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COMPARISON OF UNREGULATED AND REGULATED STREAMFLOW FOR THE YAKIMA RIVER AT UNION GAP AND NEAR PARKER, WASHINGTON

By J. J. Vaccaro

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Multiply	By	To Obtain
inches (in.)	2.540	centimeters (cm)
square miles (mi^2)	2.590	square kilometers (km^2)
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
acres	4047.0	square meters (m^2)
acre-feet (acre-ft)	1233.0	cubic meters (m^3)

COMPARISON OF UNREGULATED AND REGULATED STREAMFLOW FOR THE YAKIMA RIVER AT UNION GAP AND NEAR PARKER, WASHINGTON

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ABSTRACT

To estimate the effects of reservoir storage and canal diversion on streamflow in the Yakima River at Union Gap and near Parker, records of regulated daily-mean discharge for 52 water years, 1926-77, at 13 stream gaging stations, including Union Gap and Parker, were adjusted for changes in storage contents in five reservoirs and for flows diverted in 58 canals. The adjustments were made through the use of the SSARR (Streamflow Synthesis and Reservoir Regulation) numerical streamflow-routing model, which was calibrated and verified on regulated daily-mean discharges at Union Gap and near Parker within about an 11-percent error. The estimated composite error of the computed unregulated discharges, based on analyses of several possible sources of error, was 12 percent. The unregulated streamflow at Union Gap and near Parker was shown to be approximately equal.

The effects of regulation on the Yakima River were appraised in terms of the annual means, monthly means, and annual minimum 7-day and 183-day averages of the computed unregulated and the recorded regulated daily- mean discharges. Regulation has reduced the unregulated 52-year mean- annual discharge from 4,800 cubic feet per second (ft^3/s) at both sites to 3,800 ft^3/s at Union Gap and to 2,300 ft^3/s near Parker. The losses were due primarily to diversion for (agricultural) irrigation and to export of water from the Upper Yakima basin to the Lower Yakima basin.

Regulation has reduced springtime high flows at Union Gap and near Parker and has increased August-September low flows at Union Gap. But three canals between Union Gap and Parker—Sunnyside Canal and New and Old Reservation Canals—cause summer flows in the Yakima River near Parker to diminish to very low values for days and, in some years, for months. During the irrigation season, April through October, the average unregulated monthly mean at both sites and the average regulated monthly means at Union Gap and near Parker range from high values, in May, of 12,000 (both, unregulated), 7,400 (Union Gap, regulated), and 4,300 ft^3/s (Parker, regulated), to low values, in September, of 1,400, 2,600, and 330 ft^3/s, respectively. Similar results are observed in the average annual minimum 7-day means of 930, 1,100, and 130 ft^3/s and in the average annual minimum 183-day means of 2,400, 2,300, and 980 ft^3/s.

Regulation has reduced the standard deviations of the monthly- and annual-mean discharges at Union Gap and near Parker, and has increased the coefficients of variation of the monthly- and annual-mean discharges near Parker and the winter-spring monthly-mean discharges at Union Gap.

INTRODUCTION

A significant part of the Yakima River basin in south-central Washington is composed of the Reservation of the Yakima Indian Nation (fig. 1), whose people depend on a part of the flow of the Yakima River to support their agricultural, fisheries, and other needs. However, the Yakima River system upstream of the Reservation (fig. 2) is regulated by the operation of five storage reservoirs and the diversion of water by more than 58 canals. In 1978, the U.S. Geological Survey (USGS) undertook a cooperative study with the Yakima Indian Nation to determine the effect of storage and diversion on the flow of the Yakima River at Union Gap, where the river first reaches the Reservation. As part of this effort, a preliminary investigation was conducted (C. H. Swift, USGS, Tacoma, WA; written commun., 1981) to determine the feasibility of such a study and establish its scope.

The preliminary investigation determined that the effects of storage and diversion on streamflow upstream of Union Gap could be quantified by using the Streamflow Synthesis and Reservoir Regulation (SSARR) digital model (U.S. Army Corps of Engineers, 1972) to compute unregulated streamflow at Union Gap. The term "unregulated streamflow," as used in this report, represents the model-derived estimate of natural riverflow that would have occurred had there been no operating storage reservoirs and no diversion canals. The term "regulated streamflow" represents the historic observed-discharge values or discharge values synthesized by the addition of several historic records at gaging stations.

The preliminary investigation determined that a digital streamflow model, and a mass-balance storage-routing model in particular, would best meet the objective of quantifying the effects of regulation on the streamflow in the upper Yakima River basin for the following reasons: (1) the vast amount of discharge records needed to accurately quantify the effects could be most efficiently processed through a computer; (2) the need for accurate unregulated daily values to compute minimum 7-day and monthly discharge values could not be met from a mass-balance deregulation accounting, which could not take into account the time lag of streamflow; (3) it is necessary to assess the accuracy of the unregulated flow values; (4) a tool (a digital model) should be available to study future alterations and/or changes in the river system; (5) previous use of digital models by investigators studying complex and widely different systems has given good results; and (6) a storage routing model is a good median between simple deregulation accounting with no streamflow timing factors and a dynamic model that solves the equation of fluid motion, but whose operating costs and data requirements would have been prohibitive for more than 1 water year of simulations.

Purpose and Scope

The objective of this study was to determine the extent to which reservoir storage and canal diversion upstream from the Reservation altered the flow of the Yakima River. The determinations were made for two points about 3 miles apart, at Union Gap and near Parker. The Parker site was included in the study because the Yakima Indian Nation wanted to determine the effects of three large canals that divert streamflow from the short reach of the Yakima River between Union Gap and Parker.

Approach

The approach used to accomplish the objective for the basin upstream of Parker was tc collect the available discharge and reservoir storage records, extend the record of regulated discharge for Union Gap to the base period, calibrate the SSARR storage routing model for the river system using regulated flows, verify that model, use the verified model to route unregulated flows to the Union Gap and Parker stations, estimate the accuracy of the computed unregulated flows, and compare the regulated and unregulated flows at the two stations.

Records were collected and checked for 5 reservoirs, 58 canals, and 13 streamflow stations. The sites at which the reservoir, canal, and streamflow records were collected and the length and type of those records are identified in Appendix A (p. 51).

The verified model was used to compute daily discharge values for unregulated streamflow at Union Gap and near Parker for 52 water years, 1926-1977, where a water year is a period of 12 consecutive months, ending September 30. The accuracy of the model-computed unregulated discharge values was estimated on the basis of the verification results and on factors that were included in the computation of unregulated streamflow but not included in the model verification for regulated streamflow. The historic regulated and model-computed unregulated daily discharges that were compared for Union Gap and near Parker were annual-mean, monthly-mean, and annual minimum 7-day and 183-day averages of daily discharges for 1926-77.

Acknowledgments

The author expresses appreciation to the Yakima Indian Tribe for their cooperation in this study. Sincere appreciation is also extended to the U.S. Bureau of Reclamation personnel for providing streamflow, canal, and storage records.

DESCRIPTION OF THE STUDY AREA

The Yakima River basin is in south-central Washington (fig. 1), and the upper basin, upstream of Union Gap, encompasses a drainage area of 3,652 mi^2. The upper basin varies greatly in climate, topography, vegetation, agricultural land use, and surface-water runoff. Precipitation ranges from about 100 in. in the Cascade Range, which borders the basin on the west, to less than 10 in. in the lower plateau areas to the east and south near Union Gap. The surface-water runoff is topographically separated into a subbasin terminating at Umtanum Ridge south of Ellensburg and a subbasin terminating at Ahtanum Ridge at Union Gap (fig. 2).

There are over 200,000 irrigated acres in the basin that are served by diversion canals and pumping plants. The diversions from surface-water average about 1,300,000 acre-feet annually, most of the water diverted for irrigation. Some of the major canals divert up to an average annual rate of 400 ft^3/s, although the majority of the canals divert at an annual average rate of about 10 ft^3/s. Most of the diversions are made during the irrigation season, but a few diversions continue year-round.

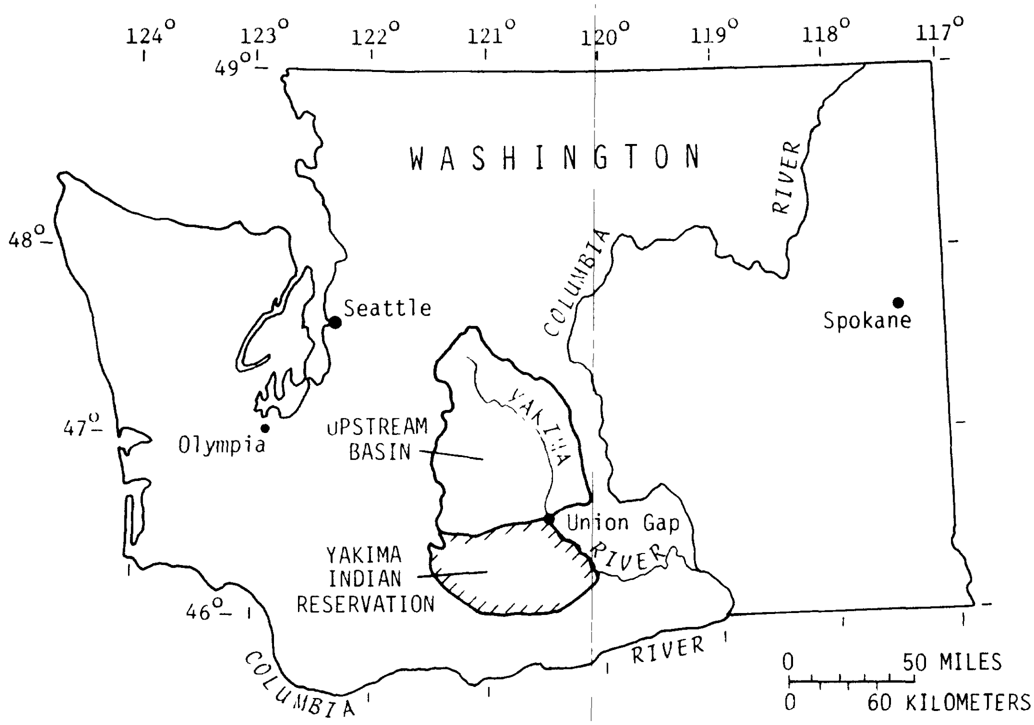


FIGURE 1.--Location of the Upper Yakima River basin.

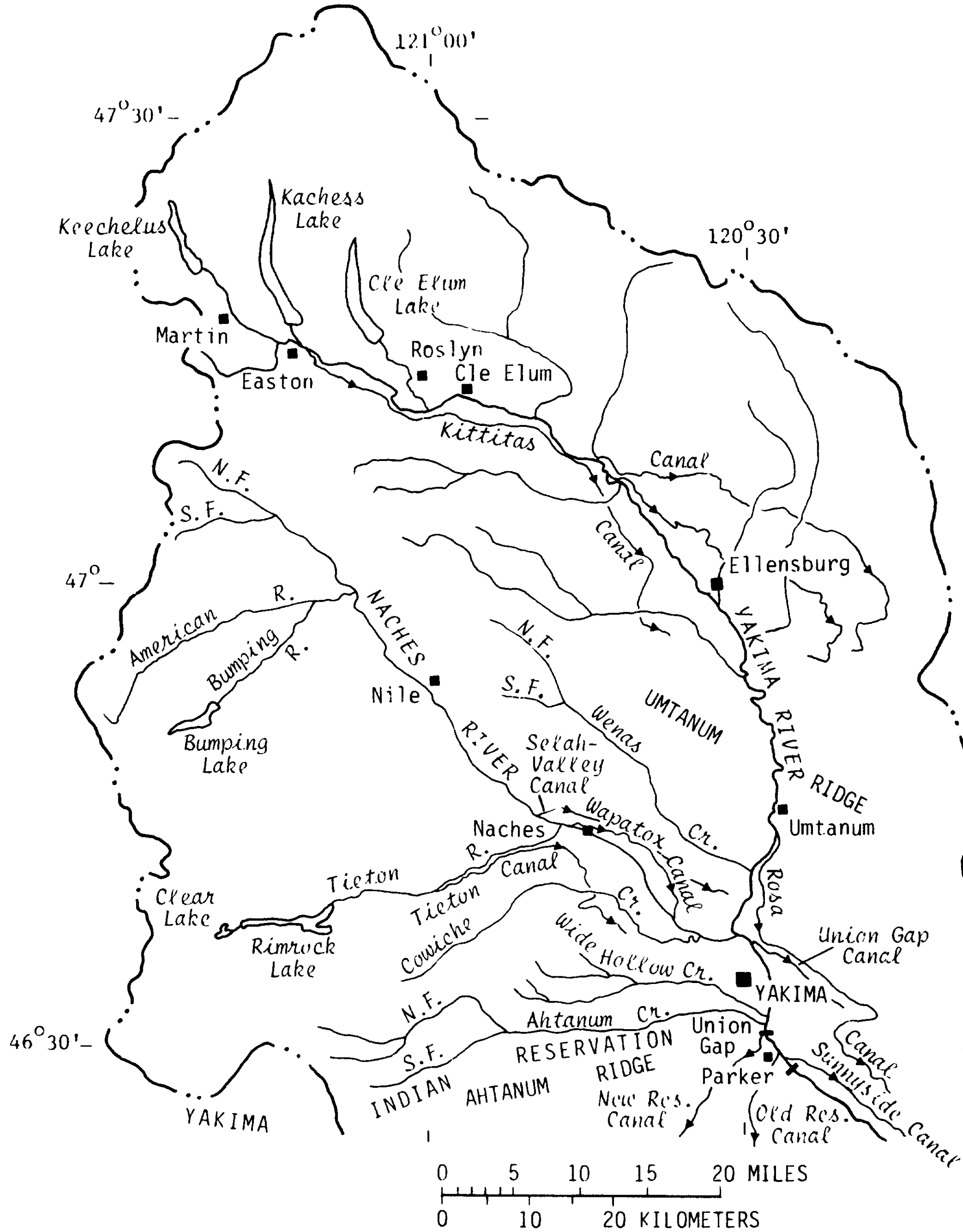


FIGURE 2.--Major streams, reservoirs, and some major canals in the Upper Yakima River basin.

METHOD OF ANALYSIS

The method of analysis in this study consisted of the seven steps mentioned in the Approach section of the Introduction (p. 3). These steps were to: 1) collect available data; 2) extend streamflow records for the Yakima River at Union Gap; 3) calibrate the SSARR model for regulated conditions; 4) verify the calibrated model for regulated conditions; 5) compute unregulated streamflow for 52 water years; 6) estimate error of computed unregulated streamflow; and 7) determine effects of reservoir storage and canal diversion on streamflow at Union Gap and near Parker by comparing regulated and unregulated discharge values and statistics. This section presents the information and methods used for the first six steps. The last step, the comparison, is discussed separately.

Reservoir, Canal, and Streamflow Records

A data base of historic reservoir, canal, and streamflow records was needed for the study. The data base that was established included records for 5 reservoirs, 13 streamflow sites, and 58 canals (Appendix A, p. 51).

The 58 canals include all of those in the basin upstream of Parker with average annual discharges exceeding 10 ft^3/s. Continuous (day-by-day) records of discharge were available for all 17 major canals (those that have average annual flows exceeding 30 ft^3/s). Continuous records were also available for 11 of the smaller canals, and many of those records were obtained from the files of the U.S. Bureau of Reclamation (USBR) (Perela, written commun., 1980). Estimates of daily discharges for the remaining 30 smaller canals were obtained from monthly values (in acre-feet) furnished by USBR (Wensman, written commun., 1980). The daily estimates were obtained by dividing the monthly values by the number of days in the month and multiplying this by a conversion factor to obtain the estimate in cubic feet per second. The estimates were tested by comparing the daily discharge estimates obtained from the monthly acre-feet values with partial continuous records that were available for some of the smaller canals. These estimates for the 30 smaller canals account for about 15 percent of the flow diverted by all 58 canals. There are some smaller diversions in the basin, but the percentage of diverted flow unaccounted for by the 58 canals is believed to be insignificant for this study.

The 13 streamflow stations in the data base include 6 on the Yakima River and two of its major tributaries upstream of the Naches River, 4 on the Naches River and its major tributaries, and 2 on the Yakima River and 1 on Ahtanum Creek downstream of the Naches River. There are a number of small tributary streams in the basin for which there are few, if any, continuous streamflow records, but the flow in those stream is represented in the records for stations further downstream on the receiving rivers. The stations on the Yakima River at Union Gap and near Parker account for all of the streamflow from the Yakima basin, except that which bypasses the two stations in canals and is accounted for separately. The station at Umtamum on the Yakima River, upstream of the Naches River, accounts for all of the streamflow in the Yakima basin upstream of Umtanum. The station near Naches on the Naches River, downstream of the Tieton River, accounts for all of the streamflow from the Naches basin upstream of Naches, except that which bypasses the station in canals and is accounted for separately.

Five of the 13 streamflow stations provide continuous records of outflow from the five major reservoirs in the basin (two reservoirs in the Naches River drainage and three in the Yakima River drainage upstream of Cle Elum). The useable storage capacities of the five reservoirs range from 33,700 to 436,000 acre-feet, and the total capacity (1,065,400 acre-feet) accounts for over 95 percent of the existing storage capacity in the basin. Clear Lake and Wenas Creek reservoirs account for most of the remaining 5 percent. They are not included in this study because Clear Lake reservoir (capacity 5,300 acre-feet) is upstream of one of the five major reservoirs included, and the outflow of Wenas Creek reservoir (capacity 1,050 acre-feet) is small.

Synthesis of Historic Streamflow Record for Union Gap

One of the comparisons of streamflow to be made in this study was for the Yakima River at Union Gap. However, the only record collected there was for the water years 1897-1914 and 1964. Therefore, a record for Union Gap had to be synthesized and extended for the more recent years. The record was synthesized in two ways.

In the first synthesis, the record for the Yakima River at Union Gap was obtained by adding the records for two stations: Yakima River above Ahtanum Creek at Union Gap and Ahtanum Creek at Union Gap. Those two stations are near Union Gap, and the summation of their records should represent a realistic record for Union Gap. However, the summation of these two records could only be done for the 1967 through 1977 water years because the Ahtanum Creek station was operated only since October 1, 1966.

In the second synthesis, a record for Union Gap was obtained for the water years 1926 through 1977 by adding records for four stations: New and Old Reservation Canals, Sunnyside Canal, and Yakima River at Parker.

To obtain an estimate of the accuracy of the synthetic record for Union Gap for the water years preceding 1967, statistics for the two synthetic records for the 1968-77 period were compared; the results are shown in table 1. As an additional comparison for the 1968-77 period, a linear regression was calculated between daily discharges obtained by the two methods of synthesis. The standard error of estimate for the regression relation was about 230 ft^3/s (about 5 percent of the average flow) and the correlation coefficient was greater than 0.99. The observed record for the 1964 water year for the Yakima River at Union Gap also compared favorably with the estimates, and the results are shown in table 1. The statistics of the two synthetic records, the comparison for the 1964 water year, and the linear regression for 1968-77 indicate that the estimates for the regulated flow for the Yakima River at Union Gap are approximately equal.

Calibration and Verification of the Model

The Streamflow Synthesis and Reservoir Regulation (SSARR) model used in this study is a numerical model that has been programmed to simulate daily-mean discharges at a downstream location by routing daily-mean discharge values given at upstream locations through stream reaches. The stream reaches are represented by routing parameters that reflect travel time and channel storage of the streamflow. The upstream discharge values are obtained from upstream gaging stations, some of which record the outflow from the five reservoirs. Between the given upstream discharge and the simulated downstream discharge, water may enter or leave the reach by diversion, return flow from diversion, or inflow from the "local" intermediate drainage area. Diversion amounts are recorded or estimated average daily flow values, return flows are defined as percentages of diverted flows and are returned over a 3-month period, and "local" inflows are estimated by the difference between recorded upstream and downstream discharges after accounting for diversions and returns. Configuration of the model consists of defining the routing sequence in which the discharge data are utilized and routed along these reaches.

There are several assumptions that are used in the modeling effort: (1) the model parameters are independent of whether the streamflow is regulated or unregulated; (2) the local inflow discharge values that are computed for regulated flow are the same for unregulated flow; and (3) the ground-water component of the river discharge that is implicitly included in the local inflow computations is the same for both regulated and unregulated streamflow. These assumptions are discussed further in this section.

To simulate streamflow correctly, a numerical model must be first calibrated and then verified. The model calibration is an iterative process in which the model is operated with a given set of variables and the routing parameters are successively adjusted until an acceptable match of computed and observed values is achieved; the observed values used in the process are chosen as a representative subset of the sample space of all the observed values. Verification is the process of validating the parameters obtained from the calibration. In the verification procedure, the model-computed streamflow values are compared against observed streamflow values that were not used during calibration.

TABLE 1.--Comparison of annual, monthly and 7-day mean discharges synthesized two different ways for the Yakima River at Union Gap for the period 1968-1977

	Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Mean annual mean
Ten-year monthly means, (ft^3/s)	A	1,812	1,779	3,014	3,861	3,813	4,387	5,542	7,815	7,303	4,330	3,535	2,815	4,168
	B	1,767	1,708	2,930	3,820	3,700	4,309	5,596	7,854	7,330	4,310	3,509	2,798	4,137
1964 water year monthly means, (ft^3/s)	B	1,406	1,219	1,223	1,472	1,539	2,070	3,429	4,090	7,270	4,580	3,489	2,848	2,885
	C	1,437	1,207	1,201	1,452	1,586	2,093	3,409	4,123	7,467	4,805	3,765	3,066	2,967

	YEAR	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Annual means, (ft^3/s)	A	3,815	4,237	2,857	4,250	6,771	2,680	5,436	4,405	5,324	1,907
	B	3,757	4,115	2,809	4,283	6,714	2,700	5,450	4,373	5,276	1,895
Annual lowest means for 7 consecutive days, (ft^3/s)	A	1,540	1,130	893	859	1,670	1,100	951	1,410	1,640	645
	B	1,310	1,250	933	979	1,710	1,150	829	1,160	1,560	642
Annual highest means for 7 consecutive days, (ft^3/s)	A	12,100	14,200	8,260	14,000	16,800	6,380	18,600	13,000	18,200	3,270
	B	11,400	13,500	8,040	14,000	17,200	6,670	19,700	12,800	17,400	3,290

A = Record synthesized for Union Gap by adding Yakima River above Ahtanum Creek at Union Gap and Ahtanum Creek at Union Gap.
B = Record synthesized for Union Gap by adding Yakima River near Parker, Sunnyside Canal, Old Reservation Canal, and New Reservation Canal.
C = Record observed for Union Gap for the 1964 water year (station number 12503000).

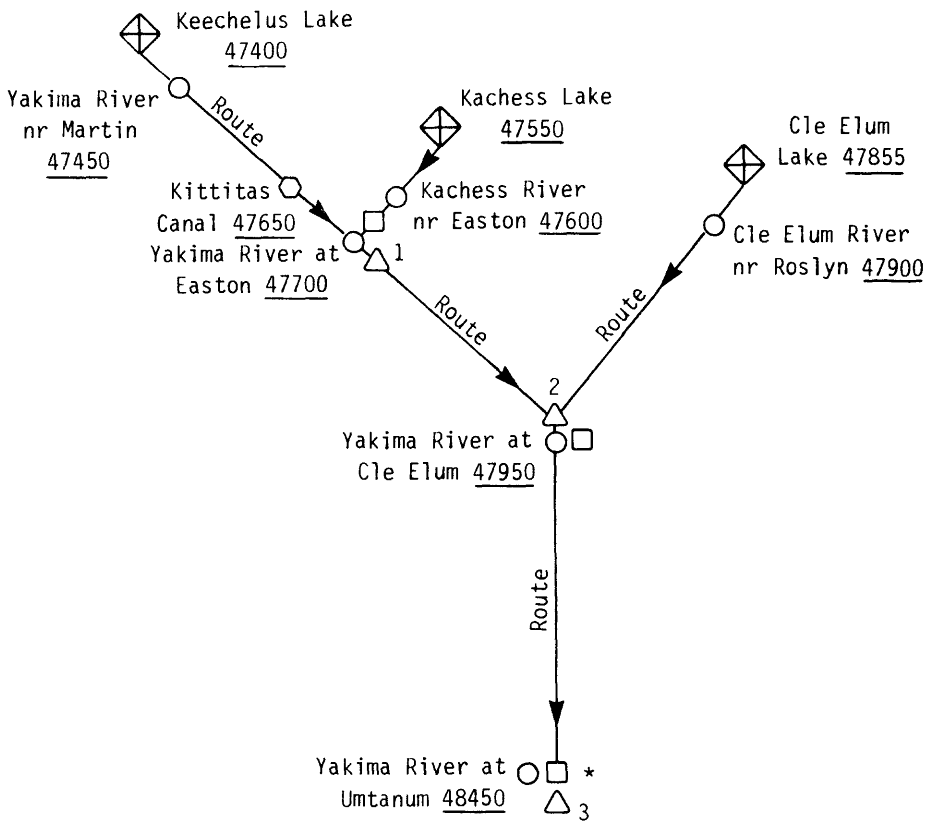
The first step in the calibration and verification process is the configuration of the model. To facilitate calibration, the Upper Yakima River basin was separated into three subbasins - the Umtanum, Naches, and Union Gap subbasins. The configurations of the subbasins (figs. 3 - 5) show the records used to calibrate, verify, and operate the model and where flow routing and summing computations take place.

In each configuration (figs. 3-5) the routed flow consists of two parts. The first part is the local inflow, and the second part includes streamflow that is adjusted for diversions and returns, routed to a downstream site, and summed there with local inflow. Local inflow is the ungaged inflow to a reach and consists of tributary inflow, surface runoff, and ground-water inflow or outflow. Definitions for each of the local inflows included in the model are given in table 2. In general, each local inflow is computed in the following order:

1. Local computation is initiated with the discharge recorded at an upstream river site or reservoir-outflow site.
2. Diversions from streamflow are subtracted from the streamflow recorded at the upstream river site;
3. Returns from diversion, determined as a percentage of the amounts diverted, are added to the streamflow recorded at the upstream river site;
4. Tributary inflows are added to the streamflow recorded at the upstream river site;
5. The result of step 4 is subtracted from the streamflow recorded at a downstream river site.

The inclusion of diversion return flows in the computation of local inflow is an important aspect that provides the basis for the assumption that the difference between regulated and unregulated local inflow values is small. Return flows from diversion are intended to include all returns representing the effects of regulation; that is, wasteways, drains, increased or decreased tributary inflow, and increases or decreases in the ground-water component of the riverflow. Thus, local inflow is intended to represent the natural contribution to riverflow from the local inflow area; that is, the natural surface runoff, tributary inflow, and ground-water recharge/discharge component. However small the difference between regulated and unregulated local inflow values really is depends on the accuracy of the daily streamflow records, diversion records, and return-flow estimates used to determine the local inflow values.

The percentage of each diversion that is return flow was estimated from the work of USBR (1979). Generally, about 55 percent of the daily amount diverted was returned over a 3-month period following the day of diversion. In the model, the return flow from each diversion was assumed to accumulate in a parallel reach and was then routed to the appropriate sum point to be used in the calculation of the local for that sum point. The routing of the accumulated return flows was done such that the arrival time of a return flow at a downstream sum point from each diversion approximated the 3-month return period.



EXPLANATION

Yakima River - Name of stream, lake, or canal

Route - Denotes a river reach where streamflow is computationally routed from one end of the reach to the other

47700 - Third through seventh digits of station indentification number (See Appendix I)

⟐ Reservoir storage record

○ Stream discharge record

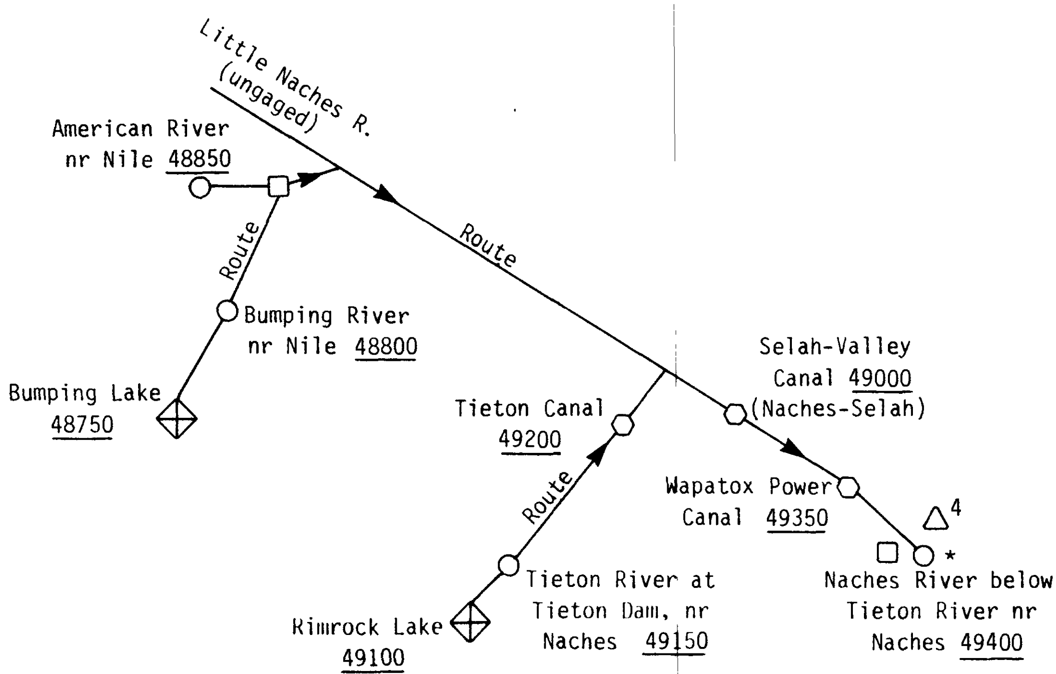
△ Local (ungaged) inflow computation point; number corresponds to identification given in table 2.

⬡ Canal diverson record; only nine largest of 58 shown

□ Summation point for upstream unregulated flows

* Summation point for upstream canal diversions minus returns

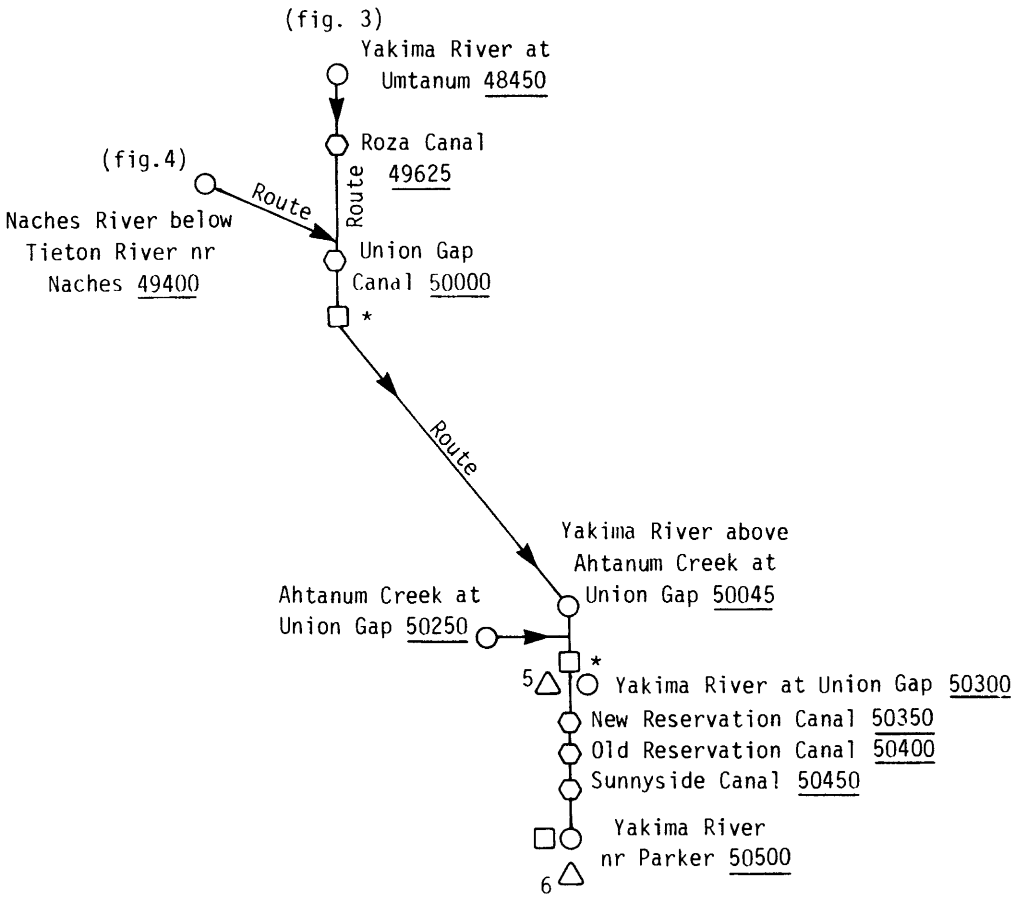
FIGURE 3.--SSARR model configuration for the Umtanum subbasin.



EXPLANATION

Tieton Canal	- Name of stream, lake, or canal
Route	- Denotes a river reach where streamflow is computationally routed from one end of the reach to the other
49400	- Third through seventh digits of station identification number (See Appendix I)
⊕	Reservoir storage record
○	Stream discharge record
△	Local (ungaged) inflow computation point; number corresponds to identification given in table 2.
⬡	Canal diversion record; only nine largest of 58 shown
□	Summation point for upstream unregulated flows
*	Summation point for upstream canal diversions minus returns

FIGURE 4.--SSARR model configuration for the Naches subbasin.



EXPLANATION

Roza Canal	- Name of stream, lake, or canal
Route	- Denotes a river reach where streamflow is computationally routed from one end of the reach to the other
50500	- Third through seventh digits of station identification number (See Appendix I)
⊕	Reservoir storage record
○	Stream discharge record
△	Local (ungaged) inflow computation point; number corresponds to identification given in table 2.
⬡	Canal diversion record; only nine largest of 58 shown
□	Summation point for upstream unregulated flows
*	Summation point for upstream canal diversions minus returns

FIGURE 5.--SSARR model configuration for the Union Gap subbasin.

TABLE 2.--Equations used to compute daily discharges for the six local watersheds in the SSARR model

Local 1/ Number	Equation
1	Yakima River at Easton minus Kachess River minus Yakima River at Martin plus Kittitas Canal diversions
2	Yakima River at Cle Elum minus Cle Elum River minus Yakima River at Easton minus Kittitas Canal returns
3	Yakima River at Umtanum minus Yakima River at Cle Elum minus Kittitas Canal and intermediate returns plus all other intermediate diversions
4	Naches River below Tieton River near Naches minus Tieton River at Tieton Dam minus American River near Nile minus Bumping River near Nile plus Wapatox Canal and Selah-Valley Canal and Tieton Canal and other smaller diversions minus returns from canals upstream of Naches.
5	Yakima River at Union Gap minus Naches River below Tieton River near Naches minus Yakima River at Umtanum plus Roza Canal and Union Gap Canal and other intermediate diversions minus intermediate returns of canals.
6	Yakima River near Parker minus Yakima River at Union Gap plus New, Old, and Sunnyside Canals minus intermediate returns.

1/ Local numbers are shown in figures 3-5.

The streamflow routing and summing of regulated daily flows for calibration and verification is accomplished in the model in the following order:

1. Streamflow routing is initiated with the discharge recorded at the upstream river site or reservoir outflow site;
2. Diversions from streamflow are subtracted from the streamflow recorded at the upstream site;
3. Returns from diversion, determined as a percentage of the amounts diverted, are added to the streamflow recorded at the upstream site.
4. The amount of streamflow remaining at the upstream river site is routed by a channel storage equation to the downstream river site;
5. Local inflow is added to the streamflow at the downstream river site.

The routing technique used in this model solves the following channel storage equation for each reach into which the river has been divided:

$$O_2 = \frac{I_m - O_1}{T_s + 0.5\Delta t} \Delta t + O_1 \qquad (1)$$

where:

O_1, O_2 are the outflows at time t_1 and time t_2;
I_m is the average of the inflows at times t_1 and t_2

$$I_m = \frac{I_1 + I_2}{2}$$

Δt is the time step used in routing ($\Delta t = t_2 - t_1$); and
T_s is called the time of storage per increment of a river reach.

Parameters in the equation are t and T_s. The T_s parameter represents channel storage, friction, and travel time, and must be defined by calibration for each river reach. T_s is determined for a reach in terms of I_m during the calibration process, where T_s is defined for a range of discharge (I_m) values. T_s values are further defined in terms of the number of increments that a reach is separated into. Generally, T_s values are definable for a range of discharge values between two points, usually streamflow gaging sites, which determine a reach of the river for routing. However, the travel time through the reach might be larger than the time-step size and(or) larger than the time size for which streamflow information is available, and also there might be dramatic changes in the flow regime in that reach. Thus, the reach is further divided into smaller lengths called reach-length increments. The streamflow is still computed at the two points that define the main reach, but intermediate calculations are also done. The reach-length increment for each reach is also determined during the calibration process. The parameter Δt is selected on the basis of the travel time through the river and the results of calibration. The independent variables in the equation are I_m and O_1.

None of the streamflow records available in the upper basin represent unregulated flow. Therefore, the model was calibrated and verified only on the basis of records of regulated flow. Regulation of streamflow in the Yakima River basin has been a continual process since the turn of the century, and, thus, the effects of regulation on the physical characteristics of the river (such as changes in slope, vegetation, roughness, and channel storage) are represented in the observed discharge values. As is seen later in the verification process, the differences between the measured and simulated regulated flows for the 1928 and 1968 water years are very small, indicating that 40 years of regulation had little effect upon model parameters. Given that the four physical characteristics mentioned above did not change by much, then the routing parameters used in this model are dependent only upon the quantity of the streamflow in the river. Therefore, the verified parameters are assumed to be applicable for use with both regulated and unregulated flows.

The routing parameters in equation 1 were calibrated to 2 water years of regulated daily-mean discharges - the regulated flows for the 1963 and 1964 water years. The 1963 water year was used for making initial estimates and modifications of the parameters. The model was then run to test the parameters, utilizing the discharges for 1964. Final adjustment of parameters was then completed using the 1964 discharges.

The three parameters calibrated for the model were T_s, t, and reach length increments. The time of storage per reach increment, T_s, was defined for each reach in terms of a relationship with average inflow discharge, which is based on time-of-travel curves furnished by USBR (Wensman, written commun., 1979). These time-of-travel curves are generally confirmed by the average velocities observed during measurements of river discharge by USGS. The number of reach-length increments was determined for each reach on the the basis of the results of calibration, generally ranging in number from 1 to 4. The time step size, Δt, was chosen as 6 hours on the basis of the results of calibration.

Verification of the parameters utilized the observed regulated daily-mean discharges for the 1928, 1965, 1968, and 1977 water years. These 4 water years represent different periods of development of storage and diversion, early and late periods of discharge records, dry, wet, and average years, and use of both sets of synthesized records for Yakima River at Union Gap. The results of verification are summarized in table 3. The accuracy of the numerical model is independent of whether the streamflow is regulated or unregulated, and the model will produce similar results for all years in which the routing parameters and the accuracies of the model input streamflow records remain the same. Figures 6 and 7 illustrate the results of verification for the 1968 water year for Union Gap and Parker, respectively.

Verification was accomplished for the following sites: Yakima River at Cle Elum, Yakima River at Umtanum, Naches River near Naches, Yakima River at Union Gap, and Yakima River near Parker. The results of verification are given in this report only for the Union Gap and Parker sites because defining the effects of regulation at these two sites is the objective of this study.

Computation of Unregulated Flow

The routing and summing or computation, of unregulated daily flows is accomplished similar to the routing and summing of regulated daily flows (p. 15), except that: 1) diversions are not subtracted; 2) returns from diversion are not added; and 3) the streamflow recorded at the upstream reservoir outflow sites is adjusted for the recorded daily changes in storage contents of the reservoirs. For example, the midnight storage-contents reading of a reservoir on day 2 is subtracted from the midnight storage-contents reading on day 1; this difference (acre-feet/day) is then converted to cubic feet per second and is subtracted from the mean daily regulated discharge recorded at the reservoir outflow site for day 2. The unregulated daily discharges so determined for each upstream site are routed by a channel storage equation to the downstream site where "local" inflow is added, just as it was added in the computation of regulated daily discharges.

Simulation Accuracy

The accuracy of the simulated daily unregulated discharges can be estimated from the following three sources of errors: (1) numerical model error; (2) inadequacies in the assumption that return flows are a percentage of the streamflow; and (3) inaccuracies in the records of reservoir storage contents. Each source of error is discussed below, and an estimate of the accuracy of the simulated discharge is given in this section.

The square root of the mean square error, defined as the variance of the daily differences (residuals) between the observed and predicted discharge plus the square of the bias (mean residual), at Union Gap and Parker for each year used for model verification can be combined through a root-mean-square to give an estimate of the numerical model error at each site.

TABLE 3.--Results of simulating regulated daily-mean discharges in four water years at Union Gap and near Parker

Water year	Annual Discharge Observed (ft³/s)	Annual Discharge Simulated (ft³/s)	Error (ft³/s)	Maximum daily discharge[2] Observed (ft³/s)	Maximum daily discharge[2] Simulated (ft³/s)	Maximum daily discharge[2] Error (ft³/s)	Minimum daily discharge Observed (ft³/s)	Minimum daily discharge Simulated (ft³/s)	Minimum daily discharge Error (ft³/s)	Maximum daily error (ft³/s)	Observed discharge on day of maximum daily error (ft³/s)	Mean[3] residual (ft³/s)	Sum of[4] residual (ft³/s)	Residual standard deviation (daily error) (ft³/s)
							A. Union Gap[1]							
1928	4,727	4,732	5	19,200	20,100	900	1,440	1,510	70	6,440	15,700	-4.99	-1,826	547.8
1965	4,459	4,458	1	21,500	20,300	1,200	1,070	1,080	10	3,460	14,000	1.0	364	339.6
1968	3,915	3,914	1	13,900	14,800	900	1,490	1,460	30	2,290	4,720	1.34	489	367.6
1977	1,907	1,908	1	3,480	3,560	80	601	522	79	810	2,640	-1.3	-476	125.9
							B. Parker							
1928	3,433	3,425	5	19,200	19,300	100	96	6	90	7,420	15,700	-5.49	-2,010	635.0
1965	2,909	2,910	1	21,500	19,200	2,300	52	11	41	4,260	14,000	1.02	373	432.5
1968	2,207	2,208	1	13,600	14,400	800	77	65	12	3,000	10,900	1.44	527	433.6
1977	497	496	1	2,510	2,510	0	1	162	161	981	2,370	-1.47	-537	138.3

1 Record for Union Gap synthesized as described in text and table 2.
2 Model discharge is that on same date as recorded maximum or minimum.
3 Mean residual is the average of the differences between the observed and simulated daily discharges for the water year.
4 Residual is the year-end sum of the arithmetic differences in recorded and simulated daily-mean discharges.

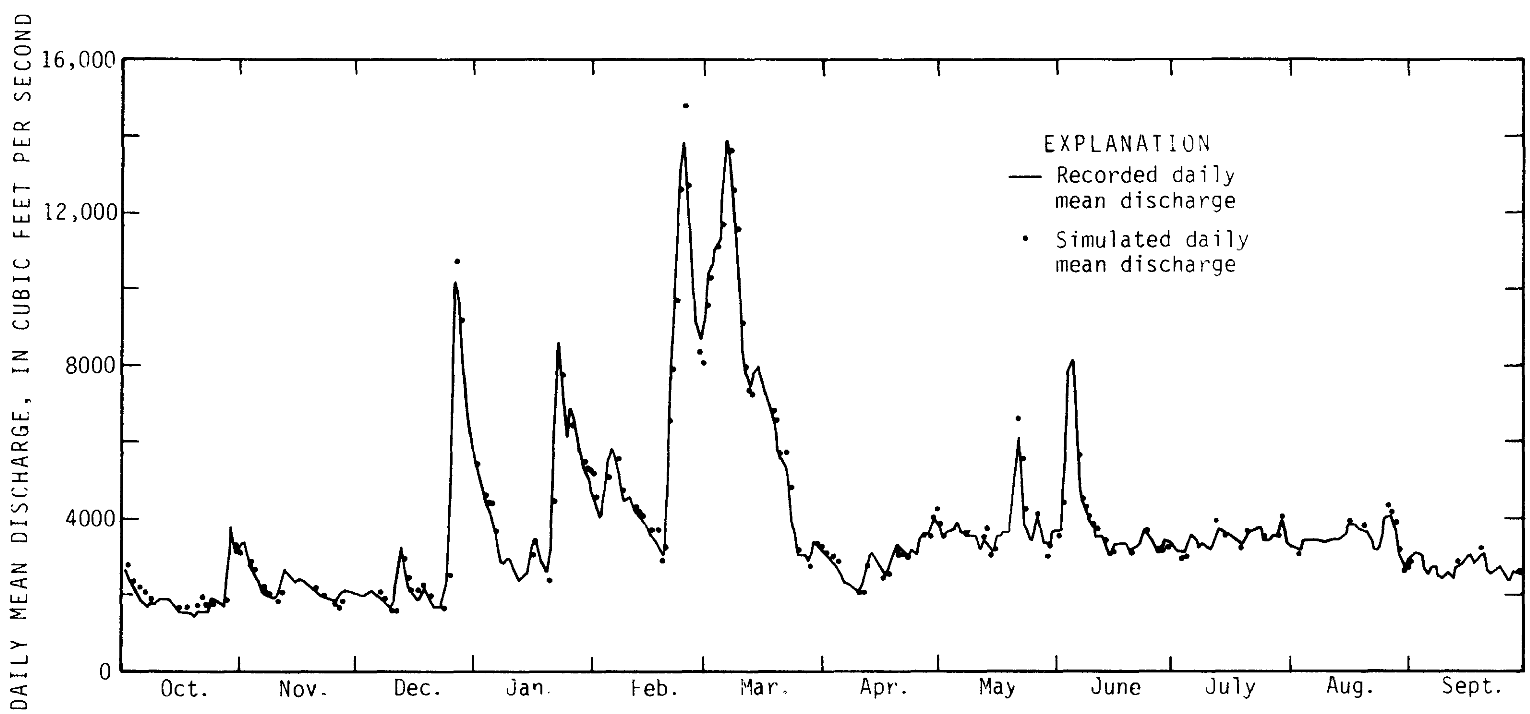


FIGURE 6.--Daily mean discharges of the Yakima River at Union Gap for the 1968 water year. Simulated discharges are shown only where significantly different from recorded discharges.

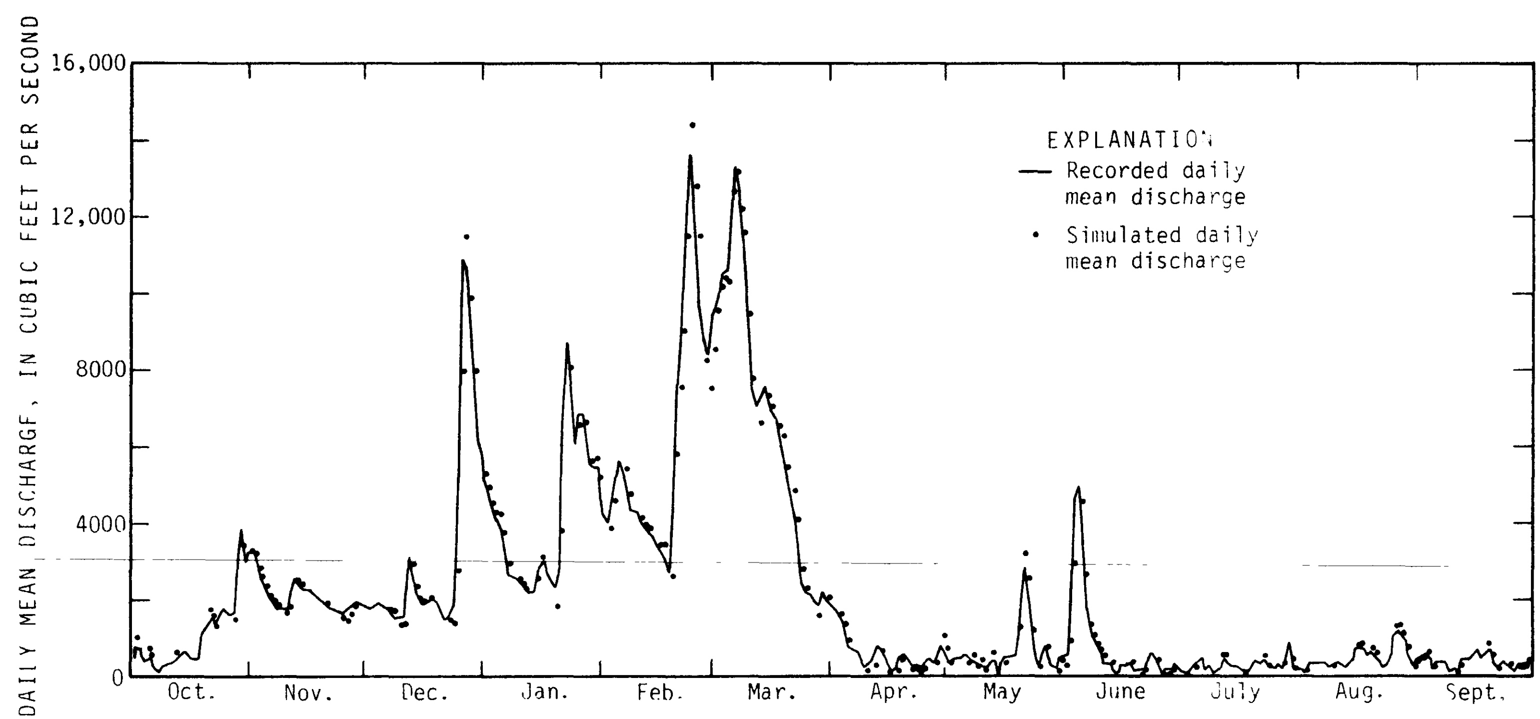


FIGURE 7.--Daily mean discharges of the Yakima River near Parker for the 1968 water year. Simulated discharges are shown only where significantly different from recorded discharges.

The model error is estimated from an analysis of the values in table 3 to be 10 percent of the daily discharge at Union Gap and 19 percent of the daily discharge near Parker. The reason for the difference in percentage error between sites is that the daily discharges at Parker are smaller than at Union Gap, while the model error, in cubic feet per second, is approximately the same at both sites.

Returns to streamflow from the diversions that are removed from streamflow are computed in the SSARR model as percentages of the quantities diverted, routed back to the stream. The accuracies of the amounts diverted are not published and the return-flow percentages are estimated. Because the errors in diversions and return flows cannot be defined, the difference between total diversion and return-flow quantities was tested by sensitivity analyses. In the test, based on the 1965 water year, a plus or minus 30-percent change in the net difference between diversions and returns resulted in about a 7-percent difference in the computed unregulated flows. This difference is taken to be the approximate error that might result from possible inaccuracies in diversion and return-flow quantities.

The component error due to inaccuracies in the measurement of storage contents was estimated by determining the effect that a ±0.1-foot error in reading stage at maximum storage capacity at the five reservoirs could have on the average annual unregulated discharge at Union Gap. The effects on the unregulated discharges at Union Gap of storage contents errors resulting from such inaccuracies in the reading of stage was estimated to be 7 percent. The 7 percent is probably a high value because inaccuracies of 0.1 ft in stage are probably unusual.

The error of the computed unregulated streamflow is estimated by combining the three component errors into a root-mean-square error. The composite error for the computed daily-mean unregulated discharges is estimated to be about 12 percent of the daily discharge computed as the root-mean-square of model errors (10 and 19 percent), return-flow percentage errors (7 percent), and stage-contents errors (7 percent).

COMPARISON OF REGULATED AND UNREGULATED STREAMFLOW

The objective of this study was to determine the extent that regulation (reservoir storage and canal diversion) has affected streamflow of the Yakima River at Union Gap and near Parker. The extent to which streamflow has been affected by regulation upstream of Union Gap and Parker was determined by:

1. Comparing the mean, standard deviation, and distribution percentiles of unregulated with regulated annual discharges (averages of 365 or 366 daily values) using all 52 years;
2. Comparing the mean, standard deviation, and distribution percentiles of unregulated with regulated monthly discharges (means of 27, 28, 30, or 31 daily values) for each of the 12 months of the year using all 52 years;
3. Comparing mean, standard deviation, and distribution percentiles of unregulated with regulated minimum 7-day and 183-day average discharges (annual lowest averages for 7 or 183 consecutive days) using all 52 years.

In the study, the daily unregulated discharges were computed for every day of the 52-year period from 1926 through 1977. To simplify presentation, the daily discharges for both regulated and unregulated conditions have been summarized as annual, monthly, and minimum flow statistics.

The results are given in the form of some graphs (figs. 8-11) that illustrate the effects of regulation and as numerical values (tables 4-18) that quantify the effects of regulation. The format and type of numerical values are identical in each of the tables. Referring to table 4 for annual discharges, each table has two major parts: 1) recorded regulated and computed unregulated discharges; and 2) the difference between unregulated and regulated discharges. Table 4 will be discussed in the following paragraphs in order to identify the type and meaning of the numerical values presented.

In the first part of the table, from left to right, the first column identifies the location and type of flow, the next three columns give the mean, standard deviation, and coefficient of variation for the 52 annual discharges, and the final five columns show the percent of years that the annual value exceeded specified discharges.

The standard deviation is a common statistical measure of the dispersion (variability) of a set of values about the mean of the values in the set. The larger the standard deviation, the greater is the dispersion. The storage in reservoirs during periods of high streamflow and the release from storage during periods of low streamflow often reduce the within-year variability of daily and monthly streamflow, thus producing lower values of standard deviation. Diversion from streamflow can cause standard deviation to either increase or decrease.

The coefficient of variation given in the fourth column is the dimensionless ratio of standard deviation to the mean discharge, thus providing a statistic comparing the relative variabilities of two or more flow records of different magnitudes. The larger the coefficient of variation, the greater the relative dispersion. Storage and diversion may cause the coefficient of variation to be either increased or decreased.

The distribution percentiles were computed from frequency curves of the 52 annual, monthly, and minimum discharge values obtained from the unregulated and regulated daily values for each water year. These distribution percentiles represent the percent of time, in years, that a discharge value either exceeded that indicated or was less than that indicated. The percentage of time (in years) that the observed or simulated discharge values are exceeded is useful for comparing flows that are much less or much more than the average. These relative discharge values of regulated and unregulated flow can be used to describe the effects of storage and diversion on the other-than-average flows. As an example, in table 4 it is shown that in 99 percent of the 52 water years of record, the unregulated annual discharge was greater than 2,000 ft^3/s. However, in 99 percent of the 52 water years of record the regulated annual discharge at Parker was greater than 430 ft^3/s. Although the discharge values given can be compared, they should not be interpreted as probability values, but rather as relative values that were exceeded a certain percentage of time. In the example given above, larger unregulated annual flows "occurred" than did regulated flows. Thus, the effect of regulation on annual discharge values at Parker was to lower the annual discharge quantity.

All values in the tables are reduced to two significant digits, in keeping with the accuracy of the numerical model. The unregulated discharge values computed by the model were slightly different for Union Gap and Parker, but are considered herein to be identical. A small difference logically would be expected from local effects between those two locations, but the amount of this local effect is judged to be considerably smaller than the composite error in the simulated record.

The differences presented in the second part of the tables represent the actual discharge quantity, the effect, that has resulted from regulation. For example, in table 4 it is seen that the average annual discharge at Union Gap has been reduced by 1,000 ft^3/s and the standard deviation has been reduced by 200 ft^3/s due to regulation. The differences for the distribution percentiles are not to be interpreted as a frequency distribution, but rather as a guide to ascertaining the effects of regulation on non-normal flows. These discharge differences quantify the effects of regulation on the spectrum of flows.

Annual Discharges

The annual discharges for regulated (patterned graphs) and unregulated (unpatterned graph) streamflow at Union Gap and Parker are shown in figure 8. The difference between the two patterned graphs is large, and is nearly all due to the three diversion canals (fig. 5) operating downstream of Union Gap and upstream of the Parker gage site. These canals deplete the streamflow that passes Union Gap, and the amount of depletion for any water year is the difference between the two graphs. For the long-term average (52 years), the difference is 1,500 ft^3/s. Figure 8 shows that unregulated annual discharges are always greater than regulated annual discharges.

In table 4, the average annual unregulated streamflow is 4,800 ft^3/s, which is larger than the regulated streamflow near Parker (2,300 ft^3/s) and larger than the regulated flow at Union Gap (3,800 ft^3/s). The difference at Union Gap (1,000 ft^3/s) represents losses due mostly to diversion, increased evapotranspiration, leakage to ground water, consumptive losses, and water exported out of the upper Yakima River basin - for example, Roza Canal water, which is tranported to the lower basin. The difference of 1,000 ft^3/s also directly affects the Parker site and, thus, the remaining difference at Parker 1,500 ft^3/s (3,800 ft^3/s minus 2,300 ft^3/s) is due to the three diversion canals between Union Gap and Parker. The differences between unregulated and regulated annual discharges (1,000 and 2,500 ft^3/s) far exceed the estimate of a 12-percent composite error of $\pm$ 576 ft^3/s in the average unregulated discharge.

The standard deviations of regulated annual discharges (1,200 ft^3/s) are less than the standard deviation of the unregulated annual discharges (1,400 ft^3/s). This indicates that the overall effect of storage and diversion in the upper basin is reduction of the variabilty of annual-mean discharges. The coefficients of variation for regulated flows show, however, that the relative variability has been nearly unchanged at Union Gap (0.32 versus 0.29) and has actually increased near Parker (0.52 versus 0.29).

The discharge value shown in table 4 that was exceeded 50 percent of the time is the median value of the 52 annual discharge values. The above comparisons and conclusions made for the average annual discharges can be applied to the median discharge. For the discharge value that was exceeded 99 percent of the time by the annual discharges, the spread between unregulated and regulated discharges is less than at the 50-percent level, which is in turn less than that at the 1-percent level. This suggests that more water is diverted and lost in wet years, when water is plentiful, than in dry years. That possibility is substantiated by examination of (1) the individual annual- mean discharges for wet and dry years shown in figure 8 and (2) a plot of the 52 unregulated annual discharge versus the difference between the unregulated and regulated annual discharges shown in figure 9.

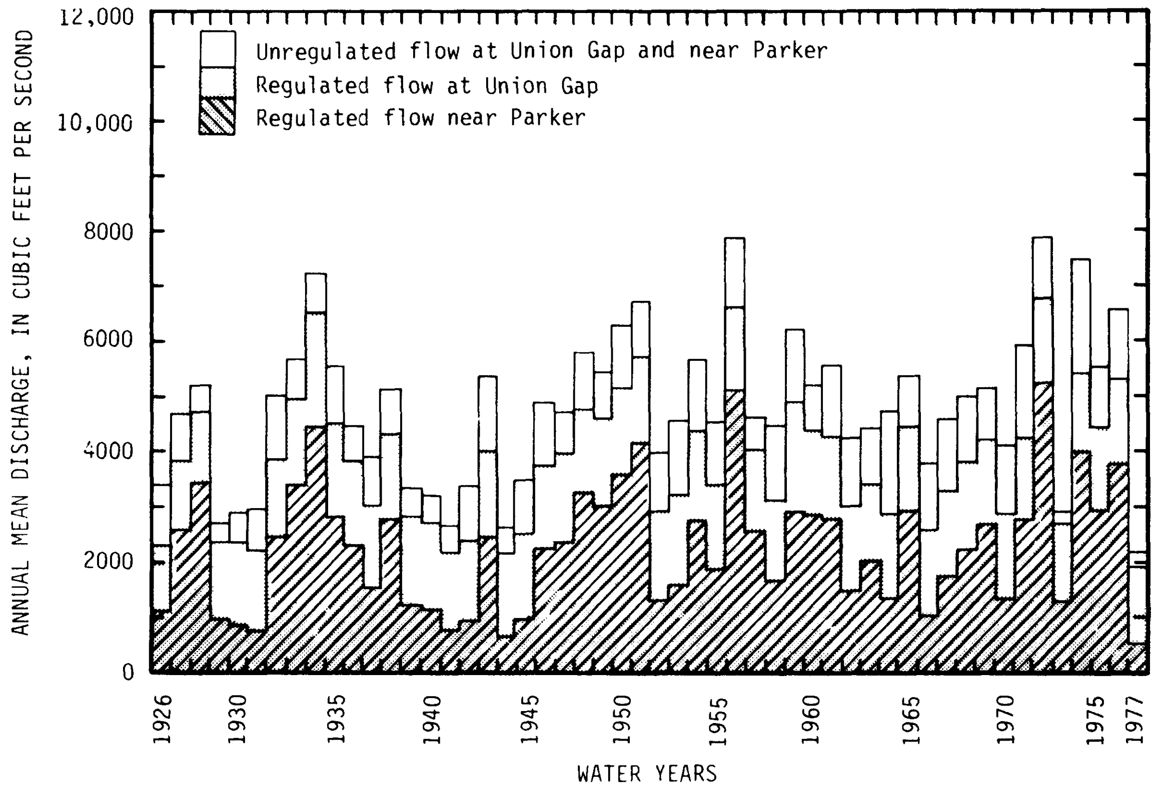


FIGURE 8.--Regulated and unregulated annual discharges at Union Gap and near Parker.

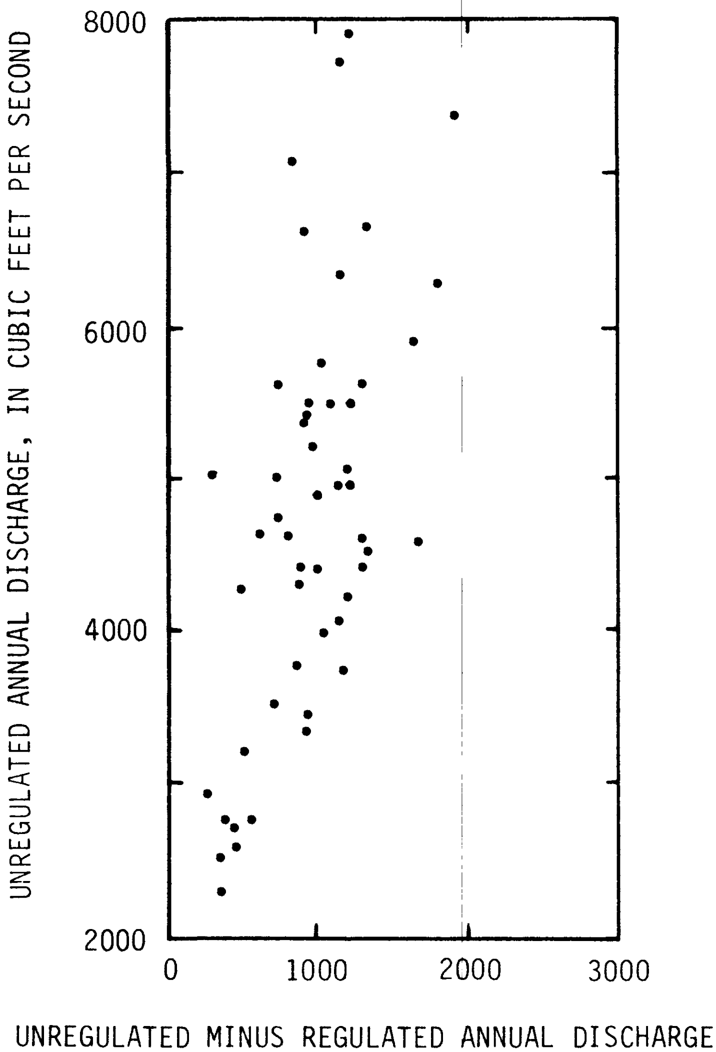


FIGURE 9.--Unregulated annual discharges and the difference between unregulated and regulated annual discharges at Union Gap, 1926-77.

TABLE 4.--Values of unregulated and regulated annual discharges at Union Gap and near Parker during the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	4,800	1,400	0.29	8,400	6,600	4,700	3,000	2,000
Yakima River at Union Gap - Regulated	3,800	1,200	.32	7,500	5,400	3,600	2,400	1,700
Yakima River near Parker - Regulated	2,300	1,200	.52	6,300	4,000	2,100	920	430
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	1,000	200		900	1,200	1,100	600	300
Yakima River near Parker	2,500	200		2,100	2,600	2,600	2,100	1,600

Monthly Discharges

The average monthly discharges for regulated and unregulated streamflow at Union Gap and near Parker are shown graphically in figure 10, and the numerical results of the analysis of monthly discharges are summarized by month in tables 5 through 16.

Figure 10 illustrates several aspects of the effects of regulation on streamflow. Outside the irrigation season, the monthly values of regulated flow at Union Gap and near Parker are basically the same. During the April-through-October irrigation season, the mean-monthly regulated flows near Parker are smaller than at Union Gap because streamflow is diverted by the three canals downstream of Union Gap and upstream of Parker. Monthly regulated flow near Parker is always less than the monthly unregulated flow. The monthly regulated flow at Union Gap is less than the unregulated flow, except for the low-flow months of August and September. Generally, the differences between the unregulated and regulated curves shown in figure 10 illustrate the month-by-month effects of winter-spring storage of runoff, the seasonal diversion and returns, and the seasonal release of stored water to produce flows higher than would otherwise occur at Union Gap during August and September.

The summarized values of the monthly-mean discharge for January are shown in table 5. A comparision of the unregulated and regulated values for January, with respect to February (table 6) and December (table 16), shows that for the winter months flow has been similarily affected by regulation. Therefore, only January will be discussed, and similar conclusions of the comparsion can be made for February and December. The storage of winter runoff has resulted in about a 36-percent reduction in the unregulated January monthly discharge at Union Gap and near Parker. The difference in the monthly flow is 900 ft^3/s, which is much larger than a 12-percent composite error in the computed unregulated monthly discharge, ± 456 ft^3/s. A comparision of the standard deviation shows that there has not been a reduction in the variability of the January monthly discharges, 2,200 ft^3/s for unregulated and regulated flow. However, the coefficient of variation indicates that there was an increase in variability of the regulated flow with respect to the mean- monthly flow. The monthly discharge values that were exceeded indicate that storage has reduced the December-through-February monthly discharges for all percentages of time.

The values for unregulated and regulated March monthly discharges are shown in table 7. A comparison of the unregulated and regulated values at Union Gap shows that they are similar to the previously discussed month of January and, thus, the conclusions drawn for the months December through February can be applied to March for Union Gap. An analysis of the percentage of time that indicated discharges have been exceeded by March regulated monthly discharges for Parker shows three important factors resulting from the regulation of the three canals downstream of Union Gap and upstream of Parker: (1) there has been a reduction in high flows; (2) the median discharge (discharge exceeded 50-percent of the time) near Parker is larger than the average March monthly discharge, indicating that most March discharges near Parker are high, but some are very low; and (3) the March regulated flows have generally been decreased from Union Gap to Parker, except at the median level.

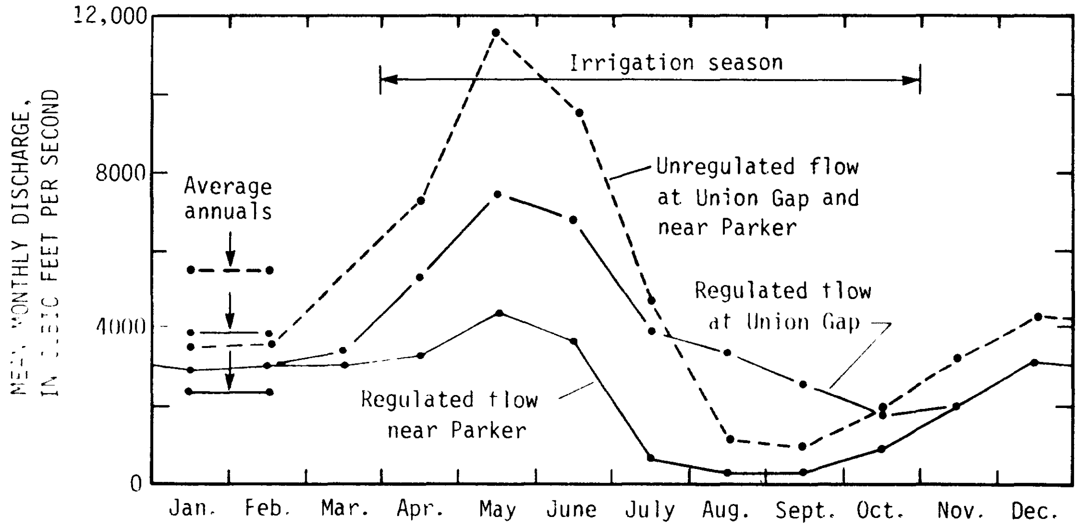


FIGURE 10.--Regulated and unregulated mean monthly discharges at Union Gap and near Parker, 1926-77.

TABLE 5.--Values of unregulated and regulated monthly discharge for January, based on the period 1926-1977

Station and type of fl-w	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	3,800	2,200	0.58	12,000	6,600	3,200	1,600	870
Yakima River at Union Gap - Regulated	2,900	2,200	.76	13,000	5,600	2,300	1,000	550
Yakima River near Parker - Regulated	2,900	2,200	.76	12,000	5,600	2,300	1,000	540
	<u>Regulated flow subtracted from unregulated flow (ft^3/s)</u>							
Yakima River at Union Gap	900	0		-1,000	1,000	900	600	320
Yakima River near Parker	900	0		0	1,000	900	600	330

TABLE 6.--Values of unregulated and regulated monthly discharge for February, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	3,800	2,200	0.57	13,000	6,700	3,200	1,700	1,000
Yakima River at Union Gap - Regulated	3,000	1,900	.63	11,000	5,500	2,500	1,100	500
Yakima River near Parker - Regulated	3,000	1,900	.63	9,900	5,500	2,500	1,100	500
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	800	300		2,000	1,200	700	600	500
Yakima River near Parker	800	300		3,100	1,200	700	600	500

TABLE 7.--Values of unregulated and regulated monthly discharge for March at Union Gap, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	4,400	2,300	0.52	13,000	6,900	3,800	2,600	2,100
Yakima River at Union Gap - Regulated	3,400	2,200	.65	12,000	5,900	2,800	1,500	1,000
Yakima River near Parker - Regulated	3,000	2,300	.77	4,000	4,000	3,400	770	30
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	1,000	100		1,000	1,000	1,000	1,100	1,100
Yakima River near Parker	1,400	0		9,000	2,900	400	1,800	2,100

The above analysis suggests that storage is the principal cause of differences between mean-monthly regulated and unregulated discharges at Union Gap for the months of December through March. Similarily, the results can be applied to Parker for December through February, but not for March. March differences near Parker are the composite effect of both storage and diversion, where the effect of diversion on Parker is the difference between Parker and Union Gap regulated monthly flows.

Tables 8, 9, and 10 show the monthly values for the spring runoff period of April through June. For Union Gap, the monthly values are similiar for this period. The monthly unregulated discharge at Union Gap for the spring runoff period has been reduced by 2,400 ft^3/s in April (a 32-percent reduction) due to regulation. The reduction in the April median value (2,500) is about the same as the reduction in the mean value (2,400 ft^3/s).

Near Parker there is the additional large effect of the three diversion canals on the monthly unregulated discharges for April through June. This effect is similar for all 3 months. Regulation has caused a 4,400-ft^3/s-reduction (58 percent) in the April monthly unregulated discharge near Parker. This is 2,000 ft^3/s (26 percent) more reduction than at Union Gap. The coefficients of variation show that the variability of April monthly means relative to the monthly discharge has significantly increased, more than doubled. April monthly discharges are generally lower near Parker than at Union Gap, exemplified by discharge values that were exceeded more than 90 percent of the time.

Table 11 summarizes results for the month of July, a transition month from high to low runoff. The July unregulated flow has been increased by 200 ft^3/s (5 percent) at Union Gap. A reduction of 2,900 ft^3/s (79 percent) near Parker is due to the three diversion canals. The variability of the July unregulated monthly discharge, as measured by the coefficient of variation, has been greatly reduced at Union Gap, but has more than doubled at Parker. At Parker the standard deviation is larger than the mean, indicating that July flow may, in some years, approach zero there.

The results of the analysis of the August discharges are presented in table 12, and the frequency curves are shown graphically in figure 11. The monthly discharges and coefficient variations in table 12 show that the August regulated monthly discharge at Union Gap is 1,800 ft^3/s larger (53 percent) and is less variable than the unregulated August monthly discharge.

The mean-monthly unregulated discharge for August near Parker is 1,500 ft^3/s, compared with the regulated discharge of 330 ft^3/s, a reduction of 78 percent. Compared with Union Gap, the coefficient of variation near Parker indicates that the relative variability of August mean discharges near Parker has increased somewhat. The steeper distribution curve for August regulated flows near Parker, shown in figure 11, illustrates the greater relative variability for Parker.

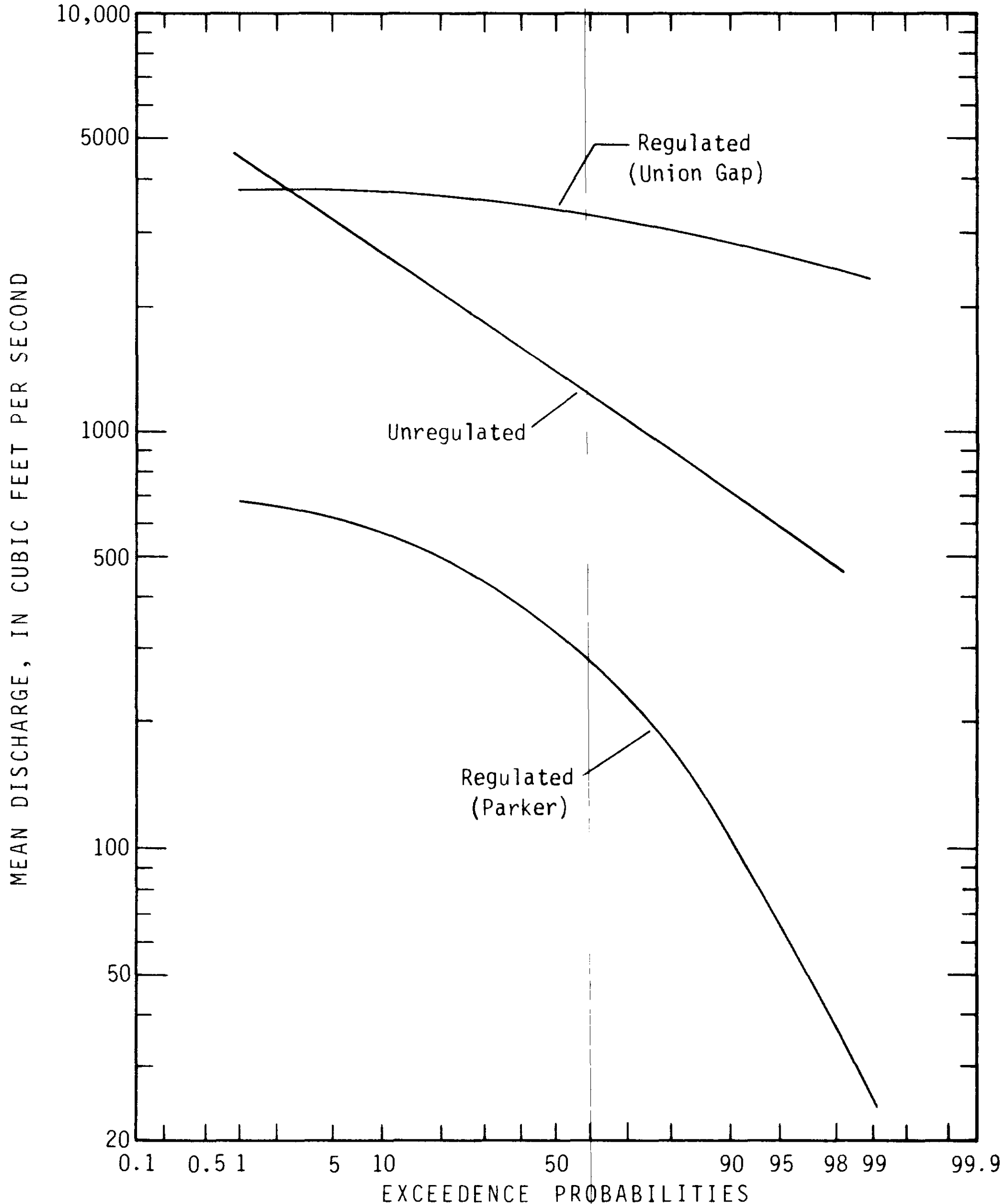


FIGURE 11.--Percentage of time, in years, that regulated and unregulated August mean discharges exceeded indicated magnitudes, 1926-77.

TABLE 8.--Values of unregulated and regulated monthly discharge for April, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	7,600	2,700	0.36	16,000	11,000	7,200	4,400	2,800
Yakima River at Union Gap - Regulated	5,200	2,500	.48	14,000	8,400	4,700	2,700	1,800
Yakima River near Parker - Regulated	3,200	2,500	.78	13,000	6,900	2,400	630	160
	Regulated flow subtracted from unregulated flow (ft^3/s)							
Yakima River at Union Gap	2,400	200		2,000	2,600	2,500	1,700	1,000
Yakima River near Parker	4,400	200		3,000	4,100	4,800	3,800	2,600

TABLE 9.--Values of unregulated and regulated monthly discharge for May, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	12,000	4,100	0.35	22,000	17,000	11,000	6,500	3,700
Yakima River at Union Gap - Regulated	7,400	3,000	.41	17,000	12,000	7,000	3,900	2,300
Yakima River near Parker - Regulated	4,300	3,000	.70	15,000	9,300	3,500	730	120
	Regulated flow subtracted from unregulated flow (ft^3/s)							
Yakima River at Union Gap	4,600	1,100		5,000	5,000	4,000	2,600	1,400
Yakima River near Parker	7,700	1,100		7,000	7,700	7,500	5,800	3,600

TABLE 10.--Values of unregulated and regulated monthly discharge for June, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	9,600	4,700	0.49	24,000	16,000	8,900	4,000	1,800
Yakima River at Union Gap - Regulated	6,800	3,300	.49	19,000	11,000	3,200	3,200	2,000
Yakima River near Parker - Regulated	3,700	3,200	.86	23,000	9,700	2,300	350	50
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	2,800	1,400		5,000	5,000	5,500	800	-200
Yakima River near Parker	5,900	1,500		1,000	6,300	6,400	3,600	1,800

TABLE 11.--Values of unregulated and regulated monthly discharge for July, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	3,700	2,400	0.64	13,000	7,100	3,100	1,300	600
Yakima River at Union Gap - Regulated	3,900	1,000	.26	7,900	5,200	3,600	3,000	2,800
Yakima River near Parker - Regulated	790	980	1.2	7,000	1,800	420	130	60
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	-200	1,400		5,100	1,900	-500	-1,700	-2,200
Yakima River near Parker	2,900	1,400		6,000	5,300	2,700	1,200	540

TABLE 12.--Values of unregulated and regulated monthly discharge for August, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	1,500	740	0.50	4,300	2,400	1,300	700	500
Yakima River at Union Gap - Regulated	3,300	330	.10	3,800	3,700	3,300	2,800	2,300
Yakima River near Parker - Regulated	330	190	.58	680	580	330	100	20
	Regulated flow subtracted from unregulated flow (ft^3/s)							
Yakima River at Union Gap	-1,800	410		500	-1,300	-2,000	-2,100	-1,800
Yakima River near Parker	1,170	550		3,600	1,800	970	600	480

The values presented in table 13 for September are similar to the values presented in table 12 for August for all sites. Therefore, the comparisons and conclusions for September are similar to those for August, though the actual numerical values differ somewhat.

The values for the month of October, the last month in the irrigation season, are presented in table 14. A comparison of October monthly values shows that the 2,100-ft^3/s unregulated monthly-mean flow has been reduced by 300 ft^3/s (14 percent) at Union Gap and by 1,200 ft^3/s (51 percent) near Parker. There is an increase in the coefficient of variation for the regulated October discharges near Parker, from the unregulated value of 0.47 to the regulated value of 0.64. Thus, the relative variability of October regulated flows near Parker is greater than at Union Gap and greater than unregulated flows near Parker.

The unregulated and regulated values for the month of November are given in table 15, and are similar to but less than the December to February values. November unregulated discharge has been decreased by 1,400 ft^3/s (41 percent), and with this decrease, regulation has caused a decrease in the coefficient of variation of these flows.

Minimum 7-Day and 183-Day Average Discharges

The minimum annual 7-day and 183-day average discharges are the lowest average discharges for 7 and 183 consecutive days of each year of recorded regulated and computed unregulated streamflow. They have been determined for this study because of a particular concern about the effects that storage and diversion have had on low flow at Union Gap and near Parker during the irrigation season.

The minimum average discharge for 7 consecutive days was selected for comparison rather than a shorter or longer period of consecutive days because it characterizes annual short-duration minimums without being strongly influenced by any unusual occurrences during any one day. It is also a discharge commonly used throughout the United States for comparing low flow among streams and in some States as a criterion for the allocation of streamflow among competing uses, and more often as a regulatory criterion for wasteload allocations.

The minimum mean discharge for 183 consecutive days was selected for comparison because it characterizes annual seasonal minimums.

TABLE 13.--Values of unregulated and regulated monthly discharge for September, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	1,400	500	0.35	3,000	2,000	1,300	870	660
Yakima River at Union Gap - Regulated	2,600	440	.17	3,100	3,000	2,700	2,000	1,200
Yakima River near Parker - Regulated	330	260	.79	1,000	650	280	90	30
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	-1,200	60		-100	-1,000	-1,400	-1,100	-540
Yakima River near Parker	1,100	240		2,000	1,400	1,000	780	630

TABLE 14.--Values of unregulated and regulated monthly discharge for October, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	2,100	1,000	0.47	6,000	3,400	1,900	1,100	820
Yakima River at Union Gap - Regulated	1,800	600	.33	3,800	2,600	1,700	1,200	880
Yakima River near Parker - Regulated	950	610	.64	3,000	1,800	820	320	130
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	300	400		2,200	800	200	-100	-60
Yakima River near Parker	1,200	390		3,000	1,600	1,100	780	690

TABLE 15. Values of unregulated and regulated monthly discharge for November, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	3,400	2,100	0.63	12,000	6,100	2,800	1,300	740
Yakima River at Union Gap - Regulated	2,000	1,200	.60	7,500	3,500	1,600	900	610
Yakima River near Parker - Regulated	2,000	1,200	.60	7,400	3,500	1,600	850	550
	Regulated flow subtracted from unregulated flow (ft^3/s)							
Yakima River at Union Gap	1,400	900		4,500	2,600	1,200	400	130
Yakima River near Parker	1,400	900		4,600	2,600	1,200	450	190

TABLE 16.--Values of unregulated and regulated monthly discharge for December, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was exceeded: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	4,200	3,100	0.84	16,000	7,700	3,400	1,600	960
Yakima River at Union Gap - Regulated	3,100	2,800	.90	17,000	6,100	2,200	960	580
Yakima River near Parker - Regulated	3,100	2,800	.90	17,000	6,000	2,100	950	570
	Regulated flow subtracted from unregulated flow (ft^3/s)							
Yakima River at Union Gap	1,100	300		-1,000	1,600	1,200	640	380
Yakima River near Parker	1,100	300		-1,000	1,700	1,300	650	390

The results of the analysis of the 52 annual minimum 183-day discharges for regulated and unregulated flow are given in table 17. The previous sections presented the results of the analysis of annual and monthly discharges in terms of the percentage of time (years) that the indicated discharge was exceeded for the 52 discharges analyzed. Minimum flows are commonly analyzed in terms of probabilities of being less than, and, thus, the percentages of time that minimum flows were less than the indicated discharge are presented. The mean 183-day unregulated value of 2,400 ft^3/s is 100 ft^3/s greater than the regulated value at Union Gap and about 1,400 ft^3/s greater than the regulated value near Parker. The differences between the minimum 183-day unregulated and regulated discharges exceed the estimated composite error in the average 183-day unregulated discharge. The difference between the 183-day regulated discharges for Union Gap and Parker (1,300 ft^3/s) is due almost entirely to the three major canals that divert streamflow between Union Gap and Parker.

The standard deviations of regulated minimum 183-day discharges are less than the standard deviation of the unregulated discharges. Notably, near Parker the 700 ft^3/s standard deviation for the regulated 183-day minimums is nearly as large as the 980 ft^3/s average 183-day minimum there, indicating that seasonal minimums were as low as 300 ft^3/s in some years. The percent-of-time distribution for Parker indicates that 1 percent of the time the 183-day minimum was less than 130 ft^3/s.

The coefficients of variation for regulated minimum 183-day flows show that the variability of those flows is less at Union Gap (0.41) than for uregulated flows there (0.44), but is greater near Parker (0.71). If the amounts of water diverted in the three major canals between Union Gap and Parker are generally uniform from year to year and month to month, which is the case indicated by figures 8 and 10, then much of the variability in regulated seasonal low flows at Union Gap and near Parker is likely due largely to the natural variability reflected in the unregulated flows. That likelihood is evidenced for unregulated flows by a greater coefficient of variation of minimum 183-day values (0.44, table 17) than for annual-mean values (0.29, table 4).

The results of the analysis for the 52 annual minimum 7-day discharges are given in table 18. The mean 7-day unregulated low flow of 930 ft^3/s is 200 ft^3/s less than the regulated values at Union Gap, and about 800 ft^3/s greater than the regulated values near Parker. An estimated error range of 12 percent applied to the average 7-day unregulated low flows equals about $\pm$112 ft^3/s, which is about the same as the difference between unregulated and regulated values given for Union Gap. Thus, the difference between those values for Union Gap may be real, or they may be due only to errors in the determination of unregulated flows. If they are due to errors, then storage and diversion have little or no effect on the short-duration low flows at Union Gap. As further evidence, the 7-day low flows listed in the percent of time distribution (table 18) are very similar for unregulated and regulated flows at Union Gap. Near Parker, however, the difference between unregulated and regulated 7-day low flows easily exceeds the error in the unregulated values, and most of the 800 ft^3/s difference is due to the three major canals that divert streamflow between Union Gap and Parker.

TABLE 17.--Values of unregulated and regulated annual minimum 183-day average discharges, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was less than indicated: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	2,400	1,100	0.44	880	1,300	2,200	3,900	6,300
Yakima River at Union Gap - Regulated	2,300	950	.41	900	1,300	2,100	3,600	5,600
Yakima River near Parker - Regulated	980	700	.71	130	300	790	1,900	3,800
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at Union Gap	100	450		-20	0	100	300	700
Yakima River near Parker	1,400	700		750	1,000	1,400	2,000	2,500

TABLE 18.--Values of unregulated and regulated annual minimum 7-day average discharges, based on the period 1926-1977

Station and type of flow	(a) Mean (ft^3/s)	(b) Standard deviation (ft^3/s)	(c) Coefficient of variation c = b ÷ a	Percent of time indicated discharge (ft^3/s) was less than indicated: 1	10	50 (median)	90	99
Yakima River at Union Gap or near Parker - Unregulated	930	310	.33	330	540	900	1,400	1,800
Yakima River at Union Gap - Regulated	1,100	390	.35	470	670	1,000	1,600	2,300
Yakima River near Parker - Regulated	130	100	.77	1	10	120	290	340
Regulated flow subtracted from unregulated flow (ft^3/s)								
Yakima River at 200 Union Gap	-200	0		-140	-130	-100	-200	-500
Yakima River near Parker	800	290		330	530	780	1,100	1,500

The regulated minimum 7-day mean discharge for 1-percent of time being less than indicated near Parker is 1 ft^3/s, or practically no flow at all in the channel of a large river. A 12-percent error ($\pm$112 ft^3/s) in the unregulated 7-day low flow for Parker is of little consequence because the regulated flow near Parker is a matter of published record, and the unregulated 7-day low flow would have been appreciably greater than 1 ft^3/s (330 ft^3/s for 1 percent of time).

The coefficients of variation for regulated and unregulated 7-day low flows at Union Gap are, for all practical purposes, the same. For Parker, the coefficient of variation for regulated 7-day low flows (0.77) represents a greater increase in variablity from that for unregulated 7-day low flows (0.33) than was observed for the 183-day seasonal low flows.

SUMMARY

Unregulated daily streamflow for the Yakima River at Union Gap and near Parker, Washington, was computed through a calibrated numerical streamflow-routing model that was verified for regulated conditions to be reliable within about a 10-percent error for Union Gap and a 19-percent error for Parker. Unregulated values of daily-mean discharge were computed for 52 water years - October 1, 1925, to September 30, 1977 - by adjusting records of regulated daily-mean discharges at 13 stream-gaging stations for changes in the storage contents of five reservoirs and the flows diverted in 58 canals. An error analysis of the computed unregulated streamflow resulted in an estimated accuracy of 12 percent for the unregulated streamflow. Statistics of annual, monthly, and annual minimum 7-day, and annual minimum 183-day discharges computed from simulated unregulated daily streamflow values were compared with similar discharges for the historical record of regulated daily streamflow to determine the effects of regulation at those two sites.

The comparison resulted in the following conclusions:

1. The difference between unregulated and regulated streamflow averages for days, months, and years at Union Gap and near Parker is significantly greater than a 12-percent error in the computation of the unregulated discharges.

2. The unregulated mean-annual streamflow is 4,800 ft^3/s ($\pm$576 ft^3/s) compared with a regulated value of 3,810 ft^3/s at Union Gap and 2,300 ft^3/s near Parker. Regulation has also reduced the range of annual-mean discharges at Union Gap and near Parker.

3. Regulated streamflow at Union Gap is greater than near Parker for all years and for March and all 7 months of irrigation season, April through October. The difference is due almost entirely to the three canals between Union Gap and Parker - Sunnyside Canal and New and Old Reservation Canals.

4. Unregulated annual means, average monthly, and average minimum 7-day and 183-day discharges are all greater than regulated values near Parker. Unregulated annual means, monthly January-through-July and October-through-December means, and average minimum 183-day discharges are all greater than regulated values at Union Gap. The average monthly regulated August and September discharges are greater than unregulated values at Union Gap. Regulation has reduced the springtime high flows and increased the August-September low flows at Union Gap, but the three canals between Union Gap and Parker cause flow in the Yakima River to diminish to very low values near Parker. By months and minimum-day periods, the average unregulated flows and the regulated flows at Union Gap and near Parker are, respectively:

a. January: 3,800 (±456); 2,900; and 2,900 ft^3/s

b. February: 3,800 (±456); 3,000; and 3,000 ft^3/s

c. March: 4,400 (±528); 3,400; and 3,000 ft^3/s

d. April: 7,600 (±912); 5,200; and 3,200 ft^3/s

e. May: 12,000 (±1,440); 7,400; and 4,300 ft^3/s

f. June: 9,600 (±1,150); 6,800; and 3,700 ft^3/s

g. July: 3,700 (±444); 3,900; and 790 ft^3/s

h. August: 1,500 (±180); 3,300; and 330 ft^3/s

i. September: 1,400 (±168); 2,600; and 330 ft^3/s

j. October: 2,100 (±252); 1,800; and 950 ft^3/s

k. November: 3,400 (±408); 2,000; and 2,000 ft^3/s

l. December: 4,200 (±504); 3,100; and 3,100 ft^3/s

m. Annual 7-day minimum: 930 (±112); 1,100; and 130 ft^3/s

n. Annual 183-day minimum: 2,400 (±288); 2,300; and 980 ft^3/s

5. Standard deviations of the annual means, monthly means, and annual minimum 7-day and 183-day means indicate that regulation has reduced the variability of discharges. However, the coefficients of variation and the ranges of probability discharges indicate that the relative variability of regulated means has, in general, been decreased in comparison with unregulated flow at Union Gap and increased in comparison with unregulated flow near Parker.

REFERENCES

U.S. Army Corps of Engineers, 1972, Program description and users manual for SSARR model, U.S. Army Engineer Division, North Pacific, Portland, Oregon, 188 p.

U.S. Bureau of Reclamation, 1979, Monthly river basin planning model documentation, 1979, Yakima Valley Water Management Study, Washington: Water and Power Resources Service, Boise, Idaho, p. 18-24.

APPENDIX A.--Identification of discharge records used in study

Streamflow Records

Name	Official station number	Water years of record used for study	Type of record[1/]
Yakima R. nr Martin	12474500	1926-77	R
Kachess R. nr Easton	12476000	1926-77	R
Yakima R. at Easton	12477000	1944-77	R
Cle Elum R. nr Roslyn	12479000	1926-77	R
Yakima R. at Cle Elum	12479500	1926-77	R
Yakima R. at Umtanum	12484500	1926-77	R
Bumping R. nr Nile	12488000	1926-77	R
American R. nr Nile	12488500	1940-77	R
Tieton R. at Tieton Dam nr Naches	12491500	1926-77	R
Naches R. blw Tieton R. nr Naches	12494000	1926-77	R
Yakima R. abv Ahtanum Cr at Union Gap	12500450	1967-77	R
Ahtanum Cr at Union Gap	12502500	1967-77	R
Yakima R. nr Parker	12505000	1926-77	R
Kittitas Canal	12476500	1930-77	R
City of Cle Elum	--	1926-76	M
M & I Canal	--	1977	R
Mills and Sons Power	--	1926-76	M
		1977	R
Ellensburg Mill & Feed	--	1926-58, 77	R
		1959-76	C
Younger Canal	--	1926-76	M
		1977	R
Cascade Canal (old)	12481500	1926-75, 77	R
		1976	M
Westside Canal	12482500	1926-77	R
Knoke (Ellison Bruton Ditch)	--	1926-76	M
		1977	R
Ellensburg Town Canal	12483000	1926-75, 77	R
		1976	M
Woldale (Olson) Canal	--	1926-75, 77	R
		1976	M
Cascade (new) Canal	--	1970-75, 77	R
		1976	M
Bull Canal	--	1926-58, 77	R
		1959-76	M

Canal Records

Name	Official station number	Water years of record used for study	Type of record[1]
Fogarty and Dyer	--	1926-76	M
		1977	R
Vertrees #2	--	1926-76	M
		1977	R
Tjossem Power	--	1926-58, 77	R
		1959-76	C
Vertrees #1	--	1926-76	M
		1977	R
Stanfield (Spring Cr Ditch)	--	1926-76	M
		1977	R
Roza at 11 mile	12479625	1941-77	R
Selah Moxee	12485500	1926-75, 77	R
		1976	M
Taylor	12486500	1926-75, 77	R
		1976	M
Anderson	--	1926-76	M
		1977	R
Emerick	--	1926-76	M
		1977	R
City of Yakima M&I (Oak flat plant)	--	1926-75	M
Nile Valley Association	--	1926-76	M
	1977	R	
Carmack and Parker	--	1926-76	M
	1977	R	
Fredricks and Hunting	--	1926-76	M
	1977	R	
Stevens Canal	--	1926-76	M
	1977	R	
Tieton Canal	12492000	1926-77	R
Cobb Upperside	--	1926-76	M
	1977	R	
Sinclair and Cobb	--	1926-76	M
	1977	R	
Tenant	--	1926-76	M
	1977	R	
Selah-Valley nr Naches	12490000	1926-77	R
Wapatox Power Canal	12493500	1926-77	R

Canal Records

Name	Official station number	Water years of record used for study	Type of record[1]/
Foster Naches	--	1926-76	M
	1977	R	
Clark	--	1926-76	M
	1977	R	
South Naches Channel Co.	--	1926-76	M
	1977	R	
Kelley	--	1926-58, 77	R
	1959-76	C	
Lowry	--	1926-58, 77	R
	1959-76	C	
City of Yakima (Gleed)	--	1971-77	M
Gleed	12494500	1926-58, 77	R
	1959-76	C	
Morrissey	--	1926-76	M
	1977	R	
Congdon	12495000	1926-77	R
Chapman and Nelson	--	1926-76	M
	1977	R	
Naches-Cowiche	12495500	1926-58, 77	R
	1959-76	M	
City of Yakima Irrigation	12489600	1926-76	M
	1977	R	
Fruitvale Power	12496000	1926-75, 77	R
	1976	M	
Old Union	12498000	1926-75, 77	R
	1976	M	
Union Gap Canal	12500000	1926-77	R
Hubbard (old)	--	1926-77	R
Hubbard-Granger (new)	--	1977	R
Granger	--	1926-76	C
Moxee Co. Canal	12499500	1926-76	M
	1977	R	
Boise-Cascade Log	--	1926-76	M
	1977	R	
Richarts	--	1926-76	M
	1977	R	
Blue Slough	--	1926-76	M
	1977	R	
Reservation (new)	12504500	1926-77	R
Reservation (old)	12504000	1926-77	R
Sunnyside	12504500	1926-77	R

Reservoir Records

Name	Official station number	Water years of record used for study	Type of record[1/]
Keechelus Lake	12474000	1926-77	R
Kachess Lake	12475500	1926-77	R
Cle Elum Lake	12478500	1926-77	R
Bumping Lake	12487500	1926-77	R
Rimrock Lake	12491000	1926-77	R

[1/] R - Daily discharges (daily contents at reservoirs) obtained from continuous record at station.
C - Daily discharges obtained by correlation of discontinuous record at station with continuous record at a different station.
M - Daily discharges estimated from monthly-mean discharges.