflow records have been obtained for 43 years at The Forks (1930-72), for 42 years at Victorville and Barstow (1931-72), and for 5 years at Wild Crossing (1966-70).

Extreme Discharges

During 42 years of streamflow record (1931-72), only 18 floods produced flow at Barstow (table 1). The volume of flow during these floods ranged from 11,700 to 325,000 acre-ft (14 to 400 hm^3) at The Forks and from 515 to 147,000 acre-ft (0.6 to 181 hm^3) at Barstow. The duration of the floods at The Forks ranged from 9 to 112 days, and the duration at Barstow ranged from 1 to 111 days. For this study, the flow duration was limited to the time of cessation of flow at Barstow. Peak discharges during the 18 floods ranged from 2,050 ft^3/s (58 m^3/s) in 1946 to 72,700 ft^3/s (2,059 m^3/s) in 1938 at The Forks and from 180 ft^3/s (5 m^3/s) in 1967 to 64,300 ft^3/s (1,820 m^3/s) in 1938 at Barstow.

River reaching Barstow (1930-72)

Victorville			Barstow			
Range in flow[1] (ft^3/s)	Average flow[1] (ft^3/s)	Total flow (acre-ft)	Range in flow[1] (ft^3/s)	Average flow[1] (ft^3/s)	Total flow (acre-ft)	Flood number
52-7,840	350	68,000	0.3-2,410	193	37,500	1
65-846	294	8,160	3-208	43	1,180	2
44-4,880	612	136,000	.1-3,950	467	104,000	3
74-16,000	1,040	166,000	7-18,100	859	138,000	4
71-3,060	640	121,000	3-2,000	509	96,000	5
74-12,200	535	113,000	6-7,380	432	91,000	6
56-1,900	360	57,800	6-1,230	226	36,200	7
38-1,250	205	37,800	.4-730	120	22,100	8
32-2,220	370	19,800	1.5-1,890	231	12,400	9
45-970	218	9,900	.8-350	56	2,570	10
64-1,340	374	43,100	1-481	108	12,400	11
260-3,960	905	71,800	4.1-2,500	253	20,000	12
40-1,760	494	8,800	0-369	41	732	13
36-4,180	692	12,400	7-576	67	1,200	14
152-5,060	1,290	22,900	1-2,460	288	5,140	15
46-6,860	989	21,600	0-3,370	328	7,160	16
25-848	227	40,000	.2-68	3	515	17
94-21,000	1,230	274,100	5-14,800	660	147,000	18

Velocity of the Flood Wave

The velocity of a crest of the flood wave in the Mojave River channel depends on the magnitude of the flood, the channel geometry, the slope of the channel, the bed friction, the water temperature, the sediment in transit, and the quantity of water that is removed from the flood because of infiltration into the permeable bed of the channel. The velocity of the flood wave will decrease for the Mojave River if the magnitude of the flood decreases or if the quantity of water that is infiltrated increases. The streamflow records for the Mojave River indicate that the time of travel of a flood peak between The Forks and Victorville ranges from about 3 to 7 hours (table 2) and that the velocity of the peak ranges from about 3 to 6 mi/h (5 to 10 km/h). The time of travel between Victorville and Barstow has ranged from about 6 to 22 hours (table 2) and the velocity of the peak in this reach has ranged from about 2 to 6 mi/h (3 to 10 km/h). This reduction of the velocity of the flood wave in the lower reach of the channel can be attributed in part to a change in the bed slope, and in part to the decrease in magnitude of the flood when passing through the upstream reach.

The rising limb of streamflow hydrographs for the Mojave River usually becomes steeper as a flood crest moves downstream. Thus, the lag time between the arrival of a flood peak at The Forks and at a point downstream is shorter than the lag time between the arrival of first flow at the same points.

Flow Duration

Streamflow in most of the study reach of the Mojave River is generally intermittent; however, perennial flow does occur at two locations--for about 1 mi (1.6 km) below The Forks, due to perennial flow in Deep Creek, and in the 15-mi (29-km) reach in the vicinity of Victorville. This perennial flow is due to natural discharge of ground water to the channel.

Duration curves for daily flow for the Mojave River at Barstow and at Victorville (fig. 4) show the effects of perennial streamflow. The curve for Barstow is typical of curves for streams in desert regions, in that the channel is dry most of the time except during infrequent floods derived from the mountains. For example, the curve for Barstow indicates that flow will exceed 1 ft^3/s (0.03 m^3/s) only 5 percent of the time, 100 ft^3/s (3 m^3/s) about 4 percent of the time, and 1,000 ft^3/s (30 m^3/s) less than 0.4 percent of the time (fig. 4). Perennial flow at Victorville causes a change in the slope of the flow-duration curve at about 60 ft^3/s (1.7 m^3/s), and the curve indicates that flow is almost always greater than 10 ft^3/s (0.3 m^3/s).

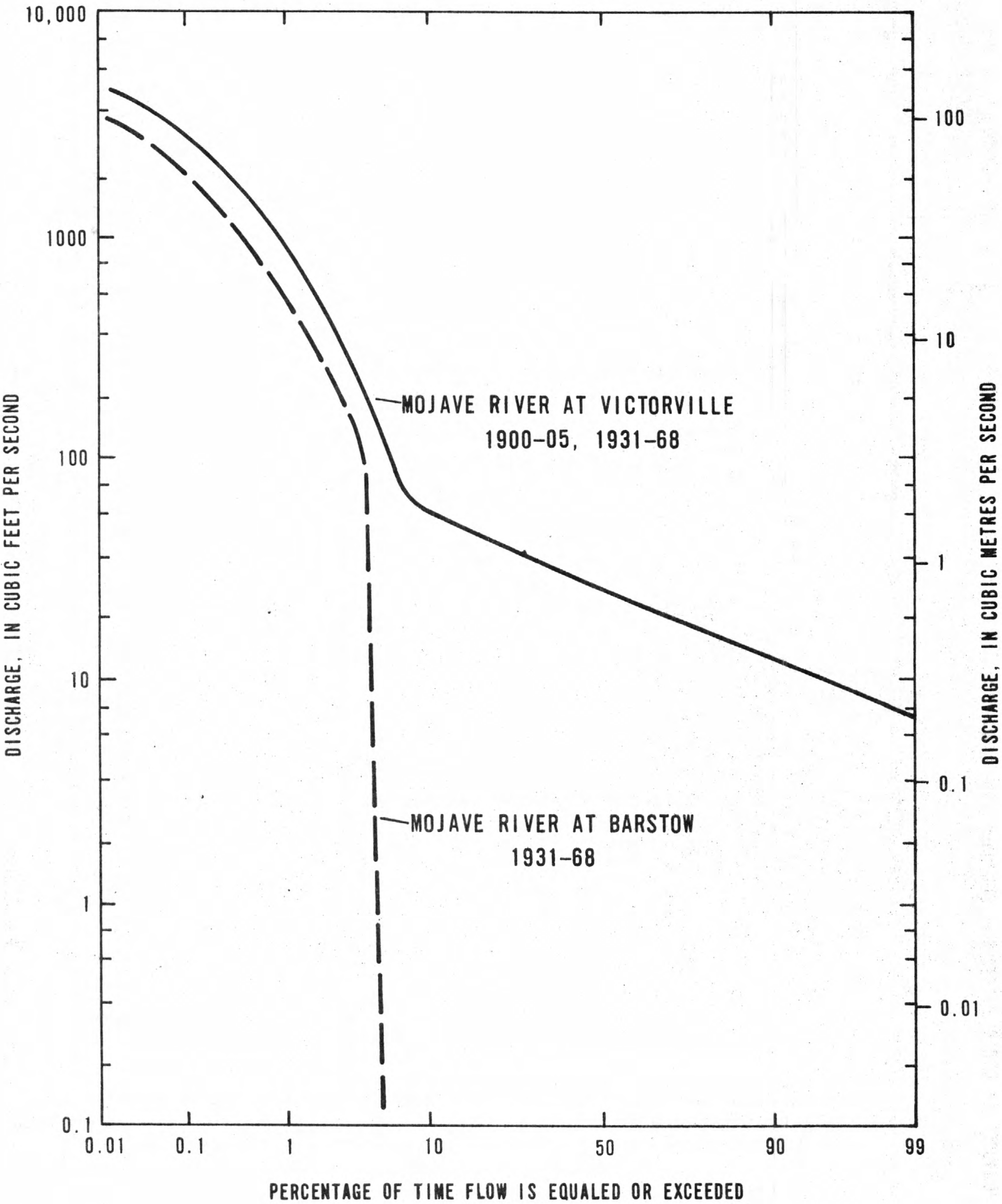


FIGURE 4.--Flow-duration curves, Mojave River at Victorville and Barstow.

TABLE 2.--*Time of travel of*

[Source data: Butler, Reid, and

Flood number	Date of flood peak	The Forks: Deep Creek: Clock time of peak (hours)	The Forks: Deep Creek: Maximum discharge (ft^3/s)	The Forks: West Fork Mojave River: Clock time of peak (hours)	The Forks: West Fork Mojave River: Maximum discharge (ft^3/s)	Estimated composite time of peak at these two stations
1	Feb. 9, 1932	0100	7,900	0000	8,500	0030
2	Apr. 8- 9, 1935	1300	2,760	1400	1,280	1330
3	Feb. 14-15, 1937	0100	6,800	--	--	0100
4	Mar. 2- 3, 1938	--	46,600	--	26,100	--
5	Feb. 20-21, 1941	2200	4,600	1300	1,860	2200
	Mar. 1, 1941	0300	1,750	0030	1,615	0200
	Mar. 14, 1941	0800	1,540	0700	1,420	0730
	Apr. 5, 1941	0300	2,280	0100	1,130	0300
6	Jan. 23, 1943	0500	19,000	0200	23,000	0200
7	Feb. 22-23, 1944	--	--	1630	6,600	1630
8	Feb. 2- 3, 1945	1300	6,350	1400	2,350	1300
9	Mar. 30-31, 1946	1600	5,300	1330	6,600	1330
10	Dec. 26-28, 1946	--	--	--	--	--
11	Mar. 15-16, 1952	1920	2,620	1810	6,780	1810
12	Mar. 16-17, 1958	0800	5,750	0630	1,300	0800
	Apr. 3, 1958	1000	12,400	1000	10,200	1000
13	Feb. 11-12, 1962	2100	7,040	1930	3,750	2000
14	Nov. 22-23, 1965	2030	21,700	2030	8,420	2030
15	Dec. 29-30, 1965	1930	20,800	1700	21,200	1815
16	Dec. 6- 7, 1966	1830	15,400	2000	6,320	1900
17	Mar. 22, 1967	0415	488	0400	1,290	0400
18	Jan. 21, 1969	0945	10,400	1000	5,820	1000
	Jan. 25, 1969	1145	23,000	1200	13,200	1145
	Feb. 25, 1969	1100	17,600	0900	20,000	0900

selected flood peaks (1932-69)

Berwick, 1966; and unpublished records]

Victorville		Barstow				
Clock time of peak (hours)	Maximum dis-charge (ft^3/s)	Clock time of peak (hours)	Maximum dis-charge (ft^3/s)	Peak lag time The Forks-Victorville (hours)	Peak lag time Victorville-Barstow (hours)	Flood number
0400	12,500	1700	8,300	3½	13	1
1900	2,200	1400	500	5½	19	2
0800	8,880	0300	6,000	7	19	3
1930	70,600	0200	64,300	--	7½	4
0300	4,480	1430	2,390	5	11½	5
0800	2,460	1700	1,920	6	9	
1400	2,440	2200	2,430	6½	8	
0900	2,890	1800	2,490	6	9	
0730	32,000	1500	26,000	5½	7½	6
2030	6,900	0530	2,300	4	9	7
1830	5,500	1300	1,750	5½	18½	8
1800	8,000	1345	3,000	4½	19¾	9
--	--	--	--	--	--	10
2220	3,690	1030	960	4⅙	12⅙	11
1430	1,680	1300	100	6½	22½	12
1330	15,900	2230	9,140	3½	9	
0000	3,860	1000	1,200	4	10	13
0100	17,100	1100	3,180	4½	10	14
2215	32,800	0700	8,970	4	8¾	15
2300	17,900	0500	9,870	4	6	16
1130	1,060	2200	348	7½	10½	17
1400	6,800	2300	1,300	4	9	18
1500	33,800	0000	29,000	3¼	9	
1200	34,500	1900	30,000	3	7	

STREAMFLOW DEPLETION BY INFILTRATION

The Mojave River is a losing stream from The Forks to Barstow. The volume of water infiltrating primarily is a function of the length of time that the channel contains water, the permeability of the channel bed, and the total area of the channel that is wetted. Flood discharge does not always reach Barstow, and the wetted area of the channel depends on both the width of the channel that is wetted and the distance that flow advances down the channel. Other factors, such as the time interval during which each point on the channel is wetted and the prior accumulation of infiltrated water, also influence the quantity of water that is infiltrated into the channel bed.

The absorption capacity of the Mojave River channel is defined as the ability to receive infiltrated water and is the volume of water that would infiltrate into the bed were there flow in the channel at all times. The absorption capacity depends on the history of flow events; in general, the absorption capacity increases as the time interval between floods increases. The absorption capacity of the channel will increase up to a certain amount as the channel dries and ground water drains away from the channel. Thereafter, the absorption capacity increases only asymptotically, no matter what the time interval between floods might be, except for the qualification that if the water table were to drop because of pumpage, the absorption capacity could continue to increase.

The absorption capacity of the Mojave River channel is limited by the space within the interstices of the material underlying the channel and nearby areas that can be occupied by infiltrating water. The availability of this space depends on the porosity and vertical hydraulic conductivity of the material, the depth to the water table, the quantity and distribution of water held within the unsaturated zone, and the rate at which ground water can move laterally away from the channel. Some of these factors relate to the physical properties of the system, and others relate to the frequency and area of channel wetting. The relative importance of these factors with respect to the amount of infiltration from a flood depends on the magnitude of the flood and the shape and duration of a flood wave.

The 18 floods between 1930-72 that produced flow at Barstow were analyzed for their recharge effect on the ground-water body. The decrease in flow between gaging stations was assumed to have been recharged to the water table. This assumption is reasonable, in that the depth to water beneath the river is very shallow, allowing a short travel time to the water table. Also, most of the floods are in the winter when evaporation from the water surface and transpiration by plants are minimal. The results are shown in table 3 and figures 5 and 6. In the reach of the Mojave River between The Forks and Victorville, the infiltration was assumed to be principally ground-water recharge and ranged from about 3,600 acre-ft (4.40 hm^3) for the 1935 flood, or 30 percent of the inflow, to about 50,400 acre-ft (62 hm^3) for the 1969 flood, or 15 percent of the inflow. In the reach of the river between Victorville and Barstow, the infiltration ranged from about 7,000 acre-ft (8.61 hm^3) for the 1935 flood, or 85 percent of the inflow to this reach, to about 128,000 acre-ft (158 hm^3) for the 1969 flood, or 46 percent of the inflow.

TABLE 3.--*Infiltration characteristics of selected floods*

(in acre-feet)

Flood number	Date	Total infiltration		Average infiltration/day[1]		Average infiltration per day per mile	
		The Forks to Victorville	Victorville to Barstow	The Forks to Victorville	Victorville to Barstow	The Forks to Victorville[2]	Victorville to Barstow[3]
1	Feb. 7, 1932 - May 14, 1932	18,500	30,500	188	311	17.1	11.1
2	Apr. 8, 1935 - Apr. 21, 1935	3,600	6,980	256	498	23.2	17.9
3	Feb. 6, 1937 - May 28, 1937	17,200	32,100	153	288	13.9	10.3
4	Feb. 27, 1938 - May 18, 1938	21,300	28,300	262	349	23.8	12.5
5	Feb. 20, 1941 - May 25, 1941	11,800	24,600	125	260	11.3	9.3
6	Jan. 21, 1943 - May 6, 1943	29,500	21,600	278	204	25.1	7.3
7	Feb. 21, 1944 - May 11, 1944	10,500	21,500	129	266	11.7	9.5
8	Feb. 1, 1945 - May 4, 1945	15,000	15,700	161	169	14.7	6.0
9	Mar. 30, 1946 - Apr. 25, 1946	9,060	7,400	337	276	30.5	9.9
10	Dec. 24, 1946 - Jan. 15, 1947	4,000	7,400	175	321	15.9	11.5
11	Mar. 12, 1952 - May 8, 1952	13,900	30,700	240	528	21.8	18.8
12	Mar. 16, 1958 - Apr. 24, 1958	17,600	51,800	462	1,290	40.3	46.2
13	Feb. 8, 1962 - Feb. 16, 1962	24,200	8,100	2,610	899	237	32.1
14	Nov. 22, 1965 - Nov. 30, 1965	28,700	11,200	3,190	1,240	290	44.2
15	Dec. 29, 1965 - Jan. 6, 1966	16,300	17,800	1,810	1,980	165	70.6
16	Dec. 3, 1966 - Dec. 13, 1966	19,300	14,400	1,750	1,310	159	46.8
17	Mar. 10, 1967 - June 6, 1967	24,300	39,500	272	444	24.6	15.9
18	Jan. 20, 1969 - May 11, 1969	50,400	128,000	450	1,140	40.9	40.6

[1]See table 1 for time duration.
[2]Seven mi perennial flow--assume 11 mi of dry channel for infiltration.
[3]Eight mi perennial flow--assume 29 mi of dry channel for infiltration.

Figures 5 and 6 graphically show relations between inflow and stream infiltration for two reaches of the river--from The Forks to Victorville, and from Victorville to Barstow. These relations reflect the wide range in stream infiltration derived from similar inflow rates. The data from table 3 show greatly increased infiltration rates after 1958, which can be correlated

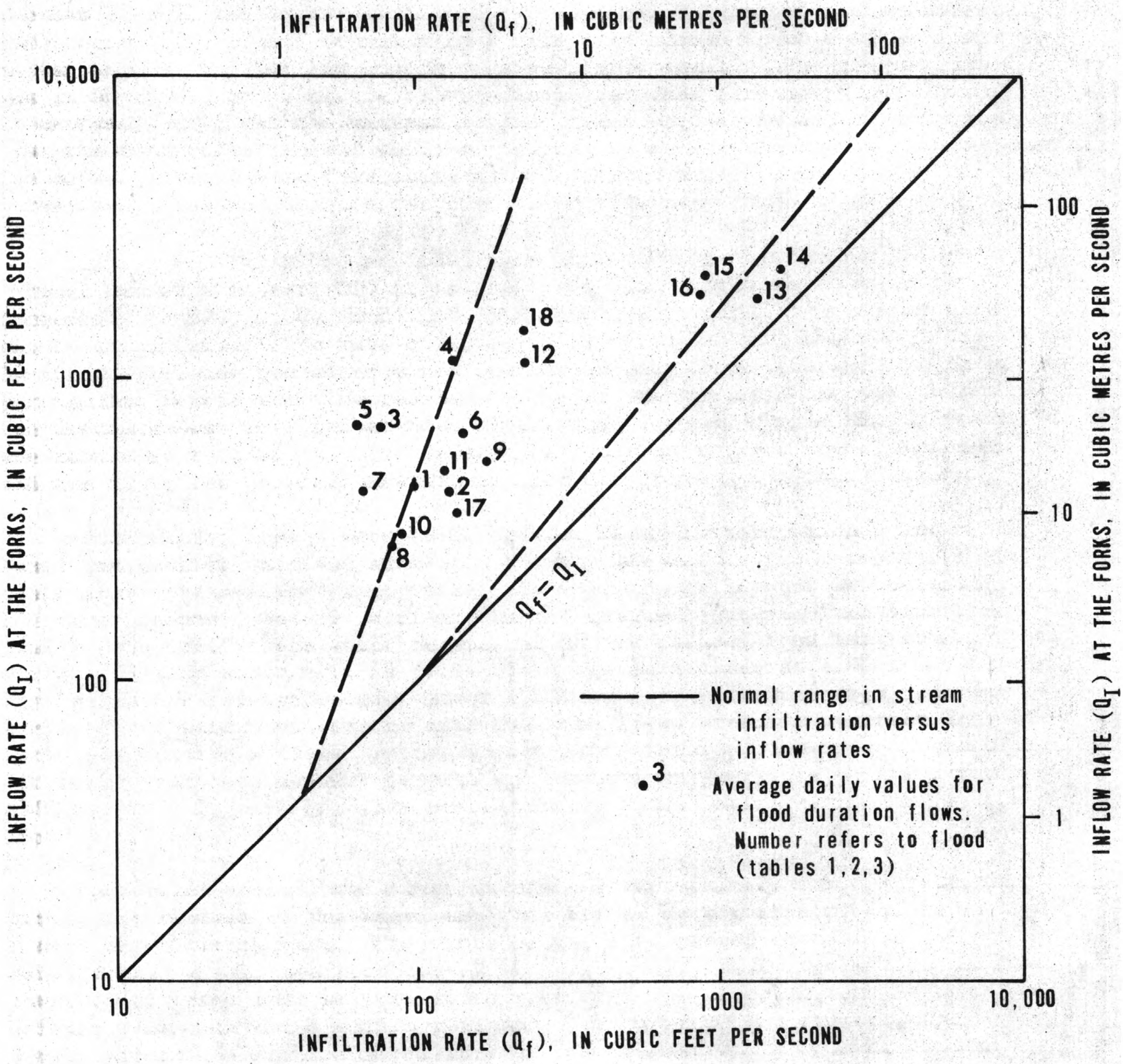


FIGURE 5.--Relation between inflow and stream infiltration, The Forks to Victorville.

with the extended dry period since 1947 (Hardt, 1971, p. 14), and lower water levels due to increased pumpage and hence, more storage capacity. These conditions allow more water to infiltrate into the ground than during previous floods when water levels were high and sediments were moist above the water table.

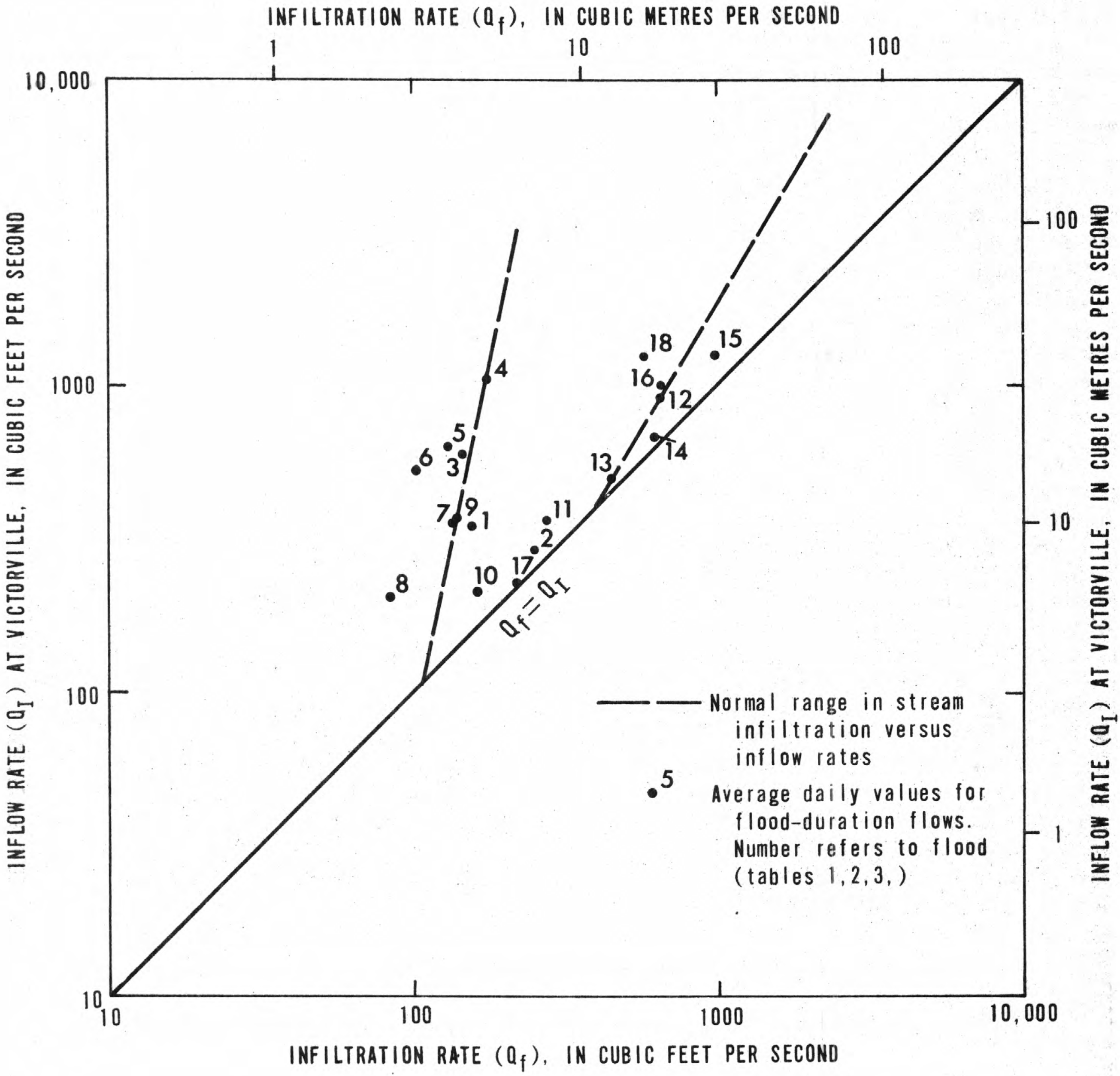


FIGURE 6.--Relation between inflow and stream infiltration, Victorville to Barstow.

EFFECTS OF THE RIVER SYSTEM ON A CONTROLLED RELEASE

During the latter part of the construction period of the Cedar Springs Dam, the natural runoff from the San Bernardino Mountains was collected above the dam while water was filling the dead-storage portion of the reservoir, and so did not flow on downstream in the West Fork Mojave River. Upon completion of the dam in 1972 the Mojave Water Agency requested release of the accumulated 3,100 acre-ft (3.8 hm^3) of runoff at a rate high enough to move water downstream as far as possible but low enough to avoid flood damage. The release date chosen was in November, prior to the flood season. At this time the river channel normally is extremely dry, and the maximum seepage rates occur. Because hydrologic data from the controlled release would be helpful in understanding the flow regimen of the Mojave River and in developing a mathematical model of the river, the Geological Survey made plans to measure the controlled flow many times at several sites.

On November 14, 1972, at 1300 hours, water was released from Cedar Springs Dam at a rate of 200 ft^3/s (5.7 m^3/s) and increased at half-hour increments to 500, 1,000, and 1,500 ft^3/s (14, 28, and 42 m^3/s). The flow was then maintained at a rate of 1,950 ft^3/s (55 m^3/s) for 18½ hours. During the release the water moved downstream only 16 mi (26 km) from Cedar Springs Dam before the flow ceased because of seepage into the sand channel. The discharge was measured at five sites (fig. 2), and the pertinent results are tabulated in table 4. The release was stopped at 0900 hours, November 15, and the riverflow dried up downstream from The Forks Dam within 7 hours.

Infiltration losses were small between Cedar Springs Dam and The Forks Dam. The loss of only 400 acre-ft (0.5 hm^3) was due to (1) lack of storage space above the shallow water table, (2) low permeability of the material in the river channel, and (3) a river-channel gradient steeper than downstream. Some of the infiltrated water reappeared in the channel from bank storage, and surface flow of about 5 ft^3/s (0.14 m^3/s) was maintained at site 2 for several days after the release ended. About 2,100 acre-ft (2.6 hm^3) or 67 percent of the released water infiltrated into the 5-mi (8-km) reach downstream from The Forks Dam to site 4 (Rock Springs Road). This reach of the river channel is extremely sandy and is very permeable. Downstream from site 4, the remaining 600 acre-ft (0.7 hm^3) of water percolated into the channel--this amount appears to be well below the channel's potential to absorb water.

The wetted area of the river channel was determined from field mapping during the release of the water and from aerial photographs of the river taken 5 days after the release. The width of the flow ranged from 100 to 600 ft (30.5 to 183 m) and averaged 200-300 ft (61-91 m). This information and the quantity of water lost between sites permitted the determination of an infiltration rate for specific reaches of the river. For example, the infiltration rate for the short time of the release was 3 to 6 ft (0.9 to 1.8 m) per day between Cedar Springs and The Forks Dam, and 10 to 15 ft (3.0 to 4.5 m) per day between The Forks Dam and site 4.

Table 4.—*Mojave River controlled release from Cedar Springs Dam, November 14–15, 1972*

Site No.	Description of measuring site	Distance downstream from Cedar Springs dam (mi)	Peak discharge (ft^3/s)	Total quantity of water past site (acre-ft)	Between sites: Total quantity of water lost or recharged (acre-ft)	Between sites: Infiltration rate in channel (acre-ft/mi)	Between sites: River-channel gradient (ft/mi)	Adjusted time for flow to arrive (hours)	Total time of flow past site (hours)	Average velocity: From Cedar Springs dam (ft/s)	Average velocity: Between sites (ft/s)
Site 1	Bridge of Hwy. 173 near Cedar Springs Dam.	<0.1	1,950	3,100				0	20	....	
					300	67	31				4.4
Site 2	Culvert near Lake Arrowhead Road.	4.5	1,950	2,800				1½	23½	4.4	
					100	83	21				4.1
Site 3	Tunnel outlet at Mojave Forks dam.	5.9	1,750	2,700				2	23½	4.3	
					2,100	420	20				1.1
Site 4	Rock Springs Road River Crossing (east of Hesperia).	10.9	825	600				8¾	17¼	1.8	
					600	140	19				.4
Site 5	Bear Valley Road Bridge Crossing (east of Victor Valley College).	15.2	10	<2				23¼	2¾	.96	
					<2	....	....				.6
End of controlled release flow		16.0	....	....				25¼	0	.92	

SUMMARY:

1. Water-realese schedule Nov. 14, 1972: 1300–1330 hours, 200 ft^3/s; 1330–1350 hours, 500 ft^3/s; 1350–1410 hours, 1,000 ft^3/s; 1410–1430 hours, 1,500 ft^3/s; 1430–0900 hours (Nov. 15, 1972), 1,950 ft^3/s. Effective time of travel was computed to begin about 1400 hours and is adjusted time used in time and travel calculations.
2. Total quantity of water released in 20 hours, 3,100 acre-ft (approximately 1 billion gal).
3. Average velocity of water front to reach maximum distance, 0.93 ft/s.
4. Silverwood Lake level declined about 5 ft during test.
5. Mojave River channel extremely dry.

The infiltration rate in the 10-mi (16-km) reach below The Forks Dam is high and probably should not be considered as a representative long-term value. For example, recharge studies of Wilson Creek recharge pit near Yucaipa (10 mi or 16 km east of San Bernardino) showed initial high infiltration rates of 17 ft (5 m) per day, decreasing to 9 ft (2.7 m) per day after 26 days of recharge (Moreland, 1970, p. 33). Also, in an environment similar to the Mojave River basin, a recharge pit adjacent to the Whitewater River near Palm Springs showed infiltration rates of 4 to 24 ft (1.2 to 7.3 m) per day based on three separate tests totaling 151 days. The infiltration rates ranged from 7 to 19 ft (2.1 to 5.8 m) per day for the initial 8 days, decreasing to about 5 ft (1.5 m) per day after the 38th day (Tyley, 1973, p. 18). These tests cannot be compared directly with infiltration rates in a stream, but together with the 18 floods in the Mojave River (table 3) do indicate much lower long-term infiltration rates than were determined from the controlled release of nearly 1 day.

SIMULATION OF FLOW IN THE MOJAVE RIVER USING A MATHEMATICAL MODEL

A mathematical model was developed (see appendix) that simulates the advance of discharge down the initially dry channel of the Mojave River. It represents an attempt to simulate physical conditions in the channel by deterministic mathematical descriptions that are based largely on the physical laws governing open-channel hydraulics and flow through a porous media. The input to the model consists of streamflow data at The Forks, either measured or synthetic, and the output from the model simulates the resulting discharge at any point along the channel.

The model was used to study the conditions by which it is possible to efficiently convey imported water down the Mojave River channel from Silverwood Reservoir to Barstow. It was also used to study the impact of The Forks Dam on the streamflow in the river.

Limitations of the Model

Streamflow in the Mojave River is affected by complex interactions between a ground-water body, discharge in the channel, and infiltration through the bed of the channel to the ground-water body. The model is designed to simulate these interactions, and a computer algorithm was developed that preserves the essential features of the prototype. The model describes explicitly the discharge in the channel and the infiltration out of the channel. However, the interaction between the infiltration rate and the ground-water body is treated only implicitly through the form of an infiltration equation.

The model is a lumped-parameter model. Physical measures that in reality have spatial and temporal variability are considered herein to be invariant, and the parameters used in the model represent the average properties of the actual physical system. Thus, the geometrical properties of the channel and, although the permeability of alluvial channels is known to change with discharge, streamflow velocity, and other factors (written commun., D. E. Burkham, 1973), the physical properties of the channel bed that affect infiltration are considered to be spatially and temporally uniform.

The channel is assumed to have a rectangular cross section of constant width, the wetted perimeter of the cross section is assumed to equal the channel width, and the channel is assumed to have a uniform bed slope. The cross section of the Mojave River channel is approximately rectangular for rates of discharge that range from about 300 to 20,000 ft^3/s (8 to 565 m^3/s) (fig. 3) and, although the width of the channel varies from point to point, there is no apparent trend in the variations in channel width. The bed slope of the channel is not strictly uniform, being somewhat steeper in the reach above Victorville (about 23 ft/mi or 4.4 m/km) than in the reach below Victorville (about 16 ft/mi or 3.0 m/km).

The model simulates infiltration at specified points, and, if time is reckoned from the moment of the initial wetting of the channel bed at a given point, the variation of the infiltration rate with time is assumed to be identical at all locations along the channel. In reality, even if commensurate time references are considered, the functional relation between the infiltration rate and time changes from point to point because of the geologic and hydrologic heterogeneity of the actual physical system. As a result, the parameters of the model that identify point infiltration represent only the average characteristics of the prototype.

Calibration of the Model

A fixed set of mathematical equations are used in the model. These equations were fitted to the Mojave River by selecting the proper set of numerical values for four critical parameters (table 5) within the mathematical equations. Values for these parameters were selected by a trial-and-error calibration that required streamflow data from concurrent floods at each of The Forks, Victorville, Wild Crossing, and Barstow. Streamflow data obtained at The Forks were used as input for the model, and the simulated streamflow at Victorville, Wild Crossing, and Barstow was then compared to the measured streamflow at these stations. Adjustments then were made to one or more of the parameter values in order to better reproduce the measured streamflow at Victorville, Wild Crossing, and Barstow. These adjustments were continued, by repeated trials, until the model reproduced the measured flows to an acceptable degree.

TABLE 5.--*Model parameters and their application to the modeling process*

Parameter	Value	Application[1]
k	135	Time coefficient in infiltration equation in ft^2/s^{1-a}.
a	.95	Exponent of time in infiltration equation (dimensionless).
f_∞	.0015	Asymptotic infiltration rate as time value approaches infinity, in ft^2/s.
α	6.0	Coefficient in stage-discharge relation in ft/s.

[1]See appendix for more detailed description of parameter applications.

The model was calibrated to two floods (table 6), but the model does not reproduce completely the observed behavior of the Mojave River. The model generally overestimates observed discharges that are greater than 5,000 ft^3/s (142 m^3/s) by about 40 percent and underestimates observed discharges that are less than 100 ft^3/s (2.8 m^3/s) by about 20 percent (fig. 7). The differences between measured and simulated discharge, for measured discharges of 100 to 5,000 ft^3/s (2.8 to 142 m^3/s), appear to be randomly distributed with respect to magnitude, sign, and time. However, in general, the total flood volumes are overestimated by as much as 30 percent.

TABLE 6.--*Measured and simulated streamflow*

Station	Period identifier[1]	Streamflow volume	
		Measured (acre-ft)	Simulated (acre-ft)
Mojave River at The Forks, near Hesperia[2]	A	323,000	--
	B	40,600	--
Mojave River at Lower Narrows, near Victorville	A	273,000	273,000
	B	21,400	30,700
Mojave River at Wild Crossing, near Helendale	A	226,000	232,000
	B	13,100	18,400
Mojave River at Barstow	A	146,000	196,000
	B	7,100	7,000

[1]Period A is January 20 to May 10, 1969, and period B is December 3-12, 1966.

[2]Combined discharge of Deep Creek near Hesperia and West Forks Mojave River near Hesperia.

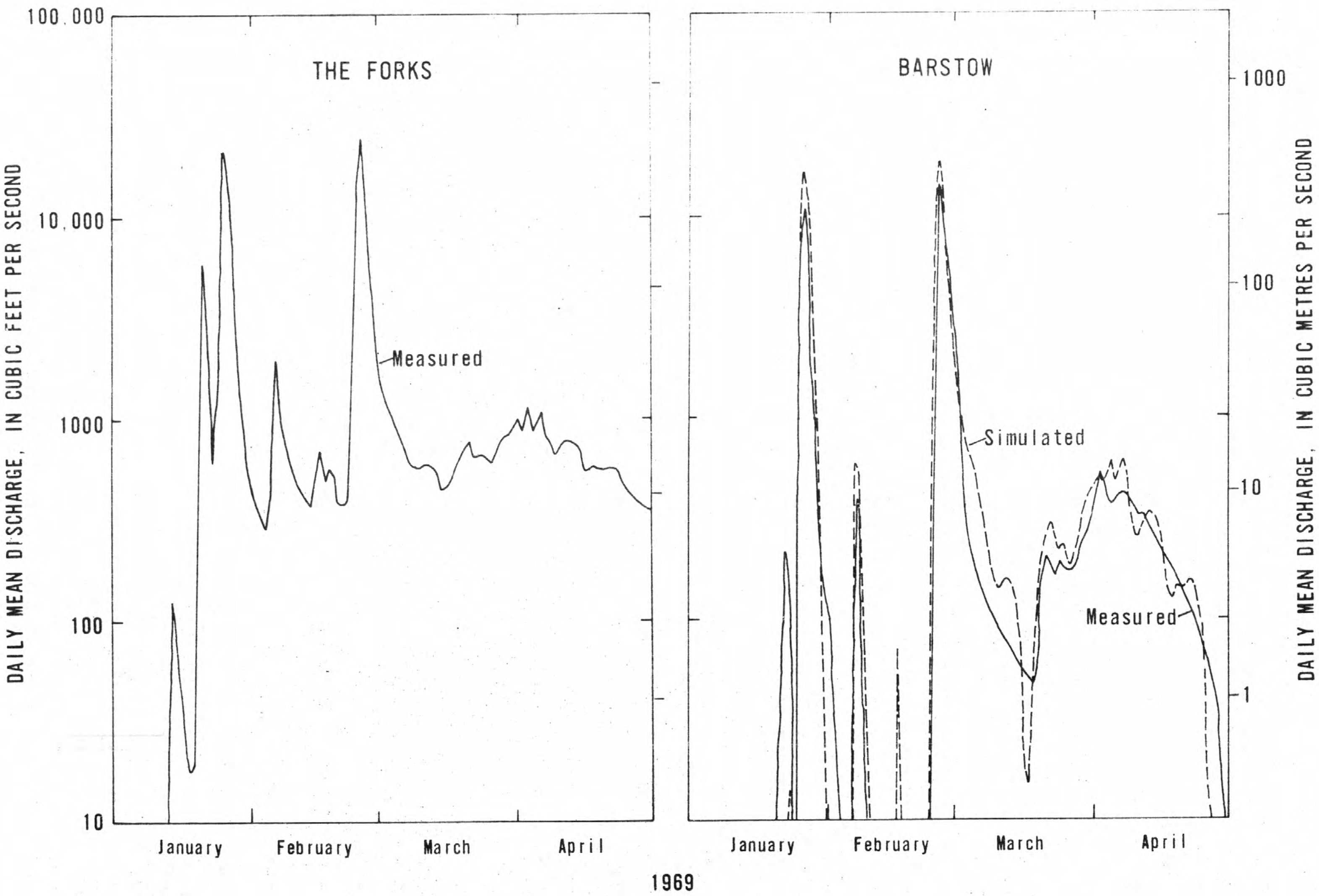


FIGURE 7.--Measured inflow hydrograph at The Forks and corresponding measured and simulated hydrographs at Barstow.

Although part of the differences between the measured and simulated discharge can be traced to error in the measured streamflow data (the standard deviation of errors in the streamflow records at Victorville, Wild Crossing, and Barstow may be as large as 20 percent of the recorded flows), these deviations can be attributed primarily to the lack of complete model equivalence to the actual physical system. The lack of model equivalence is most apparent in the assumption that the wetted perimeter of the channel cross section is a constant value for all rates of discharge. The wetted perimeter is approximately constant for a large range of discharge, but for discharges less than 300 ft^3/s (8 m^3/s) the actual wetted perimeter is smaller than the assumed constant value, and for discharges greater than 20,000 ft^3/s (566 m^3/s) the wetted perimeter is larger than the assumed constant value. Inasmuch as the infiltration rate per unit length of channel is correlated positively with the wetted perimeter, infiltration may be either underestimated or overestimated when the discharge is either very high or very low.

Conveyance of Imported Water to Barstow in the Mojave River Channel

The Mojave Water Agency, under one management plan, anticipates that it could release 20,000 acre-ft (25 hm^3) of imported water annually from Silverwood Reservoir into the channel of the Mojave River, and, to meet the requirements of the Agency, at least part of this water must reach Barstow. However, if the antecedent absorption capacity of the channel is at the maximum level, both the model results and the analysis of the historic streamflow data indicate that a release of 20,000 acre-ft (25 hm^3) of water at release rates from Silverwood Reservoir that will not endanger life or property probably will not produce flow at Barstow. Two historic floods (floods 2 and 10 of table 1) with flow volumes of less than 20,000 acre-ft (25 hm^3) have produced flow at Barstow, but in each instance the antecedent absorption capacity of the channel was not at the maximum level. In light of this, the model was used to investigate the possibility of releasing imported water from Silverwood Reservoir when the absorption capacity of the channel had been reduced by a previous flood.

The volume of imported water that will reach Barstow, if released after a flood, depends on (1) the volume of imported water that is released from Silverwood Reservoir, which, in this study, is assumed to be 20,000 acre-ft (25 hm^3), (2) the rate at which imported water is released from Silverwood Reservoir, (3) the volume of the flood at The Forks, (4) the duration of the flood at The Forks, and (5) the absorption capacity of the channel antecedent to the flood. However, in this study the influence of variations in the antecedent absorption capacity of the channel on the volume of imported water that will reach Barstow was disregarded, and the channel was assumed to be at the maximum absorption capacity (for given ground-water levels) prior to the flood. This assumption is supported to some degree by the fact that the channel is usually dry during May through November (except for previously described areas of perennial flow), and by the end of this period the channel probably has obtained the maximum absorption capacity. In addition, although several floodflows may pass The Forks in a given year, usually not more than one flood produces flow at Barstow (table 1), and small floods that occur prior to a flood that produces flow at Barstow usually affect the absorption capacity of the channel only between The Forks and Victorville. The model was calibrated to the floods of 1967 and 1969, and the values of the model parameters reflect the antecedent absorption capacity of the channel (and consequently ground-water levels) prior to these floods. After calibration, the use of the model for predictive purposes tacitly assumes that similar antecedent conditions prevail.

In order to examine the variables affecting the volume of imported water that will reach Barstow, a hypothetical input hydrograph was designed to represent streamflow at The Forks. The hydrograph (fig. 8) consists of a triangle, which represents a flood, and a rectangle, which represents the release of 20,000 acre-ft (25 hm^3) of imported water from Silverwood Reservoir. About 100 model runs were made by assigning various values to the flood volume, the flood duration, and the release rate.

The relations shown in figure 9 were derived from data that were synthesized using the hypothetical hydrograph as input to the model. The relations show a threshold value, a sloping segment, and a near-horizontal segment. For a flood volume less than the threshold value, no released flow and no floodflow will reach Barstow. For a flood volume along the sloping segment of the relations, the volume of released flow that reaches Barstow varies with the flood volume; however, none of the floodflow water reaches Barstow. For a flood volume along the near-horizontal segment of the relations, floodflow reaches Barstow, and the volume of released flow that reaches Barstow approaches a maximum value that is dependent only on the release rate.

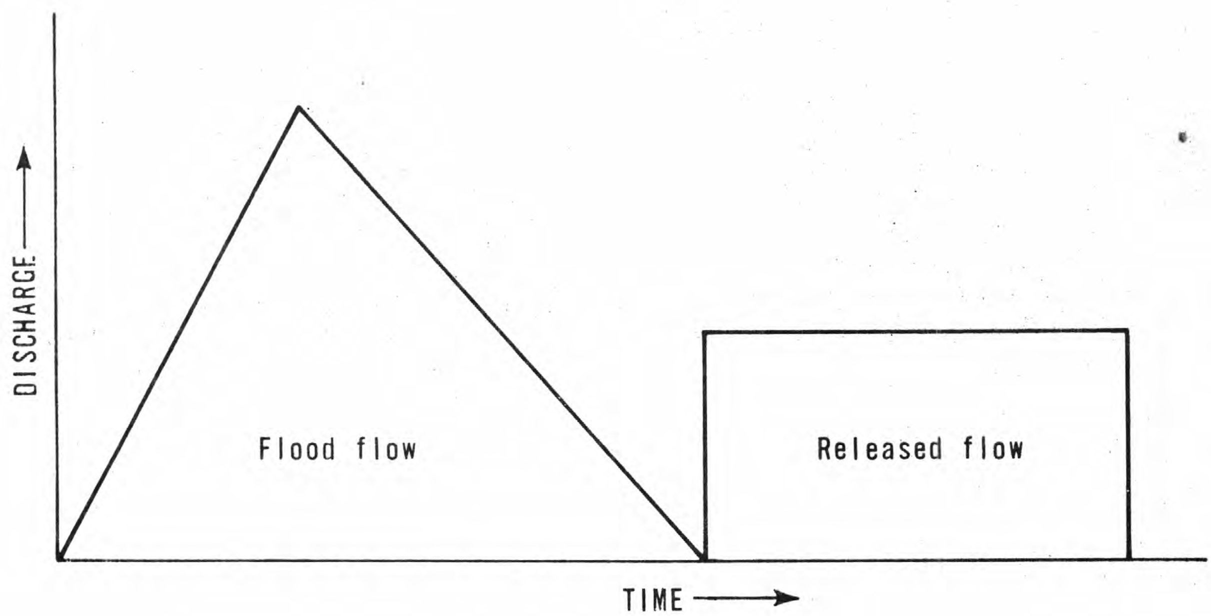


FIGURE 8.--Hypothetical input hydrograph representing streamflow at The Forks.

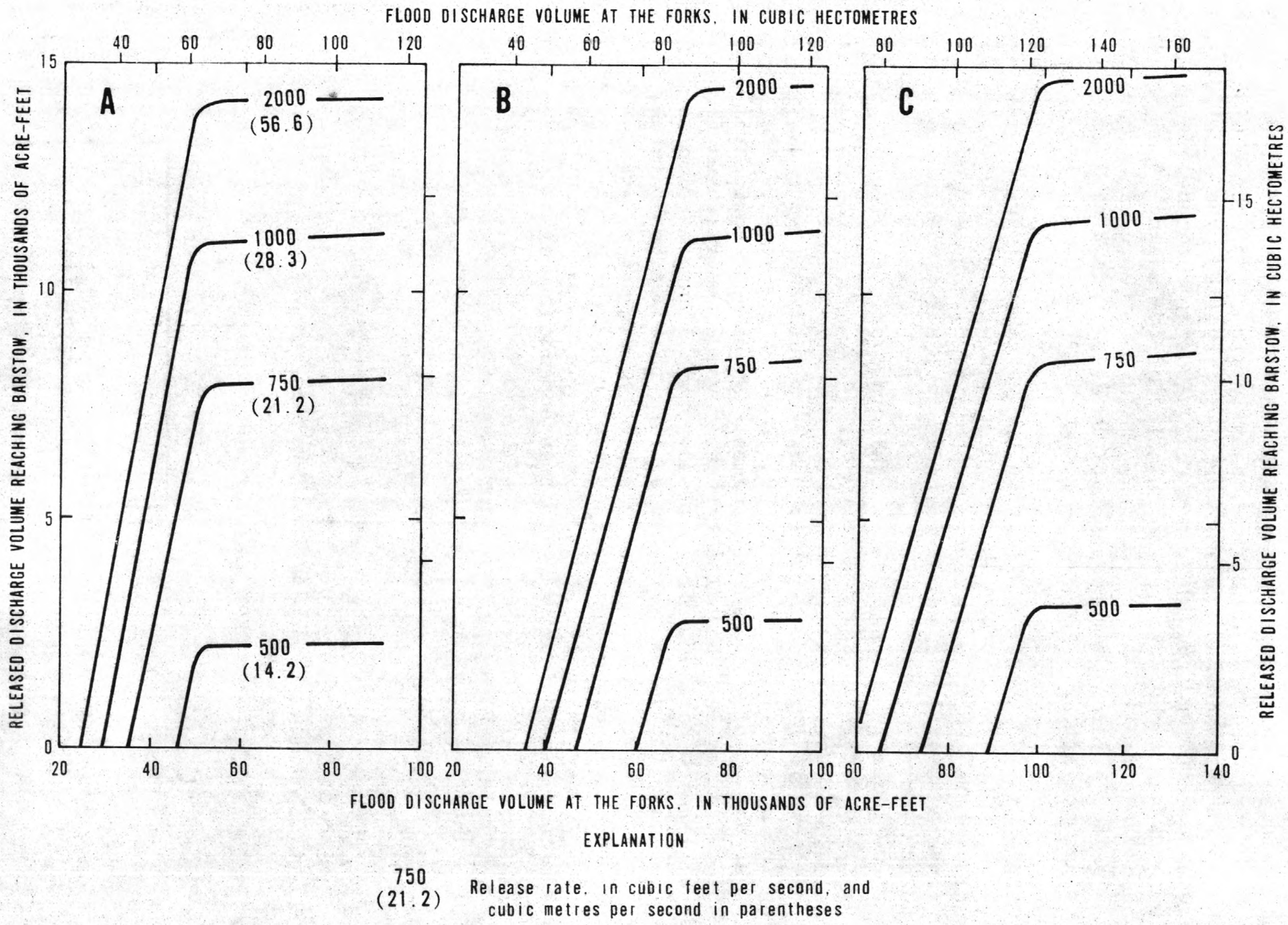


FIGURE 9.--Released volume that will reach Barstow--representing a release of 20,000 acre-feet (24 cubic hectometres) of water from Silverwood Reservoir: A, flood duration of 30 days; B, flood duration of 60 days; and C, flood duration of 120 days.

The break in the slope of the curves in figure 9 occurs for a flood volume at The Forks that represents a flood that will wet the entire length of the channel of the Mojave River between The Forks and Barstow. A flood with a volume of water less than the value at the break in slope will not wet the entire channel. In general, the length of the segment of dry channel decreases with floods of larger total volume at The Forks. The dry channel that remains between the furthest downstream advance of the flood and Barstow may infiltrate all or part of any imported water that is released into the channel subsequent to the flood. Furthermore, for a given release of water from Silverwood Reservoir, the volume of imported water that reaches Barstow approaches a maximum value when an antecedent flood leaves no segment of the channel above Barstow dry.

A comparison of the relations shown in figure 9 suggests that (for a given release rate and flood volume) the volume of released flow that reaches Barstow can decline with an increase in the duration of the antecedent flood. As an example, given a release rate of 2,000 ft^3/s (56.6 m^3/s) and a flood volume of 40,000 acre-ft (49 hm^3), 9,000 acre-ft (11 hm^3) of released water will reach Barstow if the duration of the flood is 30 days, and 2,000 acre-ft (2.5 hm^3) of released water will reach Barstow if the duration of the flood is 60 days. This result can be explained as follows: The volume of water that infiltrates into the channel bed is partly controlled by the area of the channel that is wetted (that is, the distance that a flood advances down the channel) and the length of time that water remains in the channel. Although a flood with a shorter duration may wet a greater area of the channel (that is, advance farther downstream), a flood with a longer duration may actually result in the greater infiltration of water if the increased duration is proportionally larger than the increased wetted area. This last statement seems to be true for the Mojave River channel between The Forks and Barstow.

The release of 20,000 acre-ft (25 hm^3) of imported water into the channel of the Mojave River was simulated for release rates of 500 ft^3/s (14.2 m^3/s) during a 20-day release period, 750 ft^3/s (21.2 m^3/s) during a 13-day release period, 1,000 ft^3/s (28.4 m^3/s) during a 10-day release period, and 2,000 ft^3/s (56.8 m^3/s) during a 5-day release period. As shown in figure 9, the maximum volume of released water that reached Barstow for these release rates was about 2,500, 8,000, 11,000, and 15,000 acre-ft (3.08, 9.86, 13.6, and 18.4 hm^3).

The release of imported water into the channel of the Mojave River was not simulated for release rates greater than 2,000 ft^3/s (56.8 m^3/s) because the model used in the study does not account for the attenuation effect of channel storage on a release having a short duration and high-release rate. Channel storage causes a general reduction in peak discharge in the downstream direction, independent of the reduction due to infiltration. This influence of channel storage becomes more important as the duration of flow is shortened. Release rates greater than 2,000 ft^3/s (56.8 m^3/s) are probably not being considered by the Mojave Water Agency because of potential flood damage. The controlled release from Silverwood Reservoir in November 1972 was kept less than 2,000 ft^3/s for this reason. However, because of the attenuation effect, the volume of released water that would reach Barstow, given a release rate greater than 2,000 ft^3/s (56.8 m^3/s), probably would not be much greater than the volume produced at a release rate of 2,000 ft^3/s (56.8 m^3/s). This latter statement represents a tentative conclusion, which can be verified only with the aid of more sophisticated analytical techniques than were used in this study.

The channel of the Mojave River can be used practically to convey water from Silverwood Reservoir downstream to Barstow only when the channel has been wetted by a natural flood. The success of the scheme in any given year depends on the occurrence of a flood within a specified range of duration and volume. Because the occurrence of a flood is random in character and generally cannot be predicted, the possible success of the scheme is discussed in terms of the probability of the occurrence of the desired flood.

The probability of obtaining in a given year the possible maximum volume of released water at Barstow is equal to the probability of the occurrence in a given year of a flood that produces flow at Barstow, that is, a flood with a volume (at The Forks) greater than the volume represented by the break in slope in the curves in figure 9. Based on the streamflow records for the Mojave River, the probability of the occurrence of this flood in a given year is 40 percent. The probability of obtaining in a given year no flow at Barstow owing to the release of imported water into the channel is equal to the probability of the occurrence in a given year of a flood with a volume (at The Forks) smaller than the threshold volume on the curves in figure 9. The probability of the occurrence of this flood in a given year is also 40 percent. The probability of obtaining in any given year a volume of released water at Barstow that is less than the possible maximum volume but greater than zero is equal to the probability of the occurrence of a flood with a volume (at The Forks) smaller than the volume represented by the break in slope in the curves in figure 9 but larger than the threshold volume on these curves. The probability of the occurrence of this flood in a given year is 20 percent.

Effects of The Forks Dam on Streamflow

The channel of the Mojave River can be used to convey imported water to Barstow only when the absorption capacity of the channel has been reduced by an antecedent flood. The volume of imported water that can reach Barstow depends partly on the volume and duration of the flood. However, construction of The Forks Dam at the head of the Mojave River channel was completed in 1971, and the dam will produce changes in the timing of flood inflow to the channel. The model provides a technique for making a quantitative study of the influence of The Forks Dam on the volume and duration of a flood at locations downstream from the dam.

The possible effect of The Forks Dam on streamflow in the Mojave River was investigated as follows: First, historic streamflow data at The Forks was used as input data for the model, and the streamflow response at Barstow was noted. Second, the same historic streamflow data was then routed through The Forks Dam reservoir using a method of storage routing described by Linsley, Kohler, and Paulhus (1958, p. 224-227). Outlet-capacity and reservoir-storage data, which were required for the method, were obtained from the U.S. Army Corps of Engineers (1973). The computed outflow from the reservoir was then used as input data for the model. The simulated streamflow at Barstow using computed reservoir outflow was compared to the simulated streamflow without the reservoir. Simulated streamflow data for both cases were compared in order to reduce the effect of bias in the model on the comparison.

Two historic floods were studied. The first flood occurred December 3-12, 1966, and had a total volume of 40,600 acre-ft (50 hm^3) at The Forks. The second flood occurred January 20-29, 1969, and had a total volume of 101,000 acre-ft (125 hm^3) at The Forks. The 1966 flood represents a small flood, with reference to the range of flood magnitudes for the Mojave River that produce flow at Barstow, and the 1969 flood represents a large flood. Results of simulation (summarized in figures 10 and 11 and table 7) suggest that the dam has little effect on the total volume of streamflow at Barstow. The dam does have an effect on the distribution of flow with time at both The Forks and Barstow: Peak discharge is reduced, and the flood hydrograph is broadened. However, only the crest area of the hydrograph is affected by attenuation, and the total duration of a flood is changed only slightly (figs. 10 and 11).

TABLE 7.--*Simulated effects of The Forks Dam on streamflow at Barstow*

Station	Period identifier[1]	Streamflow volume	
		Without dam (acre-ft)	With dam (acre-ft)
Measured streamflow for Mojave River at The Forks, near Hesperia[2]	A	101,000	101,000
	B	40,600	40,600
Simulated streamflow for Mojave River at Barstow	A	64,800	64,800
	B	7,000	7,000

[1]Period A is January 20-29, 1969, and period B is December 3-12, 1966.
[2]Combined discharge of Deep Creek near Hesperia and West Fork Mojave River near Hesperia.

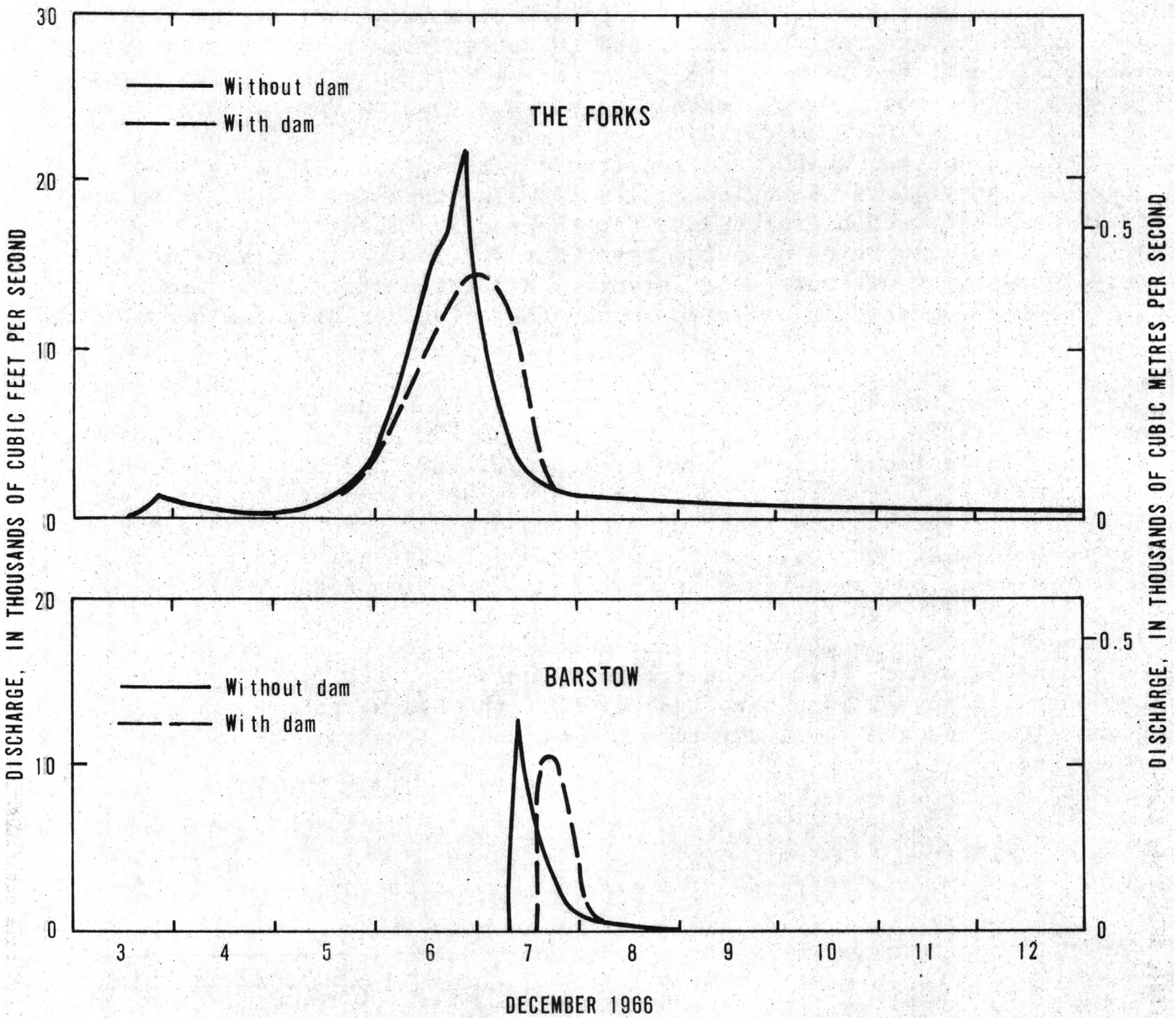


FIGURE 10.--Simulated hydrographs showing the effects of The Forks Dam on the flood of December 3-12, 1966.

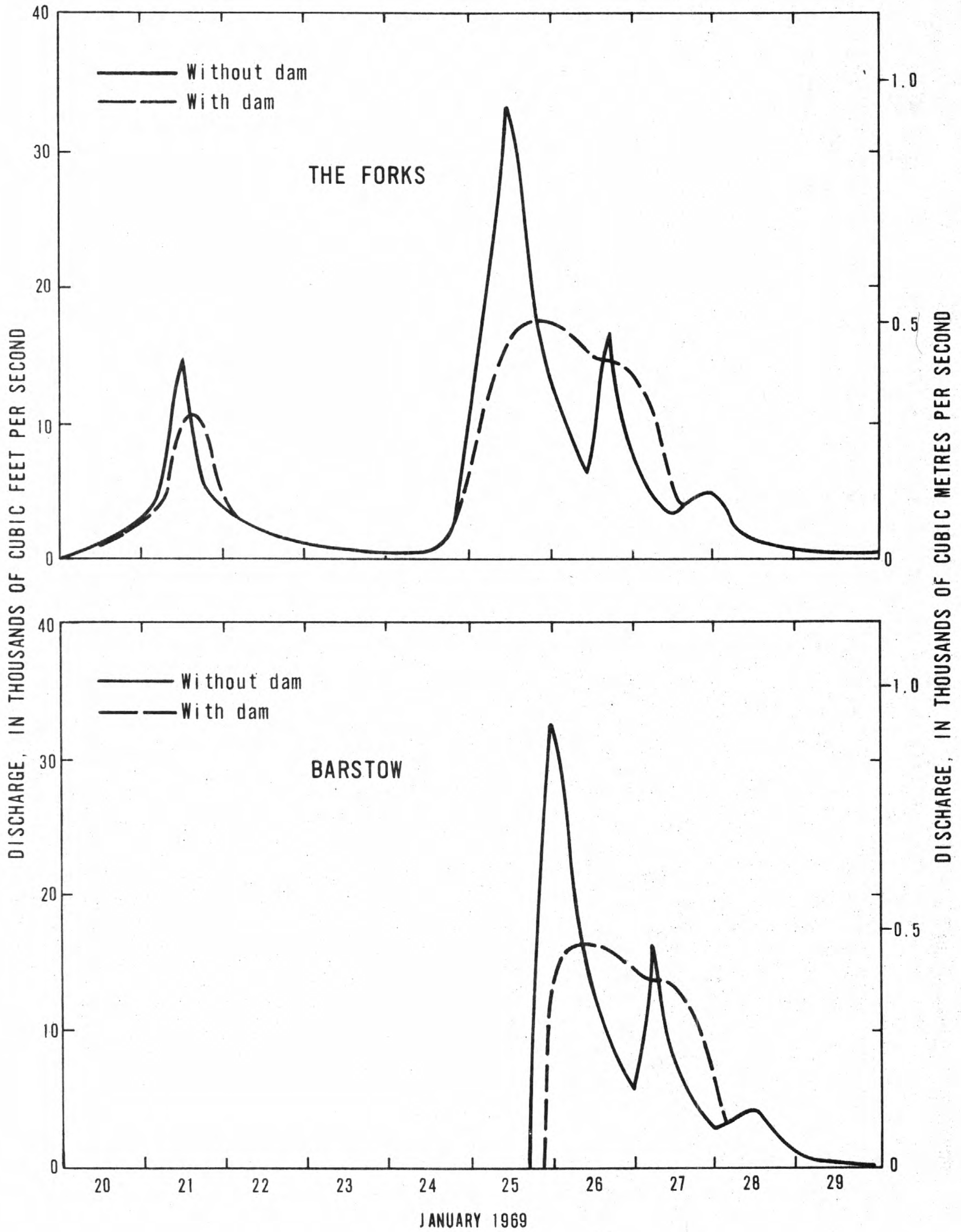


FIGURE 11.--Simulated hydrographs showing the effects of The Forks Dam on the flood of January 20-29, 1969.

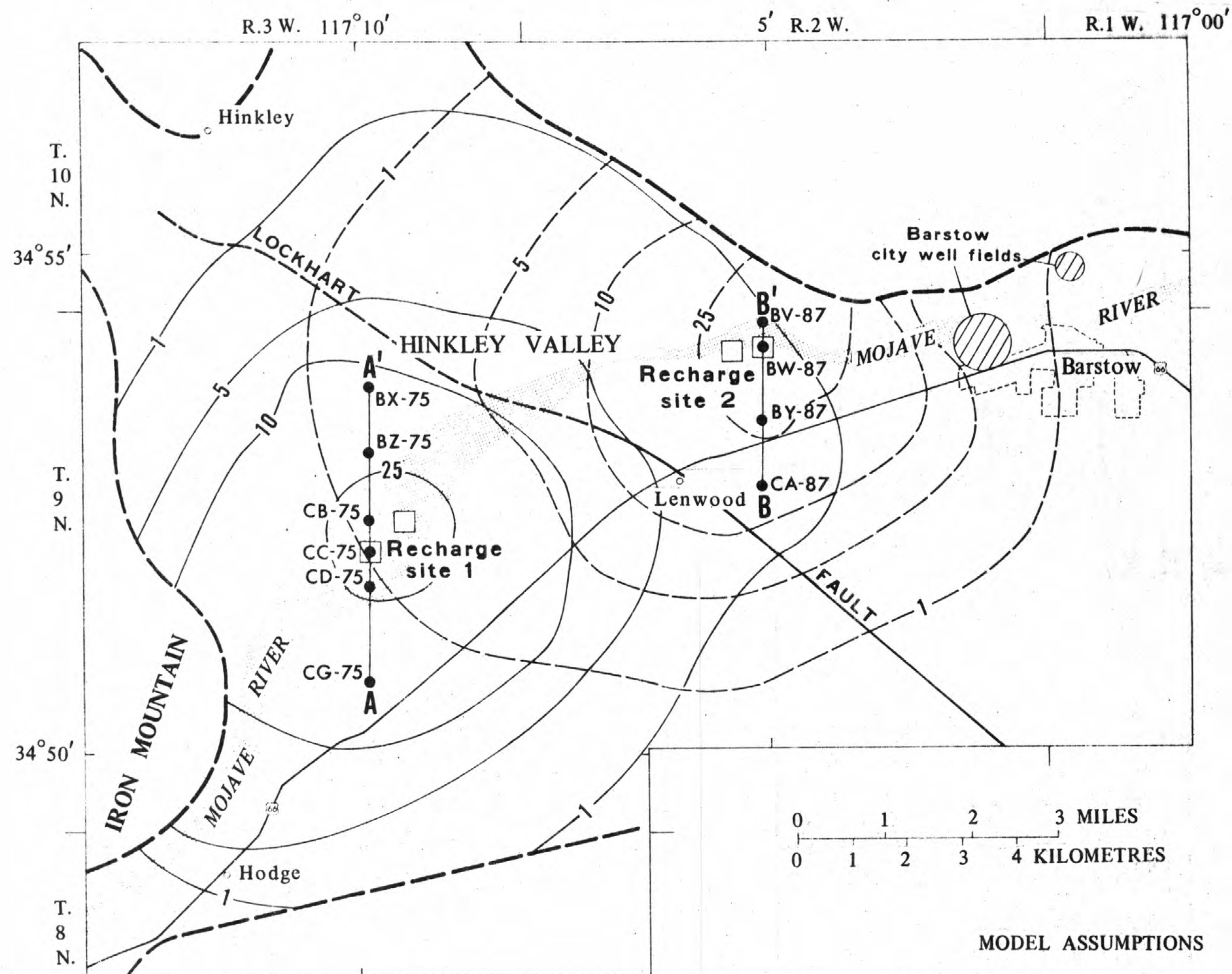
PREDICTED AQUIFER RESPONSE TO RECHARGE USING ELECTRIC ANALOG MODEL

The Mojave Water Agency is studying several ways to supply water to the Barstow area. One plan is to construct recharge pits in the Mojave River between Hodge and Barstow, using floods or imported water to replenish the aquifer. To predict the effects of this plan, an electric analog model (Hardt, 1971) was programed for 20 years of recharge. Two separate plans were devised that consisted of recharging 5,000 acre-ft (6 hm^3) per year in a 4-month period (for example, January to April) at two different sites. Site 1 was chosen to primarily replenish the Hinkley Valley area, and site 2 was chosen to replenish the Lenwood-Barstow area.

The results of the model study delineated the area of a rise in water level after 10 years of cyclic recharge in the Hinkley Valley-Barstow area (fig. 12). At each site, the yearly recharge was divided equally between two model nodes (2,000 ft or 610 m apart) which represent a line source of recharge of about 4,000 ft (1,220 m) in the Mojave River channel. All outside stresses, such as pumping, were omitted from the model in order to observe the potential areal limits of the effects of recharge. The model also assumes that all recharge water reaches the water table. If both recharge plans were put in operation simultaneously, the amount of water-level rise should be added where the two recharge cones or mounds overlap. In addition, to obtain the water-level changes due to the combined effects of pumping and recharge, the above water-level changes should be superimposed on the separate effects of pumping. The water-level changes due to pumping are described by Hardt (1971, p. 66-69).

Figure 12 is based on model-generated water levels at the end of a recharge period and before the head was dissipated away from the input nodes. The maximum stress on the model is at the recharge nodes where water levels rose 25-50 ft (7.5-15 m) after 10 years of recharge. The assumed lack of pumping during the recharge period, the point distribution of model recharge, and the time of measurements of simulated water levels due to recharge, all tend to overemphasize the response. The actual depth to water beneath the assumed recharge sites (1973) is about 25-30 ft (7.5-9 m) below land surface. Near the assumed recharge pits, simulated water levels may rise above the land surface. If this occurred, the water on the land surface would move downstream only a short distance before percolating into the channel bottom, where water levels are below the land surface. Depending on the recharge site selected, the model indicates water levels would rise 25 ft (7.6 m) or more over an area of 2 to 3 mi^2 (5.2 to 7.8 km^2) and would rise 10 ft (3.0 m) or more over an area of 10 mi^2 (25 km^2).

Hydrographs of simulated water levels at selected model nodes were chosen to show a section through the recharge sites (fig. 13). Each hydrograph shows the cyclic effect of recharge during a 20-year period. As expected, the aquifer response is greatest at the recharge node. The hydrographs show the rapid rise in head during the 4 months of recharge and the equally rapid decline of head during the 8 months of no recharge. The upward trend of the bottom part of the cyclic curve after each year of recharge indicates the net positive effect of recharge on the aquifer.



FAULT--Dashed where approximately located

MODEL BOUNDARY

RECHARGE SITE

CB-75 MODEL HYDROGRAPH--CB-75 refers to model nodal grid

A——A′ HYDROLOGIC PROFILE (See figure 13)

—1— LINE OF EQUAL WATER-LEVEL RISE FROM RECHARGE AT SITE 1--Water-level rises measured at end of 10th year of recharge cycle; interval 1, 5, 10, and 25 feet

– –5– – LINE OF EQUAL WATER-LEVEL RISE FROM RECHARGE AT SITE 2--Water-level rises measured at end of 10th year of recharge cycle; interval 1, 5, 10, and 25 feet

MODEL ASSUMPTIONS

1. Recharge of 5000 acre-feet per year in 4 months--equally divided into two nodes per site
2. No pumping or other recharge from aquifer
3. All recharge water reached water table

(Conversion factor: 1 foot=0.3048 metre
1 acre-foot=0.001233 cubic hectometre)

FIGURE 12.--Predicted aquifer response to recharge by analog model.

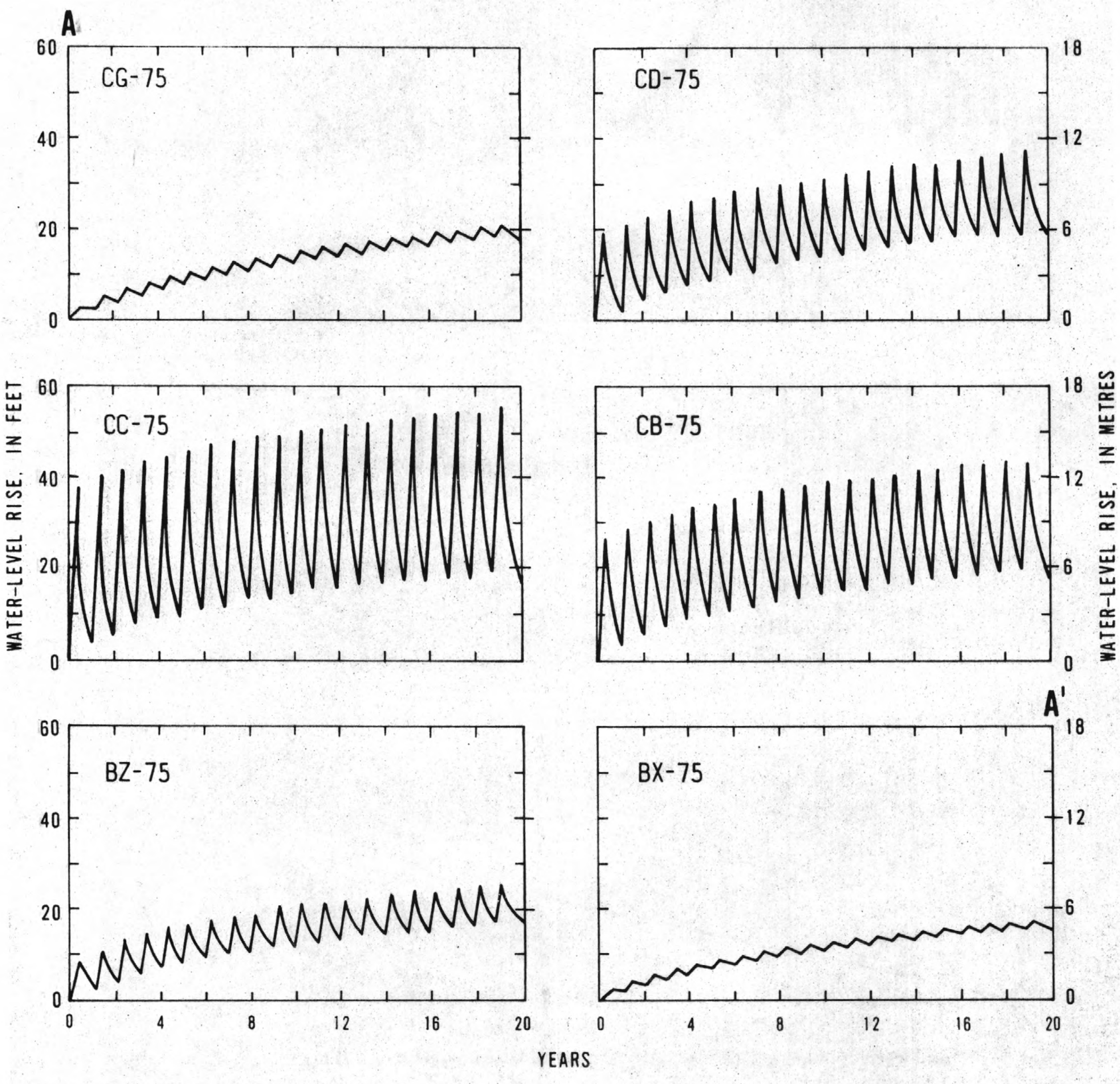


FIGURE 13.--Selected model hydrographs.

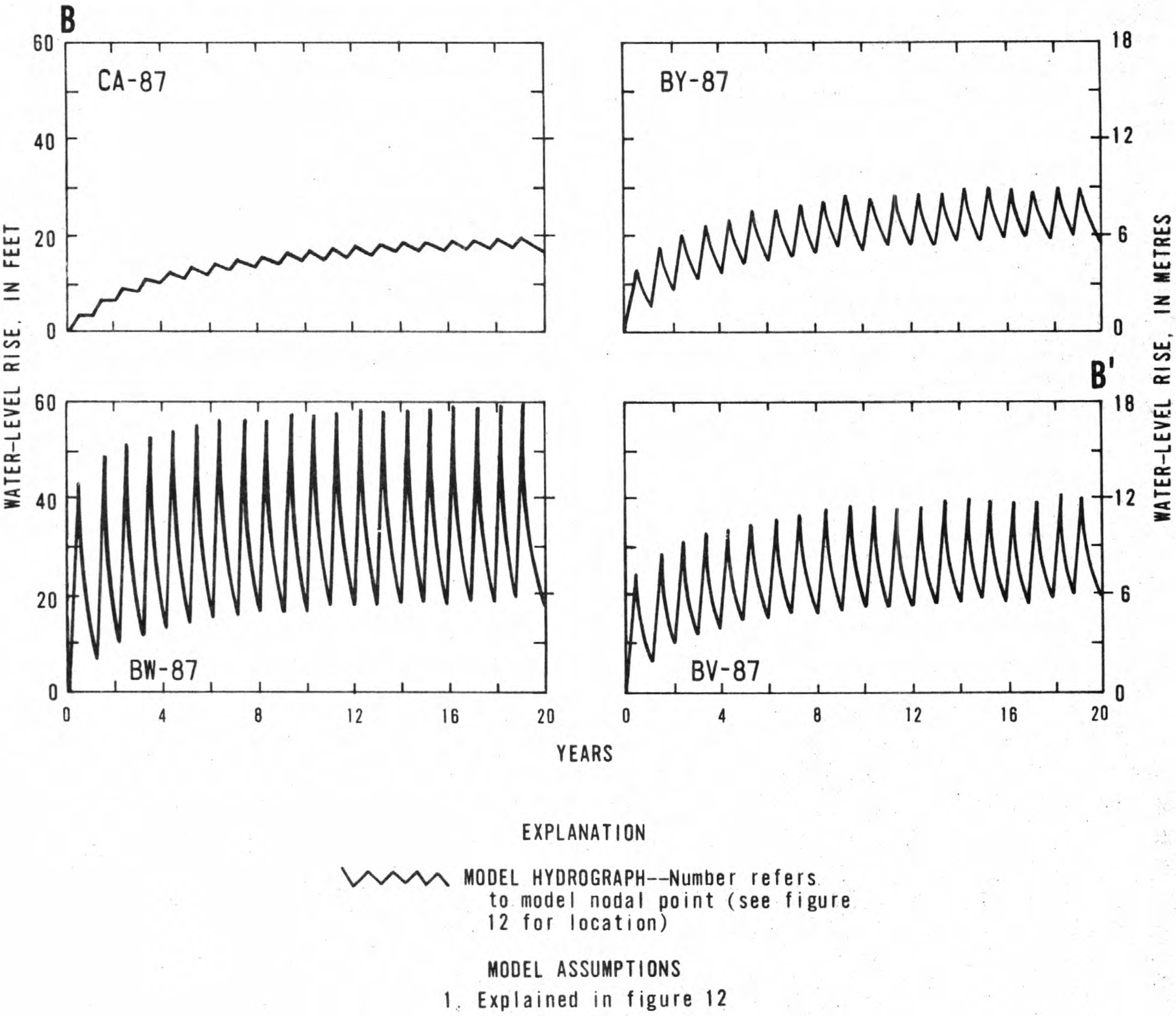


FIGURE 13.--Continued.

CONCLUSIONS

On the basis of the study findings, the following conclusions may be drawn:

1. If the absorption capacity of the channel is reduced by the occurrence of a flood prior to release of imported water, the channel of the Mojave River can be more efficiently used to convey imported water from Silverwood Reservoir downstream to the Barstow area. The volume of imported water that reaches Barstow depends largely on the volume and duration of the prior flood and on the rate at which imported water is released from Silverwood Reservoir. A release of 20,000 acre-ft (25 hm^3) at 1,000 ft^3/s (28 m^3/s) may produce as much as 11,000 acre-ft (13.6 hm^3) of flow at Barstow. A release rate of 500 ft^3/s (14.2 m^3/s) may produce as little as 2,500 acre-ft (3.08 hm^3). Given an increasingly larger flood antecedent to the release of imported water, the maximum volume of imported water that can reach Barstow is limited largely by the rate at which water is released from Silverwood Reservoir.

2. The recharge of 5,000 acre-ft (6.17 hm^3) of water for 10 years to the aquifer underlying the Barstow area would cause water levels to rise as much as 30 ft (9.2 m) at the recharge sites--the present depth to the water table. Depending on the recharge site selected, the model indicates water levels would rise 25 ft (7.6 m) or more over an area of 2 to 3 mi^2 (5.2 to 7.8 km^2) and would rise 10 ft (3.0 m) or more over an area of about 10 mi^2 (25 km^2).

3. The Forks Dam reduces the flood peak but increases the width of the flood hydrograph. However, according to the model results, the dam has little effect on the streamflow volume and the total flood duration.

SELECTED REFERENCES

Burkham, D. E., 1970, A method for relating infiltration rates to streamflow rates in perched streams, *in* Geological Survey Research, 1970: U.S. Geol. Survey Prof. Paper 700-D, p. D266-D271.

______1970, Depletion of streamflow by infiltration in the main channels of the Tucson basin, southeastern Arizona: U.S. Geol. Survey Water-Supply Paper 1939-B, 36 p.

Butler, E. B., Reid, J. K., and Berwick, V. K., 1966, Magnitude and frequency of floods in the United States, part 10, The Great Basin: U.S. Geol. Survey Water-Supply Paper 1684, 256 p.

California Department of Engineering, 1918, Report on the utilization of Mojave River for irrigation in Victor Valley, California: Bull. 5, 93 p.

SELECTED REFERENCES

California Department of Public Works, Division of Water Resources, 1934, Mojave River investigation: Bull. 47, 77 p.

California Department of Water Resources, 1965, Feasibility of serving the Mojave Water Agency from the State Water Project: Bull. 119-12, 77 p.

_____1967, Mojave River ground-water basins investigation: Bull. 84, 151 p.

Dibble, E. F., 1967, Mojave Water Agency, Water production verification program: E. F. Dibble, Redlands, Calif., 39 p.

Hardt, W. F., 1969, Mojave River basin ground-water recharge, with particular reference to the California floods of January and February 1969: U.S. Geol. Survey open-file rept., 13 p.

_____1971, Hydrologic analysis of Mojave River basin, California, using electric analog model: U.S. Geol. Survey open-file rept., 84 p.

Hewett, D. F., 1954, General geology of the Mojave Desert region, California, *in* Geology of southern California, edited by R. H. Jahns: California Div. Mines Bull. 170, v. 1, ch. 2, item 1, p. 5-20.

Jorgensen, L. N., Rose, M. A., Busch, R. D., and Bader, J. S., 1971, California streamflow characteristics: U.S. Geol. Survey open-file rept., 2 v., 1421 p.

Koebig and Koebig, Inc., 1962, Mojave Water Agency supplemental water report, Appendixes A, B, C, D: 69 p., app.

_____1965, Preliminary planning for Mojave Water Agency, alternate plans for distribution of imported water: 11 p.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1958, Hydrology for engineers: New York, McGraw-Hill Book Co., 340 p.

Meinzer, O. E., 1923, Outline of ground-water hydrology: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Miller, G. A., 1969, Water resources of the Marine Corps Supply Center area, Barstow, California: U.S. Geol. Survey open-file rept., 51 p.

Moreland, J. A., 1970, Artificial recharge, Yucaipa, California: U.S. Geol. Survey open-file rept., 44 p.

Moritz, E. A., 1952, Report on Victor project, California: U.S. Bur. Reclamation rept., 42 p.

Thompson, D. G., 1929, The Mohave Desert region, California, a geographic, geologic, and hydrologic reconnaissance: U.S. Geol. Survey Water-Supply Paper 578, 759 p.

Tyley, S. J., 1973, Artificial recharge in the Whitewater River area, Palm Springs: U.S. Geol. Survey open-file rept., 51 p.

U.S. Army Corps of Engineers, 1973, Reservoir regulation manual, Mojave River Dam, Mojave River basin, California: U.S. Army Corps of Engineers, Los Angeles, 23 p.

U.S. Geological Survey, 1960, Compilation of records of surface waters of the United States through September 1950, part 10, The Great Basin: U.S. Geol. Survey Water-Supply Paper 1314, 475 p.

_____1963, Compilation of records of surface waters of the United States, October 1950 to September 1960, part 10, The Great Basin: U.S. Geol. Survey Water-Supply Paper 1734, 311 p.

_____1961-68, Water resources data for California, part 1, Surface water records, volume 1: Colorado River basin, Southern Great Basin, and Pacific Slope Basins, excluding Central Valley: U.S. Geol. Survey annual repts., 1961, 448 p.; 1962, 479 p.; 1963, 463 p.; 1964, 498 p.; 1965, 470 p.; 1966, 482 p.; 1967, 488 p.; 1968, 498 p.

APPENDIX

DERIVATION OF A MATHEMATICAL MODEL OF FLOW IN THE MOJAVE RIVER

A mathematical model of the hydraulic behavior of the Mojave River channel was derived by combining the law of conservation of mass, an equation describing a relation between discharge and the cross-sectional area of flow, and an equation describing the loss of water from the channel due to infiltration into the channel bed (fig. A1). The phenomenon described by this model is similar to border irrigation in irrigation hydraulics, which has been described by previous investigators (Lewis and Milne, 1938; Philip and Farrell, 1964; Fok and Bishop, 1965; Chen, 1965; Wilke and Smerden, 1965; Hart and others, 1968; Kincaid, 1970; Singh and Chauhan, 1972; and Smith, 1972a). In most instances, these investigators described the response of the prototype using a nonlinear kinematic wave component and an infiltration equation that was based, at least partly, on a theoretical solution of the equation that describes the flow of water through porous media. The model derived herein consists of an infiltration equation, similar to those used by previous investigators, that is used in conjunction with a linear kinematic wave component.

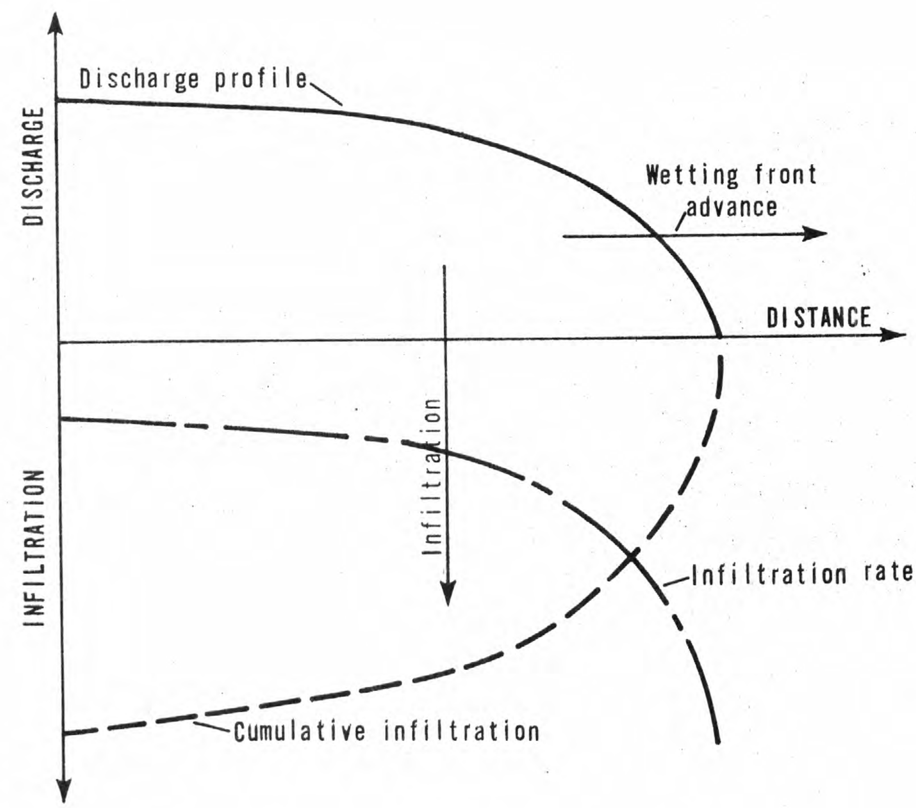


FIGURE A1.--Definition sketch for a model of the Mojave River.

A kinematic wave is described mathematically by an equation of continuity and by a single-valued stage-discharge relation (Lighthill and Whitham, 1955). The kinematic wave maintains the mass balance for the wave propagation. However, the description is based on the assumption that the momentum balance for the wave propagation can be disregarded. A nonlinear kinematic wave uses a nonlinear stage-discharge relation, and a linear wave uses a linear stage-discharge relation.

THE GOVERNING EQUATIONS

Channel Equations

The movement of a flood wave in an open channel can be described by a system of two simultaneous partial differential equations (Chow, 1959, p. 525-553). The first equation, the continuity equation, can be expressed as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + f(x,t) = 0 \tag{1}$$

where

Q is the local discharge (L^3T^{-1})
A is the cross-sectional area of flow (L^2)
$f(x,t)$ is the local lateral outflow (L^2T^{-1})
x is the distance along the channel (L)
t is the time (T).

The second equation, the dynamic equation, can be expressed as

$$\frac{\partial y}{\partial x} + \frac{V}{g}\frac{\partial V}{\partial x} - \frac{V}{gA} f(x,t) + \frac{1}{g}\frac{\partial V}{\partial t} - S_o - S_f = 0 \tag{2}$$

where

y is the water depth (L)
$V = Q/A$ is the local velocity (LT^{-1})
S_o is the channel-bed slope (L^0)
S_f is the friction slope (L^0)
g is acceleration due to gravity (LT^{-2})

and the other variables remain as before.

Considering the movement of a flood wave in an initially dry channel with a permeable bed, the quantity $f(x,t)$ is a dependent variable with a local value that is assumed herein to depend only on the time that has elapsed since the initial passing of the advancing wetting front in the channel. The solution to the problem of a flood wave in a channel with a permeable bed must be obtained by solving the system of simultaneous equations comprised of equations 1 and 2 and an appropriate infiltration equation.

However, due to the nonlinearity of these equations, analytic solutions cannot be obtained for generalized initial and generalized boundary conditions, and alternative methods of solution must be used. For this study, a solution was facilitated by using a linear kinematic approximation: The continuity equation was maintained but the dynamic equation was replaced with a discharge relation in which the local discharge is given by the linear function

$$Q = \alpha A \tag{3}$$

where α is a constant (LT^{-1}).

The important criterion for judging the validity of the linear kinematic approximation is whether or not the approximation leads to an acceptable model of the hydraulic behavior of the Mojave River. The linear kinematic approximation was introduced in order to reduce to a manageable level the mathematical complexity of the model. Fortunately, for floods in steep channels (slopes of 10 ft/mi or 1.89 m/km or more) that are greatly affected by lateral inflows or lateral outflows, the solution domain of the complete equations (eqs. 1 and 2) is dominated by the continuity equation (eq. 2), and acceptable results can be obtained from an otherwise invalid representation of the dynamic equation (eq. 1) (Lighthill and Whitham, 1955).

The linear kinematic approximation was tested by comparing a solution obtained from the complete equations (eqs. 1 and 2) with a solution obtained from the linear kinematic approximation (eqs. 1 and 3). However, a solution to the complete equations was not available for the boundary condition of lateral outflow, which has the dominant influence on flow in the Mojave River. In order to compare the results obtained from the two solutions, the comparison was made instead for the boundary condition of lateral inflow, for which a solution to the complete equations was available.

Figure A2 shows computed outflow hydrographs that were obtained from a solution of the complete equations and a solution of the linear kinematic approximation. The hydrographs represent the outflow resulting from the application of a lateral inflow to a wide rectangular channel. The lateral inflow hydrograph was sinusoidal in shape, with a base of 12 hours and a peak discharge of 0.0015 ft^2/s (0.00014 m^2/s). In addition, the channel had the following characteristics:

Length = 10,000 ft (3,048 m)
Slope = 10 ft/mi (1.89 m/km)
Chezy's friction coefficient = 50 ft$^{1/2}$/s (27.6 m$^{1/2}$/s)
Base discharge = 5 ft^3/s (0.14 m^3/s)

As indicated in figure A2, the linear kinematic approximation produced an outflow hydrograph with a higher translational velocity and higher peak discharge than the hydrograph obtained from the solution of the complete equations. However, the differences between these hydrographs were assumed, for this study, to be within acceptable limits of accuracy.

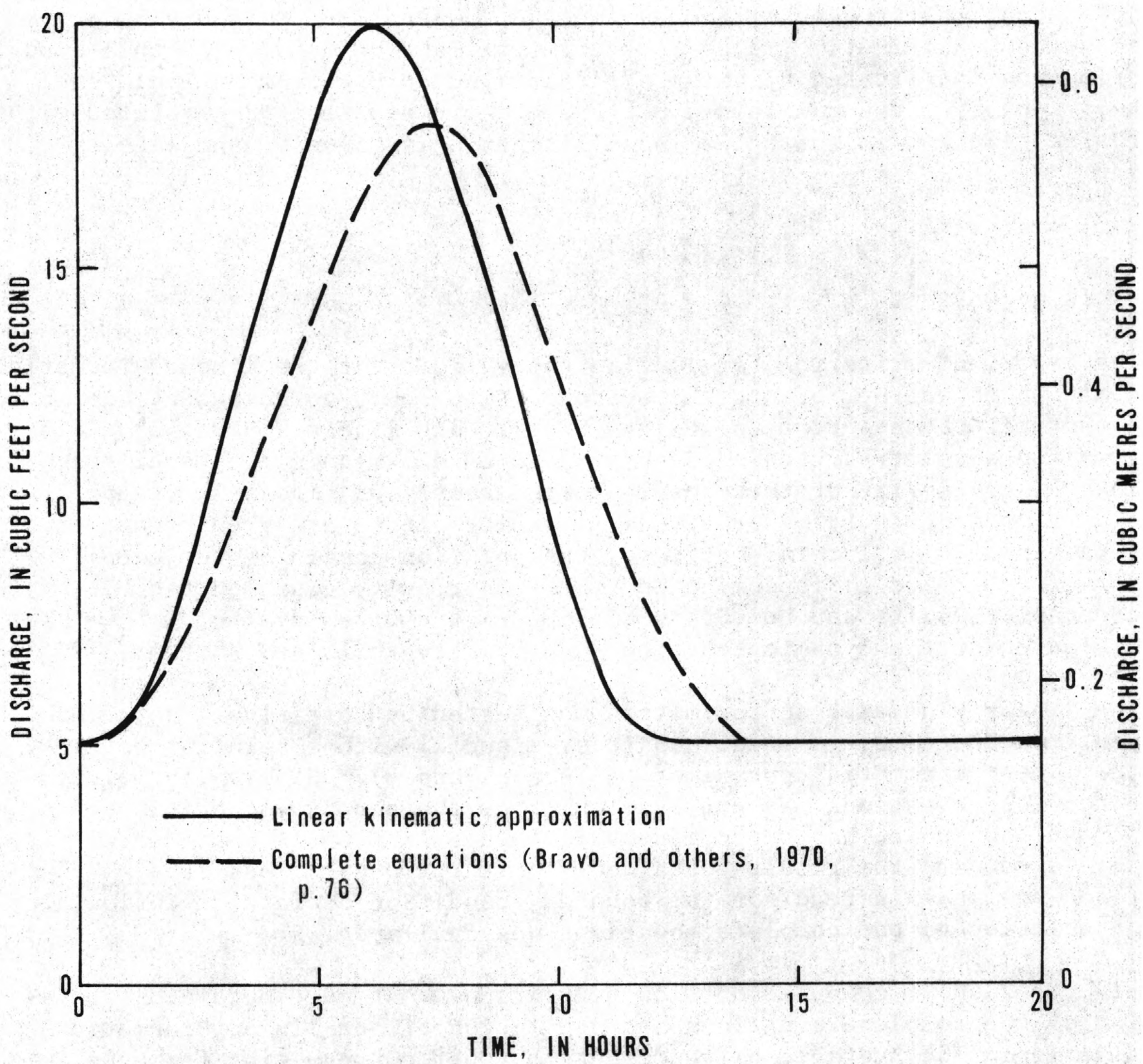


FIGURE A2.--Computed outflow hydrographs derived from solution of the linear kinematic approximation and the complete equations.

Infiltration Equation

The point infiltration rate through the channel bed was described by the relation

$$f'(x,t) = k'\tau^{-a} + f'_\infty \tag{4}$$

where

$f'(x,t)$ is the local infiltration rate (LT^{-1})

$\tau = t - t_w(x)$ is the elapsed time since the initial wetting of the channel bed (T)

$t_w(x)$ is the time of the initial wetting of the channel bed (T)

k' is an empirical coefficient (LT^{a-1})

a is an empirical exponent (L^0)

f'_∞ is asymptotic infiltration rate as $\tau \rightarrow \infty$ (LT^{-1}).

Equation 4, which is a modification of the Kostiakov equation (Kostiakov, 1932), was first proposed by Smith (1972b) and was successfully used by him to describe flow over an initially dry permeable plane (Smith, 1972a). A similar infiltration equation was used by Philip and Farrell (1964) to describe the same phenomenon.

The lateral outflow from the channel is related to the point infiltration rate by the expression

$$f(x,t) = pf'(x,t) = pk'\tau^{-a} + pf'_\infty \tag{5}$$

where p is the wetted perimeter of the cross-sectional area of flow (L). Equation 5 can be restated in the form

$$f(x,t) = k\tau^{-a} + f_\infty \tag{6}$$

where

$$k = pk' \tag{7}$$

and

$$f_\infty = pf'_\infty \tag{8}$$

The channel is assumed to be prismatic and to have a wide rectangular cross section, and p is assumed to have a constant value. Although the permeability of alluvial channels is known to change with discharge, streamflow velocity, and other factors (written commun., D. E. Burkham, 1973), the parameters k, f_∞, and a also are assumed to have constant values.

The general behavior of equation 6 is shown in figure A3. The infiltration rate is highest during the initial imbibition of moisture. However, as infiltrating water penetrates below the channel, the infiltration rate rapidly declines. Ideally the infiltration rate eventually approaches a steady-state value that is dependent on the vertical hydraulic conductivity of the geologic material underlying the channel and the rate at which ground water can move laterally away from the channel.

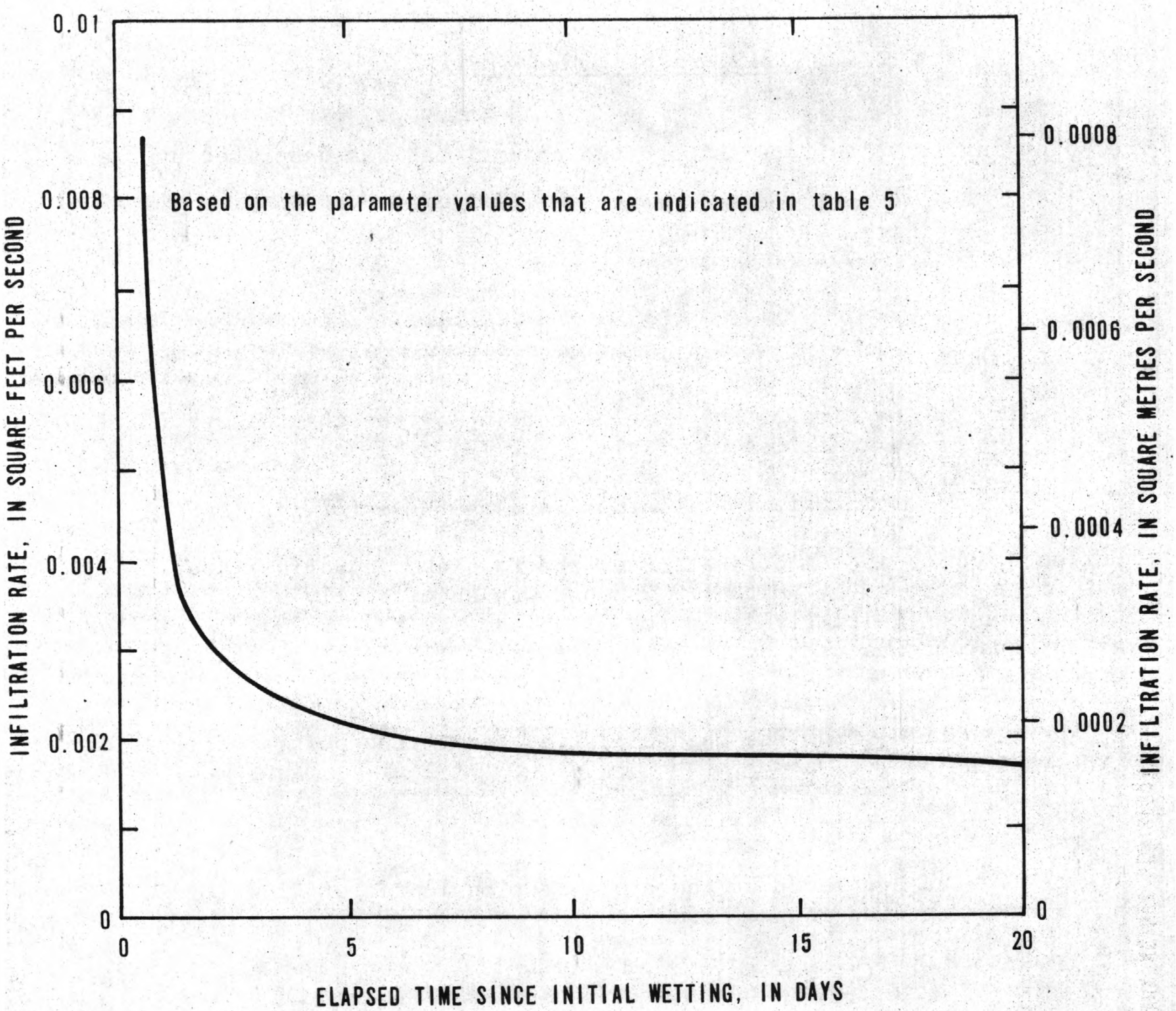


FIGURE A3.--General behavior of the infiltration equation.

SOLUTION OF THE GOVERNING EQUATIONS BY THE METHOD OF CHARACTERISTICS

Equations 1, 3, and 6 form the governing equation for a linear kinematic model of the advance of discharge down the initially dry channel of the Mojave River. The governing equations were solved by the method of characteristics. The basic rationale underlying the use of characteristics is that by an appropriate choice of coordinates the original system of partial differential equations can be replaced by a system of ordinary differential equations (Ames, 1965). As an example, a linear kinematic wave (Chow, 1959, p. 537) in a channel with an impermeable bed will travel through a reach without change in shape or velocity. To a stationary observer of the passage of the wave, stage and discharge vary both with distance from the observer and, at a fixed distance from the observer, with time. However, to an observer moving with the wave, stage and discharge do not vary, at a fixed distance from the observer, with time. In the latter case, the observer moves along a characteristic path, and the description of the solitary wave is greatly simplified. The essence of the characteristic method is to find the location of the characteristic paths and then to integrate the transformed governing equations along the characteristic to obtain a solution.

Determination of the Characteristic Equation

Stage and discharge discontinuities propagate along characteristics (Jeffrey and Taniuti, 1964, p. 100-110), and possible discontinuities may occur in the four partial derivatives of the dependent variables $\partial Q/\partial t$, $\partial Q/\partial x$, $\partial A/\partial t$, and $\partial A/\partial x$. This fact may be used to locate the characteristics (Ames, 1965, p. 418). The first step in locating the characteristics is to find four equations containing the four partial derivatives of the dependent variables. The first equation can be obtained from equation 1 rewritten as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = -f(x,t) \tag{9}$$

The second equation can be obtained by differentiating equation 3

$$\frac{\partial Q}{\partial t} - \alpha \frac{\partial A}{\partial t} = 0 \tag{10}$$

The third and fourth equations can be obtained from the definition of a total differential (Thomas, 1960, p. 689)

$$\frac{\partial Q}{\partial x}\, dx + \frac{\partial Q}{\partial t}\, dt = dQ \tag{11}$$

and

$$\frac{\partial A}{\partial x}\, dx + \frac{\partial A}{\partial t}\, dt = dA \tag{12}$$

Equations 9 through 12 can be expressed in matrix form as

$$\begin{bmatrix} 1 & 0 & 0 & 1 \\ -\alpha & 0 & 1 & 0 \\ 0 & 0 & dt & dx \\ dt & dx & 0 & 0 \end{bmatrix} \begin{bmatrix} \partial A/\partial t \\ \partial A/\partial x \\ \partial Q/\partial t \\ \partial Q/\partial x \end{bmatrix} = \begin{bmatrix} -f(x,t) \\ 0 \\ dA \\ dQ \end{bmatrix} \tag{13}$$

If the determinate of the matrix of coefficients in equation 13 is equal to zero, then the partial derivatives of the dependent variables are not determined uniquely, and possible discontinuities may occur in the partial derivatives (Ames, 1965, p. 418). Equating to zero the determinate of the matrix of coefficients (eq. 13), the characteristic equation is obtained as

$$\frac{dx}{dt} = \alpha \tag{14}$$

which can be integrated to yield the characteristics

$$x = \alpha t + \text{constant} \tag{15}$$

Equation 15 is a family of parallel lines with slope $1/\alpha$ in the x-t plane, where α represents the celerity of the wave propagation along the characteristic.

Determination of the Invariant Equation

The invariants of the solution (the description of the behavior of the wave along a characteristic) can be obtained as follows: The matrix of coefficients (eq. 13) is singular along a characteristic, and if any bounded values are to exist for the partial derivatives of the dependent variables, the vector of right-hand sides (eq. 13) must be compatible with this singularity (Ames, 1965, p. 421). The determinate formed by substituting the vector of right-hand sides for any column of the matrix of coefficients must also vanish. Upon equating this determinate to zero, the invariant equation is

$$\frac{dA}{dt} = - f(x,t) \tag{16}$$

or, since from equation 3

$$\alpha \frac{dA}{dt} = \frac{dQ}{dt} \tag{17}$$

then

$$\frac{dQ}{dt} = - \alpha f(x,t) \tag{18}$$

Equation 18 applies along the characteristics defined by equation 15.

Construction of the Solution

The characteristic solution can be constructed on the x-t plane as it is shown in figure A4. Construction of the characteristic proceeds from the upstream boundary, where discharge is specified, to the wetting front. In the region to the right of the locus of the wetting front advance (fig. A4), discharge in the channel equals zero.

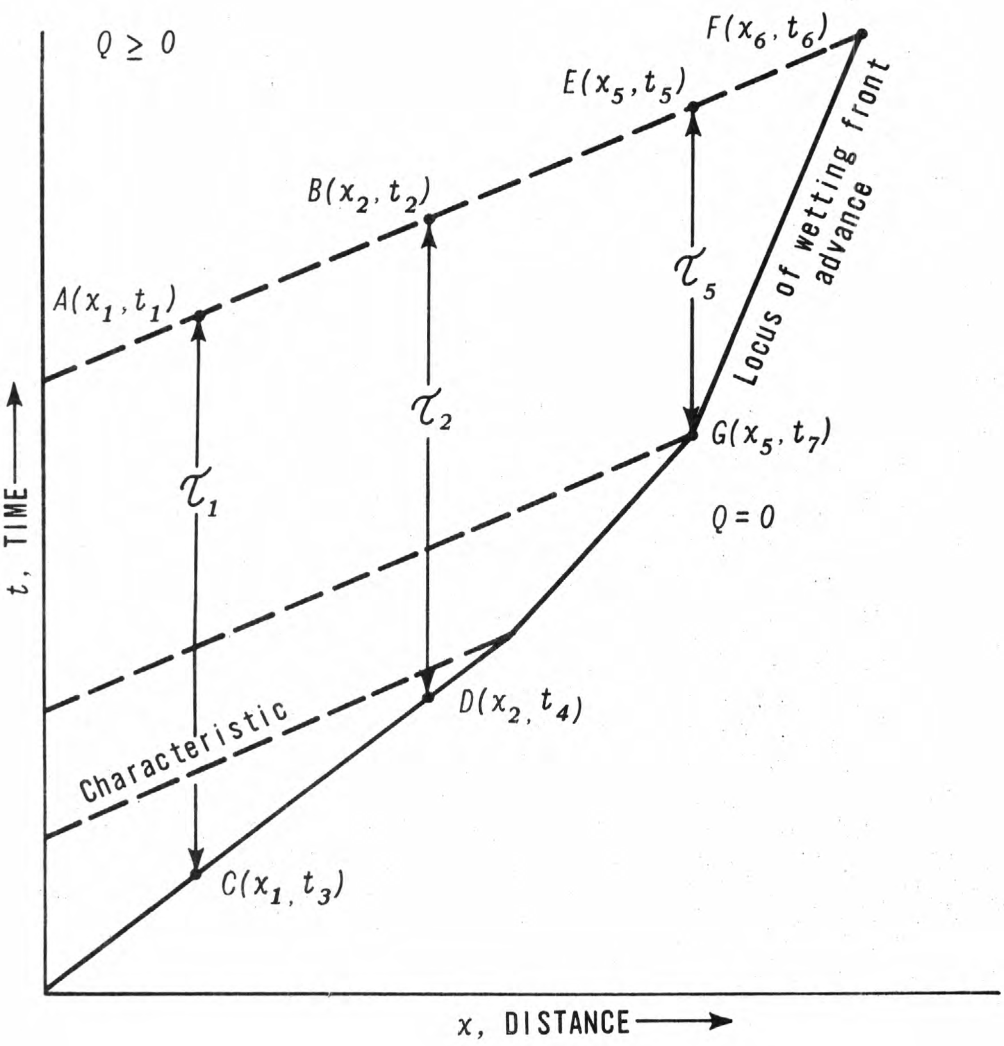


FIGURE A4.--Sketch for the construction of the solution of the wetting front advance by the method of characteristics.

Two cases in the solution for new points on the x-t plane arise: One for the extension of the characteristic behind and independent of the advancing wetting front, and another for the location of the intersection of a characteristic and the advancing wetting front.

Consider the first case: We seek the discharge Q_2 at point $B(x_2,t_2)$ in figure A4. Let the known discharge at point $A(x_1,t_1)$ be Q_1. Also, let the locus of the wetting front advance pass through points $C(x_1,t_3)$ and $D(x_2,t_4)$ such that

$$t_3 < t_1$$

and

$$t_4 < t_2$$

The locus of the wetting front advance is assumed to be represented by a straight line between points $C(x_1,t_3)$ and $D(x_2,t_4)$. The invariant equation (eq. 18)

$$\frac{dQ}{dt} = - \alpha f(x,t)$$

can be integrated to yield

$$\int_{Q_1}^{Q_2} dQ = - \alpha \int_{t_1}^{t_2} f(x,t)\,dt \tag{19}$$

or, upon substitution of equation 6 for $f(x,t)$ in equation 19

$$Q_2 - Q_1 = - \alpha \int_{t_1}^{t_2} (k\tau^{-a} + f_\infty)\,dt \tag{20}$$

where τ is the elapsed time since the initial passing of the wetting front (fig. A4). The integral in equation 20 can be evaluated to yield the relation for Q_2

$$Q_2 = Q_1 - \alpha(t_2 - t_1)\left[f_\infty + \left(\frac{k}{1-a}\right)\left(\frac{\tau_2^{1-a} - \tau_1^{1-a}}{\tau_2 - \tau_1}\right)\right] \tag{21}$$

where

$$\tau_1 = t_1 - t_3 \tag{22}$$

and

$$\tau_2 = t_2 - t_4 \tag{23}$$

Consider the second case: We seek the intersection at point $F(x_6,t_6)$ in figure A4 of the locus of the wetting front advance with the extension of the characteristic passing through point $E(x_5,t_5)$. Let the known discharge at point $E(x_5,t_5)$ be Q_5. Also let the locus of the wetting front advance pass through point $G(x_5,t_7)$ and be represented by a straight line between point $G(x_5,t_7)$ and $F(x_6,t_6)$. The advance of the wetting front down the channel is well approximated in many cases as a shock wave or flow discontinuity (Smith, 1972a). However, if the advance of the wetting front represents only a small part of the solution domain of equations 1 and 3, the advance of the wetting front probably can be approximated as a smooth wave, without introducing significant error into the overall solution. This hypothesis, though untested, has been accepted for this study. Thus, at point $F(x_6,t_6)$ the discharge Q_6 necessarily vanishes, and equation 21 can be written as

$$t_6 = t_5 + \frac{Q_5}{\alpha\left(f_\infty + \frac{k}{1-a}\,\tau_5^{\,-a}\right)} \tag{24}$$

where

$$\tau_5 = t_5 - t_7 \tag{25}$$

The distance to the locus of the wetting front advance, x_6, at time t_6 can be determined from equation 15 such that

$$x_6 = x_5 + \frac{(t_6 - t_5)}{\alpha} \tag{26}$$

Equations 21, 24, and 26 are the basic components of a linear kinematic model of the advance of discharge down the initially dry channel of the Mojave River. The general behavior of the model is shown in figure A5.

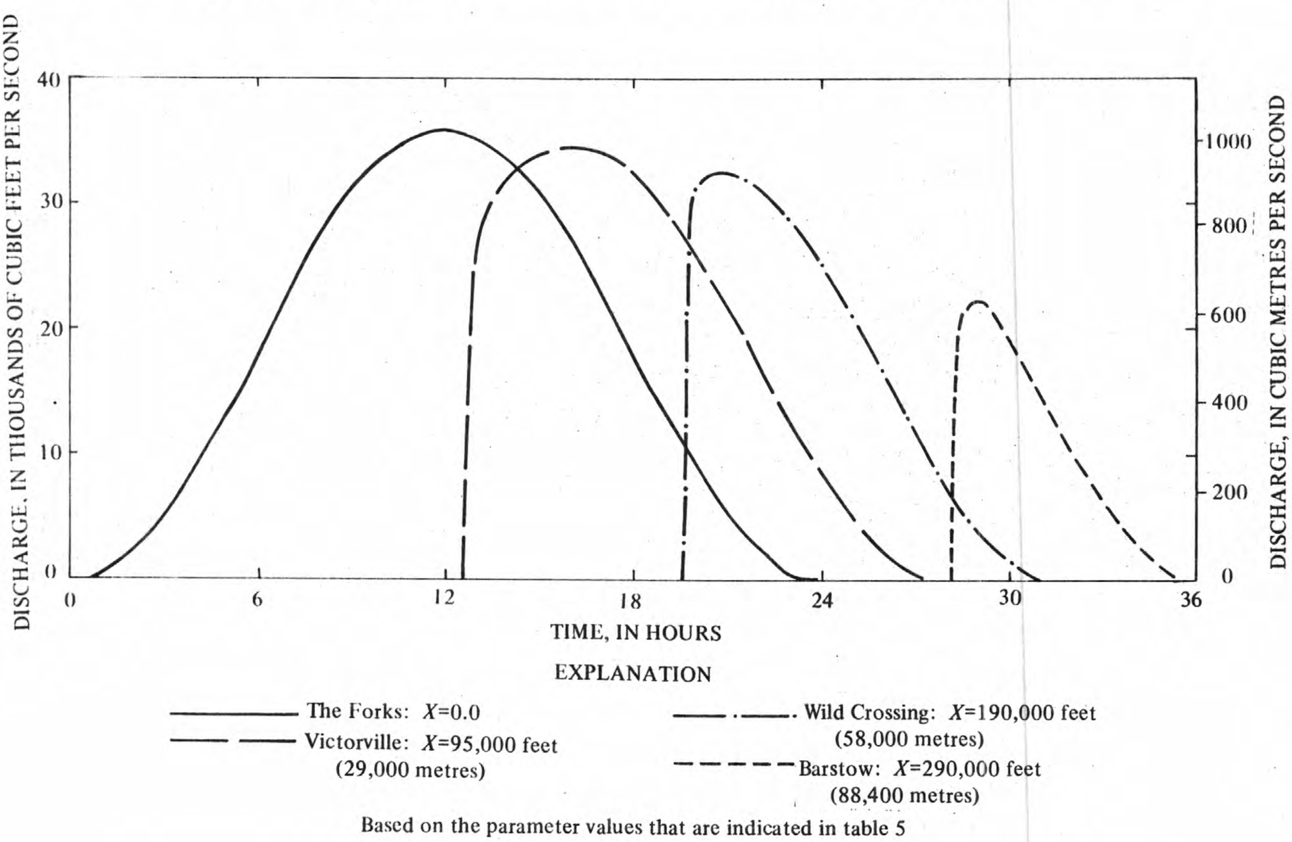


FIGURE A5.--Hydrographs showing general behavior of the model.

REFERENCES CITED

Ames, W. F., 1965, Nonlinear partial differential equations in engineering: New York, Academic Press, 510 p.

Bravo, C. A., Harley, B. M., Perkins, F. E., and Eagleson, P. S., 1970, A linear distributed model of catchment runoff: Massachusetts Inst. Technology, Hydrodynamics Lab. rept. no. 123, 147 p.

Chen, C. L., 1965, Techniques of border irrigation by a hydrologic method of routing: Water Research Lab., Utah State Univ., rept. PR-Wr11-1, 30 p.

Chow, Ven Te, 1959, Open-channel hydraulics: New York, McGraw-Hill, 680 p.

Fok, Y. S., and Bishop, A. A., 1965, Analyses of water advance in surface irrigation: Am. Soc. Civil Engineers, Irrig. Div. Jour. v. 91, no. IR1, p. 99-116.

Hart, W. E., Bassett, D. L., and Strelkoff, T., 1968, Surface irrigation hydraulics--kinematics: Am. Soc. Civil Engineers, Irrig. Div. Jour. v. 94, p. 419-440.

Jeffrey, A., and Taniuti, T., 1964, Nonlinear wave propagation: New York, Academic Press, 369 p.

Kincaid, D. C., 1970, Hydrodynamics of border irrigation: Ph. D. dissertation, Colorado State Univ., 190 p.

Kostiakov, A. R., 1932, On the dynamics of the coefficient of water percolation in soils and on the necessity for studying it from a dynamic point of view for purposes of amelioration: Trans. 6th Comm. Internat. Soc. Soil Sci., pt. A, p. 17-21.

Lewis, M. R., and Milne, W. E., 1938, Analyses of border irrigation: Agr. Eng., no. 19, p. 267-272.

Lighthill, M. J., and Whitham, G. B., 1955, On kinematic waves, I. Flood movement in long rivers: Royal Soc. [London] Proc., ser. A, v. 229, p. 281-316.

Philip, J. R., and Farrell, D. A., 1964, General solution of the infiltration-advance problem in irrigation hydraulics: Jour. Geophys. Research, v. 69, no. 4, p. 621-631.

Smith, R. E., 1972a, Border irrigation advance and ephemeral flood waves: Am. Soc. Civil Engineers, Irrig. Div. Jour., v. 98, no. IR2, p. 289-308.

_____1972b, The infiltration envelope; results from a theoretical infiltrometer: Jour. Hydrology, v. 17, p. 1-21.

Singh, Pratop, and Chauhan, H. S., 1972, Shape factors in irrigation water advance equation: Am. Soc. Civil Engineers, Irrig. Div. Jour., v. 98, no. IR3, p. 443-458.

Thomas, G. B., 1960, Calculus and analytic geometry: Palo Alto, Calif., Addison-Wesley, 1007 p.

Wilke, Otto, and Smerden, E. T., 1965, A solution of the irrigation advance problem: Am. Soc. Civil Engineers, Irrig. Div. Jour., v. 91, no. IR3, p. 23-34.