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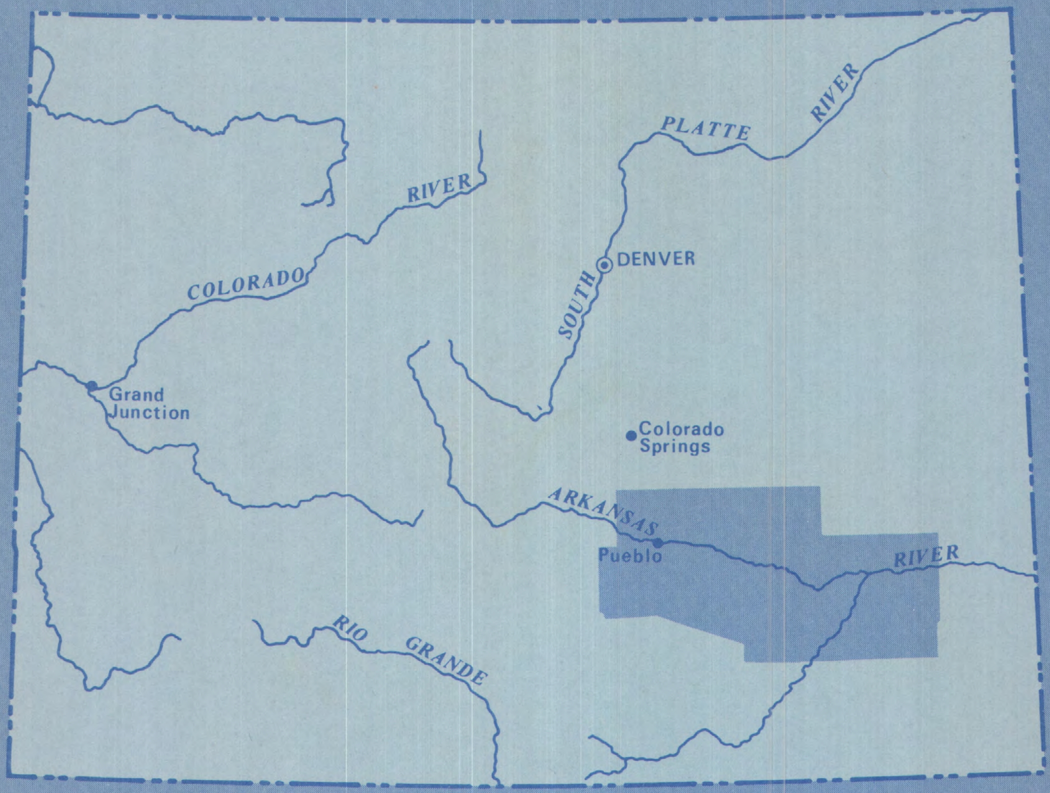
TRANSIT LOSSES AND TRAVELTIMES OF RESERVOIR RELEASES ALONG THE ARKANSAS RIVER FROM PUEBLO RESERVOIR TO JOHN MARTIN RESERVOIR, SOUTHEASTERN COLORADO

U.S. GEOLOGICAL SURVEY



Water Resources Investigations 78-75

...ared in cooperation with the
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16. Abstracts The volumes of reservoir releases are decreased or delayed during transit by bank storage, channel storage, and evaporation. Results from a computer model, calibrated by a controlled-test release from Pueblo Reservoir, indicate that transit losses are greatest for small releases of a short duration when made during periods of low antecedent streamflow. For equivalent releases, transit losses during the winter are about 7 percent less than losses during the summer.

Based on available streamflow records, the velocity of reservoir releases ranges from about 0.6 mile per hour at the downstream end of the study reach when antecedent streamflow is 10 cubic feet per second, to about 6.8 miles per hour at the upstream end of the study reach when antecedent streamflow is 3,000 cubic feet per second. Consequently, the traveltime of a release increases as antecedent streamflow diminishes.

Management practices that may be used to benefit water users include selection of the optimum time, rate, and duration of a reservoir release to minimize the transit losses, determination of an accurate traveltime, and diversion at several incremental rates.

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Southeastern Colorado Water Conservancy District

September 1978

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U.S. customary units in this report may be expressed as metric units by use of the following conversion factors:

Multiply U.S. customary unit	*By*	*To obtain metric unit*
inch (in.)	25.40	millimeter
foot (ft)	.3048	meter
foot per second (ft/s)	.3048	meter per second
mile (mi)	1.6093	kilometer
hour per mile (h/mi)	1.6093	hour per kilometer
cubic foot per second (ft^3/s)	.02832	cubic meter per second
acre-foot (acre-ft)	.001233	cubic hectometer
foot squared per day	.09290	meter squared per day
square foot	.09290	square meter

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By Russell K. Livingston

ABSTRACT

The need for accurate information regarding the transit losses and traveltimes associated with releases from Pueblo Reservoir has been stimulated by construction of the U.S. Bureau of Reclamation's Fryingpan-Arkansas Project and a proposed winter-water storage program in Pueblo Reservoir. To meet this need, the U.S. Geological Survey, in cooperation with the Southeastern Colorado Water Conservancy District, studied the Arkansas River from Pueblo Reservoir to John Martin Reservoir, a distance of 142 river miles.

The volumes of reservoir releases are decreased or delayed during transit by bank storage, channel storage, and evaporation. Results from a computer model, calibrated by a controlled-test release from Pueblo Reservoir, indicate transit losses are greatest for small releases of short duration that are made during periods of low antecedent streamflow. For equivalent releases, transit losses during the winter are about 7 percent less than losses during the summer.

Based on available streamflow records, the traveltime of reservoir releases in the study reach ranges from about 1.67 hours per mile at the downstream end of the study reach when antecedent streamflow is 10 cubic feet per second, to about 0.146 hour per mile at the upstream end of the study reach when antecedent streamflow is 3,000 cubic feet per second. Consequently, the traveltime of a release increases as antecedent streamflow diminishes.

Management practices that may be used to benefit water users in the study area include selection of the optimum time, rate, and duration of a reservoir release to minimize the transit losses, determination of an accurate traveltime, and diversion at several incremental rates.

INTRODUCTION

From Pueblo Dam to John Martin Dam, a distance of 142 river miles, the sandy channel of the Arkansas River meanders across a broad flood plain. Due to diversions for irrigation, the mean annual flow in this reach ranges from about 536,000 acre-ft at Pueblo Dam to about 182,000 acre-ft at John Martin Reservoir. More than 80 percent of the annual flow occurs during the principal irrigation season, April through September.

Throughout the study reach, the Arkansas River traverses an alluvial aquifer. This aquifer ranges from 0.3 mi to about 6 mi wide, is as much as 300 ft thick, and consists of gravel, sand, silt, and clay. Water pumped from more than 1,000 wells tapping the aquifer is used primarily for irrigation to supplement surface-water supplies and a seasonal precipitation of about 8 in.

Irrigation water is also obtained from 12 major canals that divert water from the Arkansas River between Pueblo Dam and John Martin Dam. These canals divert an average of 650,000 acre-ft annually. They are administered according to the prior-appropriation doctrine by the Office of the Colorado State Engineer.

Purpose and Scope

Colorado water law allows water users to transport their water in natural river channels from upstream storage reservoirs to a downstream delivery point provided allowances are made for transit losses (Radosevich and Hamburg, 1971). A transit loss of 0.07 percent of the reservoir release per mile of river length was established by court action for transmountain water delivered along the Arkansas River in Colorado (Sunnyside Park Ditch vs. M. S. Hinderlider, State Engineer; Court Case No. 3345; 1944-45). The transit loss for all water deliveries along the Arkansas River in Colorado is determined by the Division Engineer, Office of the Colorado State Engineer, who generally uses 0.07 percent per mile except during unusually low river conditions. The construction of Pueblo Reservoir near Pueblo (total storage capacity, 357,000 acre-ft) as part of the U.S. Bureau of Reclamations's Fryingpan-Arkansas Project together with the associated increase in transmountain diversions of water into the Arkansas River basin and proposed program of winter-water storage have increased the need for more definitive information with regard to transit losses and traveltimes of reservoir releases along the lower Arkansas River in Colorado.

In July 1974, the U.S. Geological Survey, in cooperation with the Southeastern Colorado Water Conservancy District, began a study to determine the transit losses and traveltimes associated with deliveries of reservoir water along the Arkansas River from Pueblo Reservoir near Pueblo to John Martin Reservoir near Las Animas, Colo. (fig. 1). The purpose of this report is to describe the results of that study.

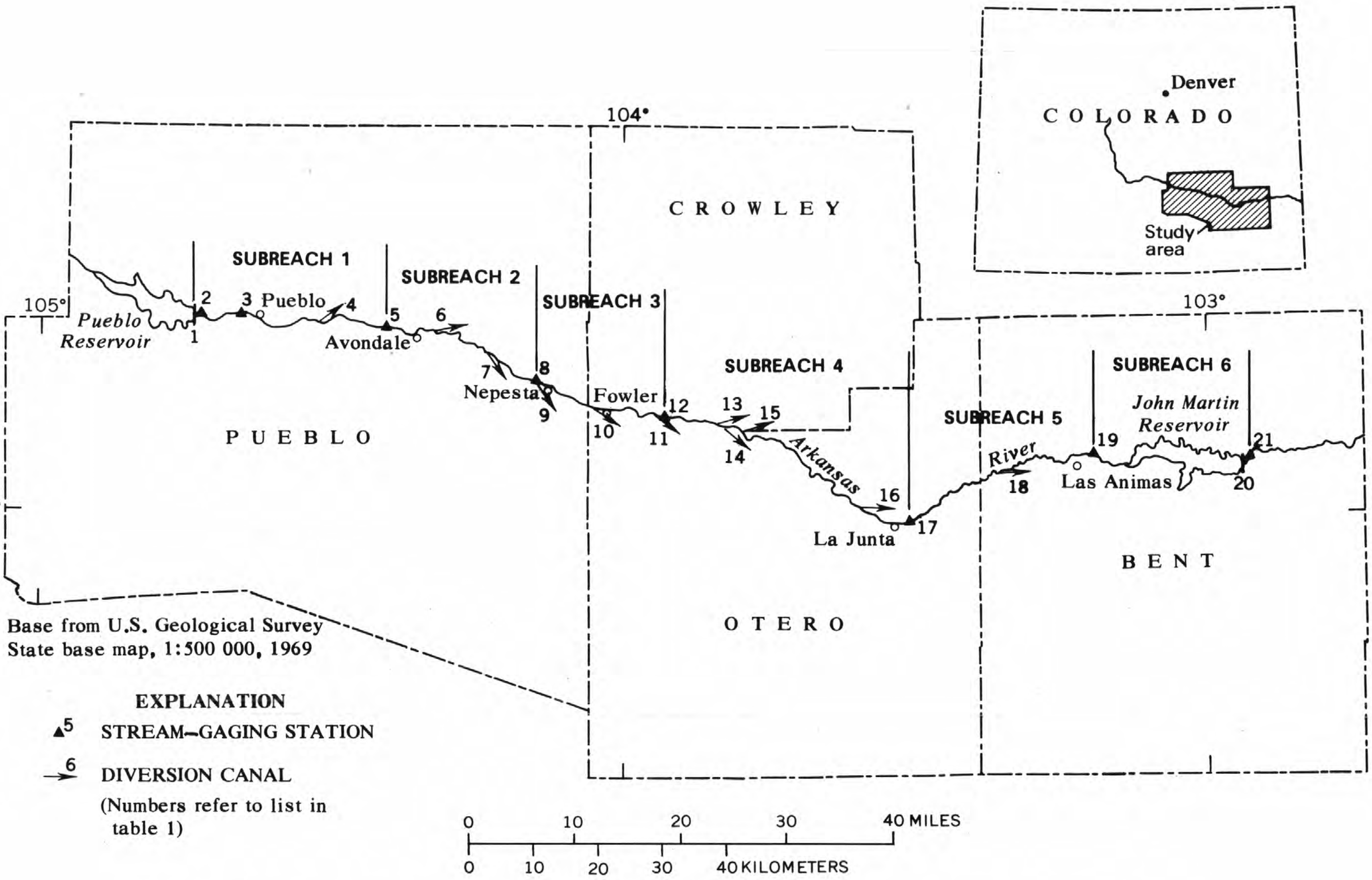

Figure 1.--Location of stream-gaging stations, diversion canals, and subreaches.

Acknowledgments

The author is grateful to the various canal companies in the study area who contributed a portion of their direct-flow water right to provide the water necessary for the controlled-test release of September 22, 1975. The Colorado Division of Water Resources, Office of the Division Engineer, cooperated in the planning of the controlled-test release and provided personnel who assisted with the collection of streamflow data during the release. Many helpful suggestions regarding the study were made by Charles L. Thomson, Manager of the Southeastern Colorado Water Conservancy District.

HYDROLOGIC MODEL FOR ROUTING RESERVOIR RELEASES

Historically, streamflow data for the Arkansas River have been collected at a minimum of 13 locations along the study reach. Eight continuous-record gaging stations on the main stem and numerous rating-flume stations on diversion ditches are currently in operation.

Available streamflow data are inadequate for determining transit losses for releases from Pueblo Reservoir. Prior to the beginning of storage in Pueblo Reservoir in 1974, releases were made from reservoirs located about 150 river miles upstream from Pueblo and the release volumes were difficult to distinguish from the natural flow downstream from Pueblo. Moreover, releases usually do not provide adequate data because of changing hydrologic conditions in the study reach. Consequently, transit losses are best investigated by theoretical methods using a hydrologic model.

A hydrologic model is a mathematical simulation of the response of a hydrologic system to various stresses placed on it. An example of such a stress is the passage of a reservoir release through a stream system. By employing a digital computer, the numerous calculations necessary to describe the hydrologic response of the system can be rapidly performed. Thus, the computer model, following calibration with observed data, can be used to simulate the effects of various hydrologic conditions.

Modification of Original Computer Model

A computer model that simulates the hydrologic response of a river reach to reservoir releases passing through it was developed and tested using data for the Arkansas River upstream from the Colorado Canal (Luckey and Livingston, 1975). The assumption was made that this model could also simulate stream hydrographs of reservoir releases in the study reach from Pueblo Reservoir to John Martin Reservoir. To adequately define the hydrologic system and to improve model response, this reach was subdivided into six subreaches as shown on figure 1. The name and river-mile location of the streamflow-gaging stations and diversion canals shown on figure 1 are listed in table 1. In order to adapt the original computer model for the somewhat different hydrologic response of the study reach to reservoir releases, several modifications were made, as described in the following sections.

Table 1.--*River-mile distances from Pueblo Reservoir downstream to selected sites along the study reach*

Site number[1]	Site name	River mile downstream from Pueblo Dam[2]
1	Pueblo Dam--	0.0
2	Arkansas River above Pueblo stream-gaging station, U.S. Geological Survey station 07099400----------	0.3
3	Arkansas River near Pueblo stream-gaging station (Northside Waterworks diversion), U.S. Geological Survey station 07099500-------------------------	5.0
4	Excelsior Canal headgate---------------------------	16.0
5	Arkansas River near Avondale stream-gaging station, U.S. Geological Survey station 07109500----------	23.6
6	Colorado Canal headgate----------------------------	29.8
7	Highline Canal headgate----------------------------	35.6
8	Arkansas River near Nepesta stream-gaging station, U.S. Geological Survey station 07117000----------	42.2
9	Oxford Canal headgate------------------------------	42.8
10	Otero Canal headgate-------------------------------	54.6
11	Catlin Canal headgate------------------------------	61.0
12	Arkansas River at Catlin Dam stream-gaging station, U.S. Geological Survey station 07119700----------	63.4
13	Holbrook Canal headgate----------------------------	68.5
14	Rocky Ford Canal headgate--------------------------	70.0
15	Fort Lyon Storage Canal headgate-------------------	71.0
16	Fort Lyon Canal headgate---------------------------	89.6
17	Arkansas River at La Junta stream-gaging station, U.S. Geological Survey station 07123000----------	94.4
18	Las Animas Consolidated Canal headgate-------------	110.8
19	Arkansas River at Las Animas stream-gaging station, U.S. Geological Survey station 07124000----------	121.4
20	John Martin Dam------------------------------------	[3]142.2
21	Arkansas River below John Martin Reservoir stream-gaging station, U.S. Geological Survey station 07130500---	142.4

[1]Location shown on figure 1.

[2]River miles are for site locations as of January 1976. Determinations are from Pueblo Dam downstream to simplify transit loss and traveltime computations and, therefore, have no relation to river-mile determinations of the U.S. Bureau of Reclamation or the U.S. Army, Corps of Engineers.

[3]Represents river mile with little or no water storage in John Martin Reservoir; effective river mile about 139 at other times.

River Evaporation

A reservoir release causes an increase in the surface area of a river and, therefore, results in additional evaporation losses from the river. Because earlier studies of transit loss had determined this evaporation loss to be only about 6 percent of the total transit loss (Livingston, 1973), it was not included in the original computer model. In contrast to the upstream reach, the Arkansas River downstream from Pueblo is generally much broader and slower moving, and traverses an area characterized by generally warmer temperatures and frequent winds. For this reason, river evaporation was expected to be more significant in the study reach, and suitable modifications to the model were required.

The basic steady-state flow equation is:

$$Q=A\bar{V}=W\bar{D}\bar{V}, \tag{1}$$

or

$$W=Q/\bar{D}\bar{V}, \tag{2}$$

where:

Q=discharge, in cubic feet per second;
A=area, in square feet;
$\bar{V}$=average velocity, in feet per second;
W=width, in feet; and
$\bar{D}$=average depth, in feet.

Analysis of numerous discharge measurements made along the study reach indicated a correlation coefficient of 0.99 between Q and product $\bar{D}\bar{V}$. This relationship is:

$$\bar{D}\bar{V}=0.69+0.0048Q. \tag{3}$$

Equation 2 can then be written as:

$$\bar{W}=Q/(0.69+0.0048Q), \tag{4}$$

and used to estimate river width for any flow in the study reach.

The original computer model was modified to compute the change in river evaporation losses resulting from a reservoir release, based on the increase in average river width from equation 4, the river-mile length of the subreach, and the average evaporation rate for the month the release is made. To determine the average monthly evaporation rate, it was assumed that river and lake evaporation are about the same in the study reach. The average lake evaporation rate is 6.0 in. per month or 2.00×10^{-7} ft/s during May through October and 2.7 in. per month or 0.86×10^{-7} ft/s during November through April (U.S. Weather Bureau, 1959).

Antecedent Streamflow and Stage-Discharge Relations

The flow of the upper Arkansas River is fairly uniform and predictable; therefore, antecedent subreach streamflow in the original model was estimated from flow at index stations. Streamflows at the upstream and downstream ends (nodes) of a subreach downstream from Pueblo Reservoir are frequently very different and unpredictable. As a result, the original computer model was modified to require antecedent streamflow as input at all nodes.

The computer model also requires stage-discharge information at both ends of each subreach. In order to add flexibility to the model and to recognize that individual ratings at gaging stations may not be representative of an entire subreach, *average* stage-discharge relations were used in the individual modified computer model. For example, the individual ratings for *both* the gages above Pueblo and near Avondale were combined into a single average relation that was used for both of those nodes. In the same manner, average stage-discharge relations were developed from ratings for the gages near Nepesta and at Catlin Dam, and for the gages at La Junta, at Las Animas, and below John Martin Reservoir. The resulting relations used for the seven nodes in the model are shown in table 2.

Inadvertent Diversions and Traveltime

Those parts of the original computer model dealing with inadvertent diversions and traveltime were removed from the modified version of the model. Due to the types of diversion structures in the study reach, inadvertent diversions are not a significant source of transit loss. Rather than being estimated with theoretical relationships, traveltime information was derived from historic data, as discussed in a later section of this report.

Determination of Aquifer and River-Channel Characteristics

The hydrologic model used in this study requires values for several aquifer and river-channel characteristics that are described in detail by Luckey and Livingston (1975). These characteristics are aquifer transmissivity, aquifer-storage coefficient, channel-storage coefficient, and length of alluvium. The model also requires the length of river for evaporation accounting purposes. These data (table 3) were determined for each subreach based on previous ground-water investigations in the Arkansas River valley (Jenkins, 1968; Major, Hurr, and Moore, 1970; Hurr and Moore, 1972; Konikow and Bredehoeft, 1974; Taylor and Luckey, 1974), on channel configuration shown on the most recent topographic maps, and on analysis of preliminary model results.

Table 2.--*Stage-discharge relations used in computer model of the Arkansas River from Pueblo Reservoir to John Martin Reservoir*

Site number[1]	Site name	Discharge, in cubic feet per second, for indicated stage, in feet									
		2.0	2.1	2.2	2.4	2.6	2.8	3.0	4.0	5.0	6.0
2	Arkansas River above Pueblo (node 1)------------------	0	20	41	88	142	200	270	780	1,600	3,000
5	Arkansas River near Avondale (node 2)------------------	0	20	41	88	142	200	270	780	1,600	3,000
8	Arkansas River near Nepesta (node 3)------------------	0	9.0	18	38	62	90	120	500	1,400	3,000
12	Arkansas River at Catlin Dam (node 4)--------------	0	9.0	18	38	62	90	120	500	1,400	3,000
17	Arkansas River at La Junta (node 5)------------------	0	1.5	3.5	9.5	22	50	92	550	1,400	3,000
19	Arkansas River at Las Animas (node 6)------------------	0	1.5	3.5	9.5	22	50	92	550	1,500	3,000
21	Arkansas River below John Martin Reservoir (node 7)-	0	1.5	3.5	9.5	22	50	92	550	1,500	3,000

[1]Locations shown by site number on figure 1.

Table 3.--*Aquifer and river-channel characteristics used in computer model of the Arkansas River from Pueblo Reservoir to John Martin Reservoir*

Subreach[1]	Transmissivity of aquifer, in feet squared per day	Storage coefficient of aquifer (dimensionless)	Storage coefficient of channel, in hours	Length of alluvium, in miles	Length of river, in miles
1	10,000	0.10	1.6	14	24
2	10,000	.10	1.3	10	18
3	12,000	.10	1.5	12	21
4	11,000	.12	1.9	19	31
5	10,000	.15	1.8	15	27
6	9,000	.15	1.4	15	21

[1]See figure 1 for location of subreach.

Calibration of Modified Computer Model

Recognizing the importance of the model-calibration phase of the study, the major ditch companies in the study reach contributed a portion of their direct-flow water right to provide the 1,000 acre-ft of water necessary for a controlled-test release from Pueblo Reservoir. After the streamflow at Pueblo had been stabilized for 2 days at 200 ft^3/s, the controlled-test release of 100 ft^3/s for 5 days was made beginning on September 22, 1975. During the following 10 days, time for the release to pass through the study reach, changes in diversion outflow and tributary inflows were minimized to simplify interpretation of system response to the test release. In addition to the data normally collected at the gaging stations and diversion canals, about 100 streamflow-discharge measurements and 150 ground-water-level measurements were made.

Following analysis of all the information collected during the controlled-test release, streamflow hydrographs simulated by the computer model were compared with streamflow hydrographs from data measured by the gaging stations located at the end of each subreach (see figs. 2-7). The volumes of the simulated-release hydrographs ranged from -4.5 to +8.4 percent of the volumes measured at the stream-gaging stations. The sudden temporary decrease in streamflow on September 24 at the stream-gaging station downstream from the Catlin Dam (fig. 4) is the result of canal sluicing, the diverted flow being returned to the river downstream from the gage. The apparent irregularities in the hydrographs for the stream-gaging stations near Nepesta (fig. 3) and at La Junta (fig. 5) could not be explained by operations of canals, changes in tributary flows, or interpretation of gage records of river stage.

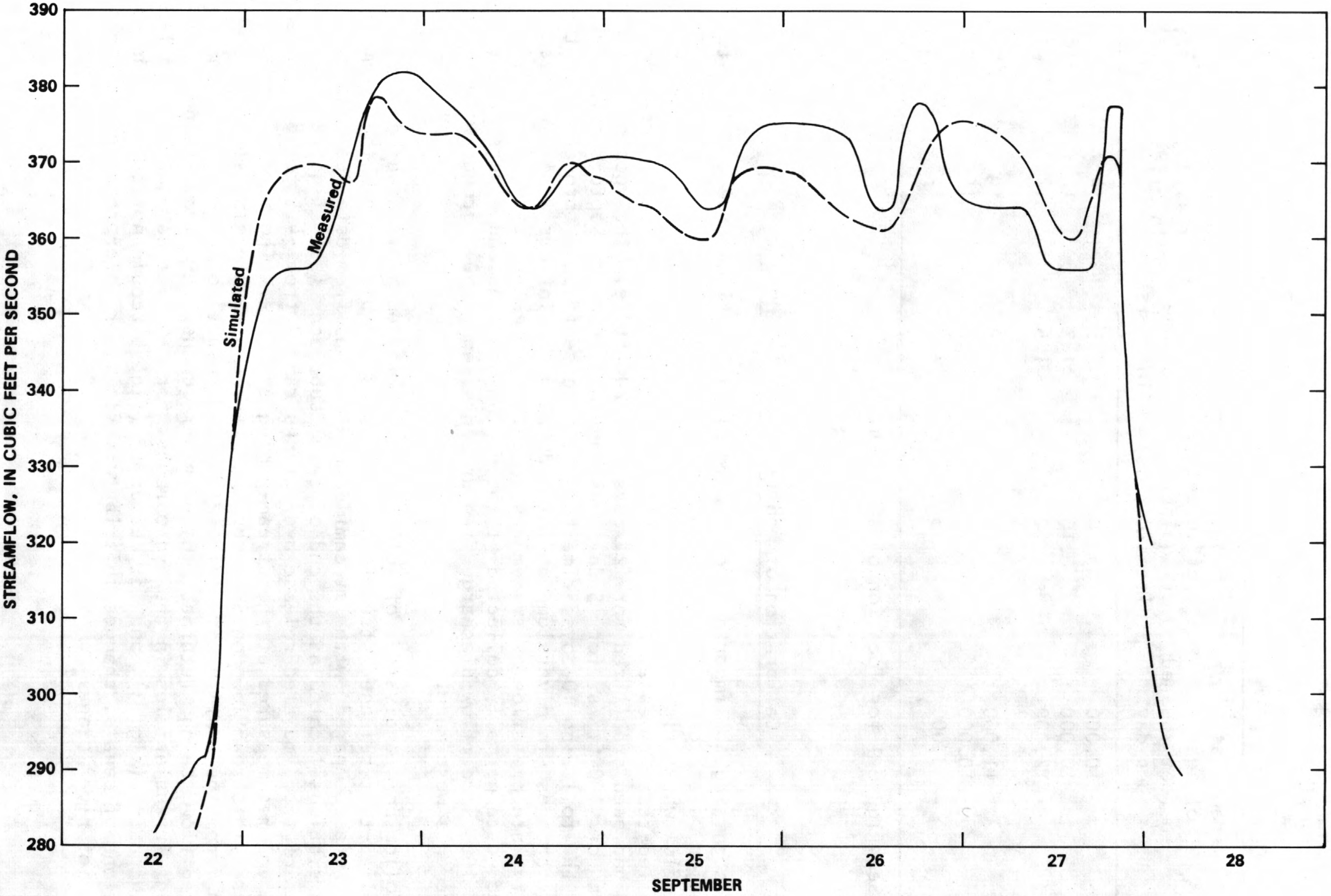

Figure 2.--Measured and simulated streamflow at the Arkansas River near Avondale stream–gaging station, September 22–28, 1975.

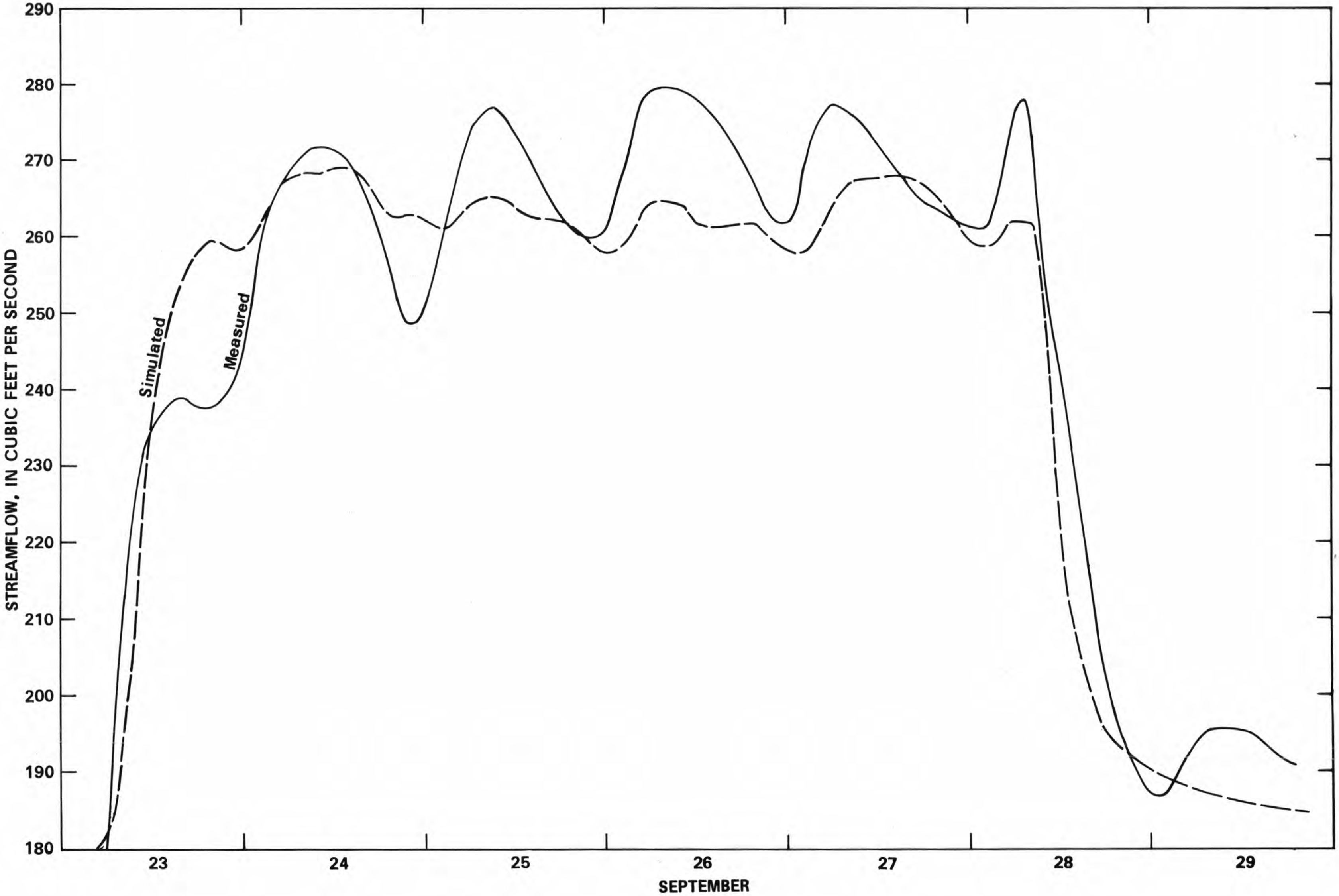

Figure 3.--Measured and simulated streamflow at the Arkansas River near Nepesta stream-gaging station, September 23-29, 1975.

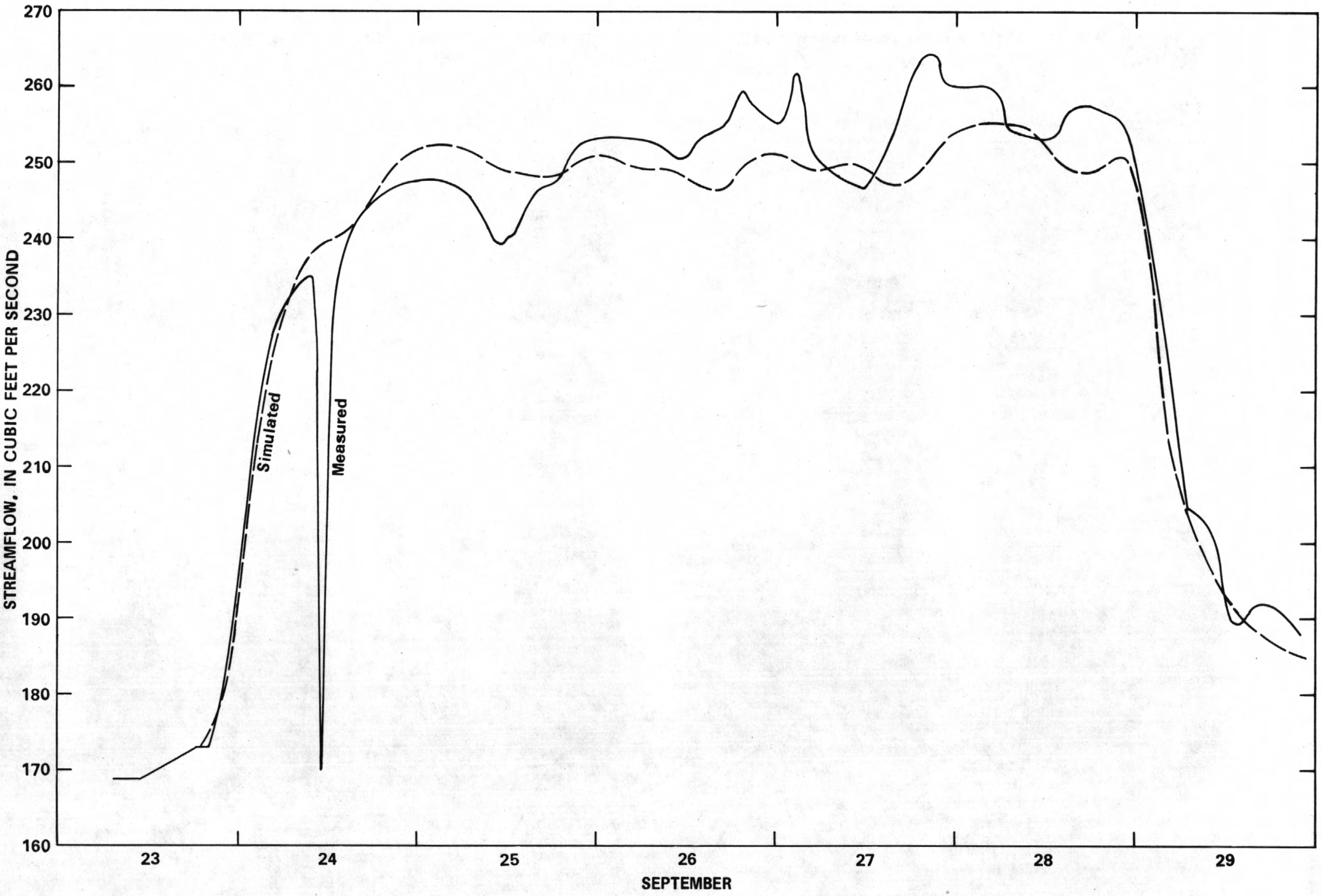

Figure 4.--Measured and simulated streamflow at the Arkansas River at Catlin Dam stream-gaging station, September 23-29, 1975.

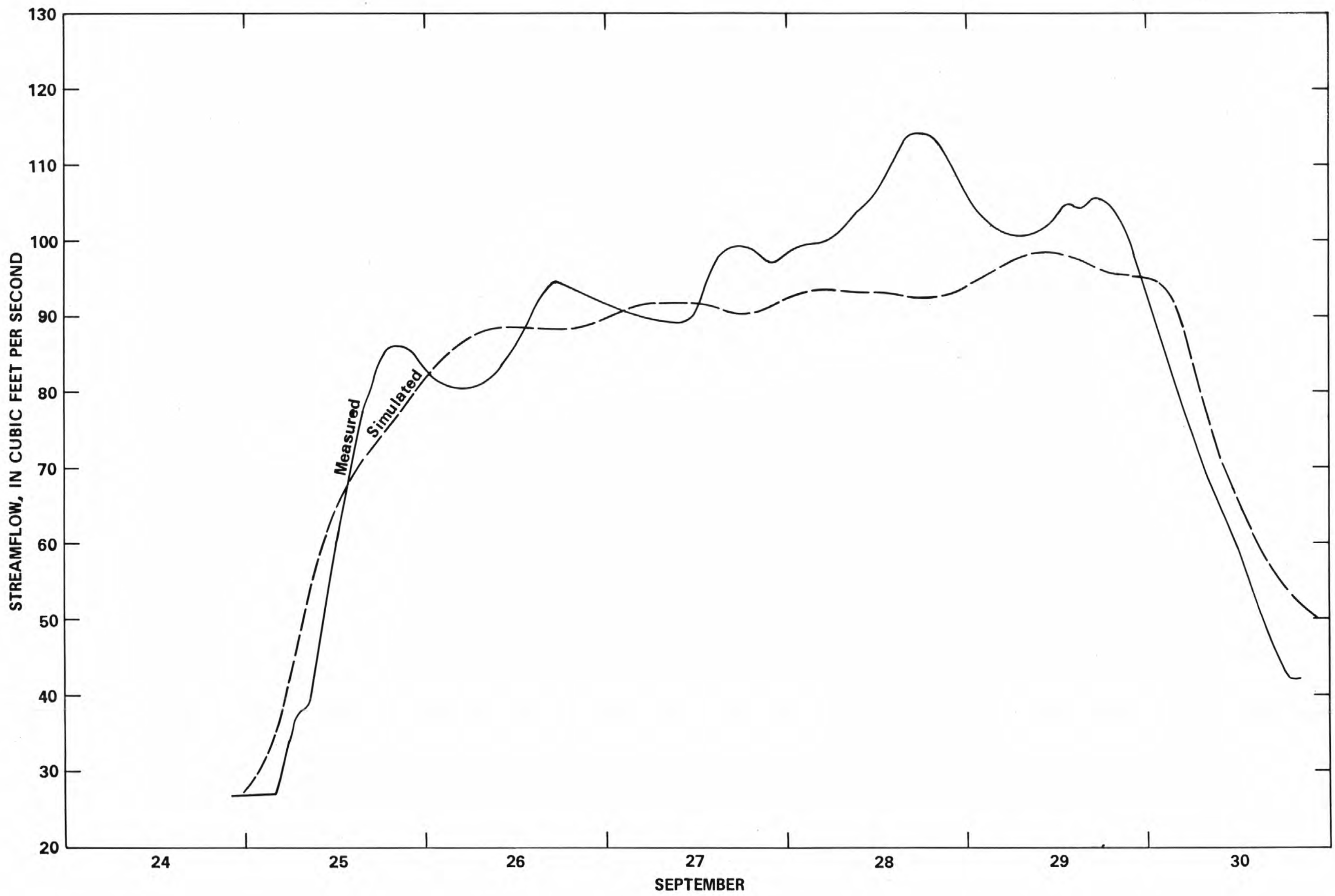

Figure 5.--Measured and simulated streamflow at the Arkansas River at La Junta stream-gaging station, September 24-30, 1975.

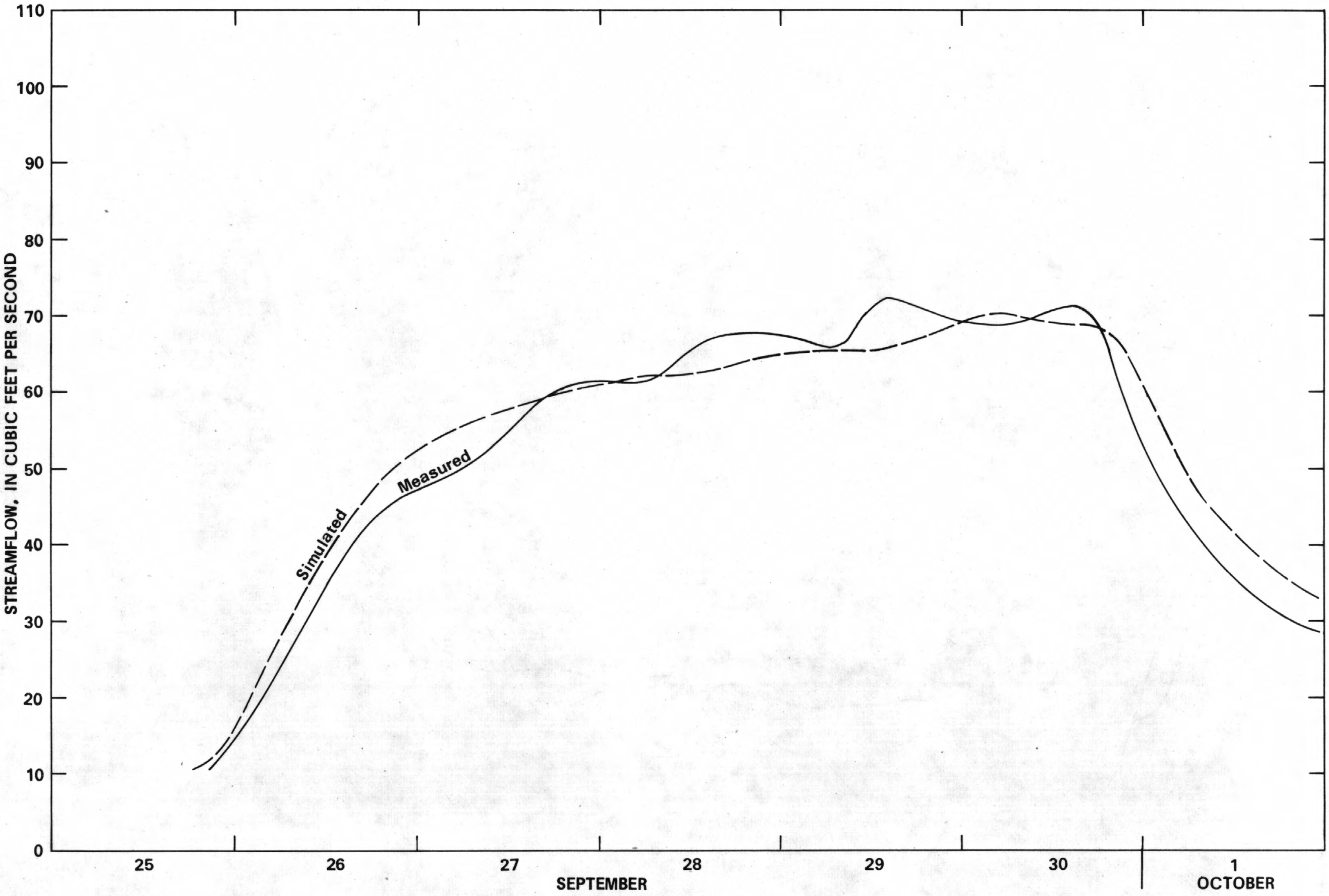

Figure 6.--Measured and simulated streamflow at the Arkansas River at Las Animas stream-gaging station, September 25–October 1, 1975.

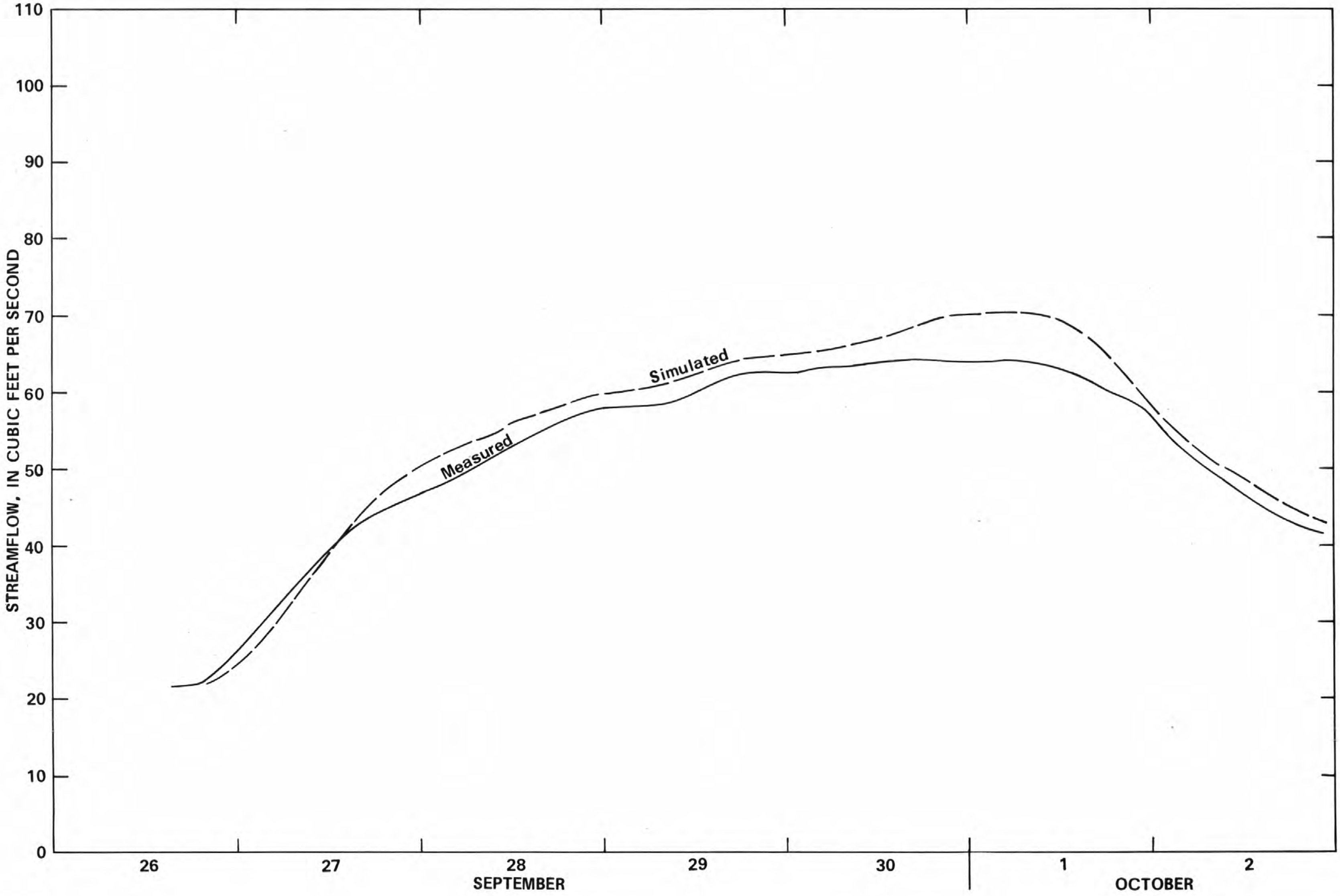

Figure 7.--Measured and simulated streamflow at the Arkansas River below John Martin Reservoir stream–gaging station, September 26–October 2, 1975.

Because of its construction, the modified-computer model can be partly verified using recorded data obtained during reservoir releases in streams other than the Arkansas River. Therefore, streamflow data for the Canadian River during a reservoir release of about 1,010 ft^3/s from Canton Lake, Okla., were used to partly verify the model. The required aquifer and river-channel characteristics have been previously defined for this reach (Moench and others, 1974). Comparison of simulated-release hydrographs produced by the model to hydrographs measured at the stream-gaging station at El Reno, about 86 river miles downstream from Canton Lake, indicated that results were within 1.5 percent of the measured release volume.

TRANSIT LOSSES DURING RESERVOIR RELEASES

To interpret results from the computer model, an administrative decision was made concerning the definition of transit loss. The volume of water released is rather easy to determine. The volume of water arriving downstream, however, is a function of time because release water leaving channel and bank storage continues to arrive at the diversion point long after the end of the release. Following discussions with representatives of the Office of the Colorado State Engineer and the Southeastern Colorado Water Conservancy District, a uniform method by which this time would be determined was established. Based on the release hydrograph predicted by the model, the specific time allowed is that required for the release discharge to diminish to less than 5 percent of its maximum rate at the diversion point. For example, if for a release rate of 120 ft^3/s the *maximum* discharge arriving at a downstream ditch is 100 ft^3/s (as predicted by the model), then the volume of release water that would arrive at the ditch *after* the release discharge had diminished to less than 5 ft^3/s (again, as predicted by the model) would be the *transit loss* as defined for this report. This method assumes that the entire release volume arriving at the downstream diversion canal (as predicted by the model) is diverted into the ditch up to this point in time.

Through analysis of the model results for numerous hypothetical releases from Pueblo Reservoir, relationships were developed for each subreach between transit loss and the antecedent river conditions, the distance downstream from Pueblo Reservoir, the rate and duration of reservoir release, and the time of year. The May-through-October transit losses in each subreach for an arbitrarily chosen *base release* of 100 ft^3/s for 10 days during various antecedent river conditions in that subreach are shown in table 4. These losses range from 0.043 percent per mile in subreach 3 when the antecedent subreach flow is 4,000 ft^3/s, to 0.481 percent per mile in subreach 5 when the antecedent subreach flow is 5 ft^3/s. Adjustment factors applied to the base-release transit loss to correct for the actual rate and duration of the release are shown in table 5. Both tables also give an example of how they are used to determine the transit loss of a hypothetical reservoir release. Because of differences in evaporation rates, transit losses for releases made during November through April are about 7 percent less than the summer losses determined from tables 4 and 5.

Model results also indicate that about 80 percent of the total loss can be attributed to bank storage and about 10 percent to channel storage. The remaining 10 percent of the transit loss is evaporated water. This evaporated water and perhaps a small part of the water in bank storage that is withdrawn by wells or is evapotranspired are the only true water losses from the stream-aquifer system. Thus, transit loss to a downstream on-channel reservoir, which has the capability of collecting virtually all water in bank and channel storage in the recession of a release from an upstream reservoir, is only about 10 percent of the transit losses as determined from tables 4 and 5.

Table 4.--*May-through-October transit losses of a base release*

Average antecedent streamflow in subreach, in cubic feet per second	Subreach 1, river miles 0 to 24		Subreach 2, river miles 24 to 42		Subreach river miles
	Percent	Percent per mile	Percent	Percent per mile	Percent
5	---	-----	---	-----	---
10	---	-----	---	-----	---
20	---	-----	---	-----	---
40	---	-----	---	-----	---
70	---	-----	---	-----	6.0
100	6.1	0.254	4.0	0.222	4.9
150	5.6	.233	3.5	.194	4.2
200	5.2	.217	3.3	.183	3.7
300	4.6	.192	2.8	.156	3.0
400	4.1	.171	2.5	.138	2.6
500	3.7	.154	2.3	.128	2.4
600	3.4	.142	2.1	.117	2.2
800	3.0	.125	1.8	.100	1.9
1,000	2.7	.112	1.7	.094	1.7
1,200	2.5	.104	1.6	.089	1.6
1,600	2.1	.088	1.4	.078	1.4
2,000	1.9	.079	1.3	.072	1.3
2,500	1.7	.071	1.2	.067	1.1
3,000	1.5	.062	1.1	.061	1.0
4,000	1.3	.054	1.0	.056	0.9

THE FOLLOWING IS AN EXAMPLE

Problem

What is the transit loss to the Catlin Canal headgate for a June base release (100 ft^3/s for 10 days) when antecedent streamflow is 500 ft^3/s in subreach 1, 500 ft^3/s in subreach 2, and 400 ft^3/s in subreach 3?

(100 cubic feet per second for 10 days) from Pueblo Reservoir

3, 42 to 63	Subreach 4, river miles 63 to 94		Subreach 5, river miles 94 to 121		Subreach 6, river miles 121 to 142	
Percent per mile	Percent	Percent per mile	Percent	Percent per mile	Percent	Percent per mile
-----	----	-----	13.0	0.481	9.5	0.452
-----	----	-----	10.4	.385	8.0	.381
-----	11.5	0.371	8.2	.304	6.3	.300
-----	9.6	.310	7.0	.259	5.5	.262
0.286	8.1	.261	6.2	.230	5.0	.238
.233	7.2	.232	5.3	.196	4.3	.205
.200	6.1	.197	4.1	.152	3.4	.167
.176	5.4	.174	3.5	.130	2.9	.138
.143	4.4	.142	3.0	.111	2.5	.119
.124	3.8	.123	2.7	.100	2.3	.110
.114	3.4	.110	2.5	.093	2.1	.100
.105	3.1	.100	2.3	.085	1.9	.090
.090	2.8	.090	2.1	.078	1.7	.081
.081	2.5	.081	2.0	.074	1.6	.076
.076	2.4	.077	1.9	.070	1.5	.071
.067	2.0	.065	1.7	.063	1.4	.067
.062	1.7	.055	1.5	.056	1.3	.062
.053	1.5	.048	----	-----	---	-----
.048	1.4	.045	----	-----	---	-----
.043	----	-----	----	-----	---	-----

OF THE USE OF THIS TABLE:

Solution

The Catlin Canal headgate is at river mile 61.0 (table 1). Transit losses in subreaches 1 and 2 are shown directly in the above table as 3.7 percent for subreach 1 and 2.3 percent for subreach 2. Transit loss in subreach 3 is 2.4 percent (19 miles×0.124 percent per mile) for the 19 miles (61 miles - 42 miles) in subreach 3. The total transit loss for a base release to Catlin Canal is, therefore, 8.4 percent (3.7 + 2.3 + 2.4 percent).

Table 5.--*Factors for adjusting transit loss for the rate and duration of reservoir releases*

Adjustment factor[1]	Release rate, in cubic feet per second	Release duration, in days
2.00	-----	1.0
1.60	-----	2.0
1.35	-----	4.0
1.20	-----	6.0
1.10	-----	8.0
1.06	10.0	8.5
1.04	30.0	9.0
1.02	60.0	9.5
1.00	100.0	10.0
.98	150.0	10.5
.96	200.0	11.0
.94	270.0	11.5
.90	470.0	13.0
.84	-----	16.0
.75	-----	25.0

[1]For adjusting the percentage of transit loss shown in table 4, for other than a base release (100 ft^3/s for 10 days).

THE FOLLOWING IS AN EXAMPLE OF THE USE OF THIS TABLE:

Problem

What is the transit loss to the Catlin Canal headgate for a June release with a rate of 200 ft^3/s and a duration of 16 days when antecedent streamflow is 500 ft^3/s in subreach 1, 500 ft^3/s in subreach 2, and 400 ft^3/s in subreach 3?

Solution

The transit loss for a base release (100 ft^3/s for 10 days) to the Catlin Canal is 8.4 percent (table 4). The adjustment factor for a release discharge of 200 ft^3/s is 0.96 and for a release duration of 16 days is 0.84. The adjusted transit loss is, therefore, 6.8 percent (8.4 percent $\times 0.96 \times 0.84$).

TRAVELTIME OF RESERVOIR RELEASES

In order to analyze the traveltime of reservoir releases in the study reach from Pueblo Reservoir to John Martin Reservoir, accurate determinations of river-mile locations for major diversion points and gaging stations were necessary. These determinations were made using the latest U.S. Geological Survey topographic maps and are tabulated in table 1.

Traveltime information was primarily obtained from streamflow records of historical reservoir releases. Rainfall and changes in ditch diversions or return flows also produce abrupt discharge changes along the main stem that can be followed downstream using the stage records obtained at stream-gaging stations. The data selected were limited to releases or other discharge changes occurring after a period of relatively stable streamflow conditions to insure that the average antecedent discharge would be representative of the subreach. This type of traveltime, commonly known as wave celerity, is approximately 1.5 to 2.0 times the mean traveltime under a steady-state condition.

After determining the traveltime of more than 50 distinguishable stage changes occurring in the study reach since 1970, relationships between traveltime and antecedent subreach streamflow were developed for each of the six subreaches. The results of this analysis are summarized in table 6, which also gives an example of how the traveltime of a reservoir release to a particular diversion point can be determined. Rates of travel of reservoir releases in the study reach range from 0.146 h/mi in subreach 1 when the average antecedent streamflow is 3,000 ft^3/s, to 1.67 h/mi in subreach 6 when the average antecedent streamflow is 10 ft^3/s.

LIMITATIONS AND ACCURACY OF TRANSIT-LOSS AND TRAVELTIME RESULTS

The transit-loss results shown in tables 4 and 5 are based on the calibrated computer model, as modified for the study reach. Because this model simulates response only during steady-state conditions, the transit-loss determinations are an approximation for unsteady-state conditions during the reservoir-release period, such as changes in tributary inflows, canal diversions, or water-table conditions. The accuracy of model results for release or river conditions significantly different from those that existed during the calibration release of September 22, 1975, is uncertain. Indications are that transit-loss results are accurate within 6 percent in the general range of these conditions.

The traveltime information shown in table 6 is similar to transit-loss results in that it is valid only for the steady-state conditions on which it is based. Although the recorded data commonly indicated traveltime differences of at least 6 hours for a particular average antecedent streamflow, they were generally within 30 percent of the average subreach traveltime shown in table 6. Because of limited data for antecedent streamflows greater than 2,000 ft^3/s in subreaches 1-3, and greater than 600 ft^3/s in subreaches 4-6, the accuracy of the data in table 6 is uncertain for discharges greater than these values.

Table 6.--*Traveltimes of releases*

[Figures in parentheses beyond range

Average antecedent streamflow in subreach, in cubic feet per second	Subreach 1, river miles 0 to 24		Subreach 2, river miles 24 to 42		Subreach 3, river miles 42 to 63	
	Hours	Hours per mile	Hours	Hours per mile	Hours	Hours per mile
5	------	-------	------	-------	------	-------
10	------	-------	------	-------	------	-------
20	------	-------	------	-------	------	-------
40	------	-------	------	-------	------	-------
70	------	-------	(20.0)	(1.11)	(26.2)	(1.25)
100	(10.9)	(0.454)	16.4	.911	21.0	1.00
150	10.0	.417	13.8	.767	17.5	.833
200	9.2	.383	12.9	.717	16.2	.771
300	8.3	.346	11.2	.622	15.0	.714
400	7.5	.312	10.6	.589	13.1	.623
500	7.1	.296	9.5	.528	12.4	.590
600	6.5	.271	9.0	.500	11.1	.528
800	5.9	.246	7.8	.433	10.0	.476
1,000	5.3	.221	7.2	.400	8.8	.419
1,200	4.9	.204	6.4	.356	8.1	.326
1,600	4.4	.183	5.6	.311	6.8	.324
2,000	3.9	.162	5.0	.278	6.0	.286
2,500	(3.7)	(.154)	(4.4)	(.244)	(5.4)	(.257)
3,000	(3.5)	(.146)	(4.1)	(.228)	(4.9)	(.233)
4,000	------	-------	------	-------	------	-------

THE FOLLOWING IS AN EXAMPLE OF THE

Problem

What is the traveltime of a reservoir release to the Catlin Canal headgate when antecedent streamflow is 500 ft^3/s in subreach 1, 500 ft^3/s in subreach 2, and 400 ft^3/s in subreach 3?

from Pueblo Reservoir

of data analyzed]

Subreach 4, river miles 63 to 94		Subreach 5, river miles 94 to 121		Subreach 6, river miles 121 to 142	
Hours	Hours per mile	Hours	Hours per mile	Hours	Hours per mile
------	-------	------	-------	------	-------
------	-------	(22.5)	(0.833)	(35.0)	(1.67)
------	-------	18.0	.667	23.3	1.11
(44.3)	(1.43)	15.9	.589	19.1	.910
31.0	1.00	14.2	.526	16.2	.771
25.8	.832	13.5	.500	15.0	.714
22.1	.713	12.9	.478	14.0	.667
20.7	.668	11.7	.433	13.1	.624
18.2	.587	10.4	.385	11.7	.557
17.2	.555	9.3	.344	11.5	.548
15.5	.500	8.7	.322	9.5	.452
14.8	.477	7.9	.293	9.1	.433
(12.9)	(.416)	(7.1)	(.263)	(8.1)	(.386)
(11.9)	(.384)	(6.4)	(.237)	(7.2)	(.343)
(10.7)	(.345)	------	-------	------	-------
------	-------	------	-------	------	-------
------	-------	------	-------	------	-------
------	-------	------	-------	------	-------
------	-------	------	-------	------	-------
------	-------	------	-------	------	-------

USE OF THIS TABLE:

Solution

The Catlin Canal headgate is at river mile 61.0 (table 1). Traveltimes in subreaches 1 and 2 are shown directly in the above table as 7.1 hours for subreach 1 and 9.5 hours for subreach 2. Traveltime in subreach 3 is 11.8 hours (19 miles × 0.623 hours per mile) for the 19 miles (61 miles - 42 miles) in subreach 3. The total traveltime to Catlin Canal is, therefore, 28.4 hours (7.1 hours + 9.5 hours + 11.8 hours).

BENEFITS OF RESERVOIR-RELEASE MANAGEMENT

The data presented in tables 4 and 5 provide information on how reservoir releases may be managed to reduce transit losses. Generally, the smaller the antecedent streamflow, the greater the transit loss. For a given release volume, scheduling the release for the longest duration and during the greatest antecedent streamflow will result in the smallest transit loss. Transit losses of a base release from Pueblo Reservoir to selected sites along the study reach are shown in table 7, which was derived from tables 1 and 4. For the entire reach, transit losses for a base release range from about 7 percent or 0.05 percent per mile during a period of very high antecedent streamflow, to more than 50 percent or 0.35 percent per mile during a period of very low antecedent streamflow.

Traveltime information is valuable in the management of reservoir releases. Stage changes indicating the arrival of a release are generally difficult to recognize in the area downstream from the stream-gaging station at Catlin Dam (site 12, fig. 1), particularly when streamflow is unstable because of tributary inflows, diversion changes, canal sluicing, or other causes. Should diversion begin either too early or too late, streamflow downstream from the point of diversion may be temporarily disrupted both at the beginning and the end of the diversion period.

The use of several incremental diversion rates also will minimize unstable downstream streamflow conditions during the diversion period. Reservoir releases, although they are usually made at a single rate, attenuate rapidly as they travel downstream. If the canal diversion also is made at a single rate, the result can be a sudden decrease in downstream streamflow when the diversion begins and a sudden increase when the diversion ceases.

Average times of rise or fall for release hydrographs are given in table 8 for each subreach during various antecedent streamflow conditions. These data were obtained through analysis of hydrographs developed by the computer model. An example of how to use these times to determine a diversion schedule is given in table 8 and is illustrated on figure 8. The number of diversion increments used at both the beginning and ending of the diversion period needs to be at least equal to the subreach number in which the diversion is located to avoid significant adverse effects on water users downstream from the point of diversion. A diversion in subreach 4 would, therefore, use at least four incremental diversion rates before reaching its maximum diversion rate.

Table 7.--*May-through-October transit losses of a base release (100 cubic feet per second for 10 days) from Pueblo Reservoir to selected sites along the study reach*

Site number[1]	Site name	Transit loss, in percent, for indicated antecedent streamflow condition[2]				
		Very low	Low	Medium	High	Very high
6	Colorado Canal-------------	7.4	6.3	4.1	2.3	1.6
9	Oxford Canal headgate------	10.3	8.7	5.6	3.3	2.3
10	Otero Canal headgate-------	13.7	11.0	6.9	4.0	2.8
11	Catlin Canal headgate------	15.8	12.3	7.7	4.5	3.1
14	Rocky Ford Canal headgate--	18.7	14.5	8.9	5.2	3.5
16	Fort Lyon Canal headgate---	26.0	19.7	11.7	6.7	4.4
18	Las Animas Consolidated Canal headgate-----------	35.7	27.3	15.6	8.7	5.5
21	Arkansas River below John Martin Reservoir gage----	50.1	37.5	21.0	11.5	7.4

[1]Locations shown by site number on figure 1. River-mile locations of sites given in table 1.

[2]Defined by the following average antecedent streamflows:

Streamflow condition	*Antecedent streamflow, in cubic feet per second, for indicated subreach*					
	1	*2*	*3*	*4*	*5*	*6*
Very low--	100	100	70	20	5	5
Low-------	200	200	150	70	10	20
Medium----	600	600	500	300	100	150
High------	2,000	2,000	1,600	1,000	500	600
Very high-	4,000	4,000	4,000	3,000	2,000	2,000

Table 8.--*Average times of rise or*

Average antecedent streamflow in subreach, in cubic feet per second	Subreach 1, river miles 0 to 24		Subreach 2, river miles 24 to 42		Subreach river miles
	Hours	Hours per mile	Hours	Hours per mile	Hours
5	--	----	--	----	--
10	--	----	--	----	--
20	--	----	--	----	--
40	--	----	--	----	--
70	20	0.83	13	0.72	28
100	18	.75	12	.67	22
150	16	.67	11	.61	19
200	15	.62	10	.56	16
300	13	.54	9	.50	13
400	12	.50	8	.44	10
500	11	.46	7	.39	8
600	10	.42	7	.39	7
800	9	.38	6	.33	6
1,000	8	.33	6	.33	5
1,200	7	.29	6	.33	5
1,600	6	.25	5	.28	4
2,000	6	.25	5	.28	4
2,500	6	.25	5	.28	3
3,000	5	.21	5	.28	3
4,000	5	.21	4	.22	3

THE FOLLOWING IS AN EXAMPLE

Problem

What diversion schedule could be used at the Catlin Canal headgate to minimize adverse effects on downstream water users for a release with a rate of 200 ft^3/s and a duration of 16 days when antecedent streamflow is 500 ft^3/s in subreach 1, 500 ft^3/s in subreach 2, and 400 ft^3/s in subreach 3?

3, 42 to 63	Subreach 4, river miles 63 to 94		Subreach 5, river miles 94 to 121		Subreach 6, river miles 121 to 142	
Hours per mile	Hours	Hours per mile	Hours	Hours per mile	Hours	Hours per mile
----	--	----	60	2.22	80	3.81
----	--	----	56	2.07	75	3.57
----	85	2.74	50	1.85	66	3.14
----	72	2.32	45	1.67	56	2.67
1.33	60	1.94	35	1.30	45	2.14
1.05	51	1.65	28	1.04	40	1.90
.90	41	1.32	22	.81	32	1.52
.76	33	1.06	17	.63	26	1.24
.62	24	.77	13	.48	20	.95
.48	19	.61	10	.37	16	.76
.38	16	.52	8	.30	13	.62
.33	14	.45	6	.22	11	.52
.29	12	.39	5	.19	9	.43
.24	10	.32	4	.15	8	.38
.24	9	.29	4	.15	7	.33
.19	8	.26	3	.11	6	.29
.19	8	.26	3	.11	5	.24
.14	7	.23	--	----	--	----
.14	7	.23	--	----	--	----
.14	--	----	--	----	--	----

OF THE USE OF THIS TABLE:

Solution

The Catlin Canal headgate is at river mile 61.0 (table 1). Traveltime to the Catlin Canal headgate is 28.5 hours after the time of release from Pueblo Reservoir (table 6). Because the transit loss is 6.8 percent (table 5), the final diversion rate will be 186.4 ft^3/s (200 ft^3/s × 93.2 percent). Times of rise or fall in subreaches 1 and 2 are shown directly in the above table as 11 hours in subreach 1 and 7 hours in subreach 2. Time of rise or fall in subreach 3 is about 9 hours (10 miles × 0.48 hour per mile) for the 19 miles (61 miles - 42 miles) in subreach 3. The total time of rise or fall at Catlin Canal is, therefore, 27 hours(11 hours + 7 hours + 9 hours). To allow for at least three steps, the steps could be made at intervals of 9 hours (27 hours ÷ 3) and each step could be made in increments of 62.1 ft^3/s (186.4 ft^3/s ÷ 3). The resulting diversion schedule is shown on figure 8.

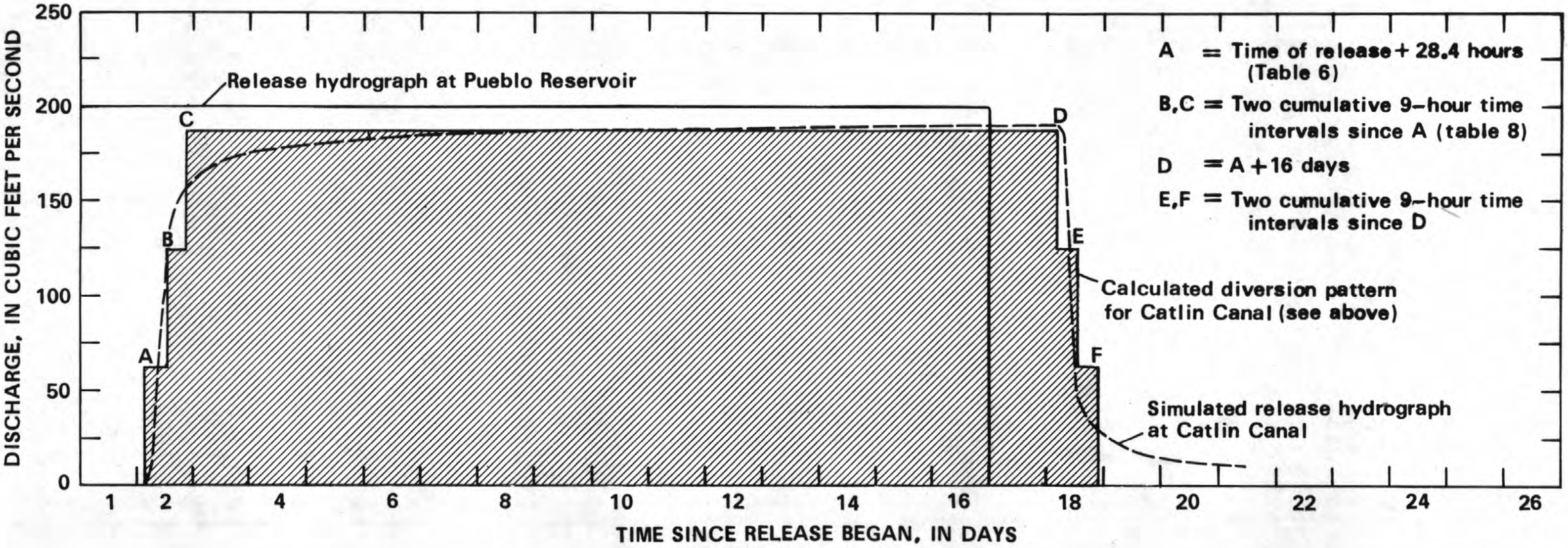

Figure 8.--Simulated-release hydrograph and calculated diversion pattern at Catlin Canal for a 16-day release of 200 cubic feet per second from Pueblo Reservoir.

SUMMARY

The investigation of transit losses and traveltimes of reservoir releases along the Arkansas River from Pueblo Reservoir near Pueblo to John Martin Reservoir near Las Animas, a distance of 142 river miles, can be summarized as follows:

1. A modified-computer model, calibrated by a controlled-test release from Pueblo Reservoir on September 22, 1975, simulates the response of the Arkansas River and the adjoining aquifer in the study reach to the passage of reservoir releases. The model produces downstream hydrographs that include the effects of bank storage, channel storage, and evaporation losses. Transit losses during steady-state conditions can be determined from these hydrographs.

2. Transit losses depend on rate and duration of the reservoir release, antecedent river conditions, time of year, and distance downstream from Pueblo Reservoir. For a 10-day release of 100 ft^3/s, the transit loss in the study reach ranges from an average of 0.35 percent per mile during very low antecedent streamflow conditions to an average of 0.05 percent per mile during very high antecedent streamflow conditions. Transit losses for releases made during November through April are about 7 percent less than the losses during other times of the year because of the smaller evaporation rate. Transit losses for releases made to an on-channel reservoir are only 10 percent of these rates if bank and channel storage are not considered as true losses. Reservoir releases of less than 100 ft^3/s increase the transit losses as much as 6 percent, whereas larger releases decrease the losses by as much as 10 percent. Similarly, releases of less than 10 days can double the transit loss, whereas longer releases can decrease the transit loss by as much as 25 percent.

3. Traveltime of a reservoir release depends on antecedent river conditions and distance downstream from Pueblo Reservoir. Rates of travel generally range from 0.146 h/mi near the upstream end of the study reach during high antecedent streamflow conditions, to 1.67 h/mi at the downstream end of the study reach during very low antecedent streamflow conditions.

4. Management practices that may be used to benefit water users in the study area include selecting the optimum time, amount, and duration of release to minimize transit losses; using traveltime data to determine the time when diversion should begin, initially diverting in increments to avoid unstable streamflow conditions downstream; using transit-loss data to determine the final diversion rate; and reducing the diversion by increments, again to prevent unstable flow downstream.

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