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APPLICATION OF STREAMFLOW TRANSPORT MODELS TO THE YAKIMA RIVER, WASHINGTON

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16. ABSTRACT

Water resource development projects must be studied with respect to their impacts on water quality. To this end, two popular streamflow transport simulation models, QUAL-II and WQRRS, were calibrated and verified using data on the Yakima River Basin in south-central Washington. Data were collected in four synoptic surveys during low-flow periods between August 1981 and November 1982. Both models gave similar results compared to observed target parameter values. Simulation of temperature, dissolved oxygen, and nitrate was reasonably accurate. Results for biochemical oxygen demand, ammonia, orthophosphate, and chlorophyll *a* were not as good, to some extent due to inadequacies in the data set. The validated models and calibrated data sets are available for use in evaluating water quality impacts of water resources development in the Yakima Basin. On the basis of ease of application, use of QUAL-II is recommended.

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APPLICATION OF STREAMFLOW TRANSPORT MODELS TO THE YAKIMA RIVER, WASHINGTON

by

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A NOTE ON UNITS

Many input data values used in the QUAL-II and WQRRS models were measured in inch-pound units. To avoid awkward model representation of the river system, these values were not converted to SI metric equivalents. Where necessary, such values will be shown in units actually used, with metric values added parenthetically. All other values, including simulation results, will be given solely in SI metric units.

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SUMMARY AND CONCLUSIONS

Streamflow transport simulation is a valuable tool for predicting the water quality impacts of water resources development projects. Two of the more widely used streamflow transport models are the EPA's (U.S. Environmental Protection Agency) QUAL-II and the COE's (U.S. Army Corp of Engineers) WQRRS. In this study, these two models were calibrated and verified using data collected on the Yakima River Basin in south-central Washington. The models were evaluated and compared based on accuracy of results and difficulty of application.

The calibrated models are intended for use by USBR (U.S. Bureau of Reclamation) and State of Washington personnel for evaluation of alternative plans to deal with water supply shortages in the basin. As part of a joint study of the Yakima River Basin Water Enhancement Project, various options are being investigated to increase reservoir storage within the basin and change operation of existing reservoirs. One goal of the project is to prevent violation of water quality standards during low-flow periods. Streamflow transport models can assist in determining the impact of project options on this goal.

Data required for model application were collected during four synoptic surveys of the Yakima Valley between August 1981 and November 1982. Two data sets were used to calibrate the models. Model coefficients were adjusted to maximize goodness of fit to observed target data. The models were then verified using the remaining two data sets.

Both models required some modification during the initial stages of calibration. Changes made to computer codes are discussed in succeeding sections. Development of model input data sets are also described.

Application and comparison of the models led to the following conclusions:

1. The QUAL-II and WQRRS streamflow transport models have been tested, modified, and validated on the USBR's centralized computer system and are available for use by interested personnel within the agency.

2. Both QUAL-II and WQRRS were calibrated and verified using data from the Yakima River Basin. The resultant input data sets are available for use in evaluating water quality impacts of Yakima River Basin Water Enhancement Project alternatives.

3. Both models produced essentially similar results. In general, simulation is reasonably accurate for temperature, dissolved oxygen, and nitrate. Simulation of biochemical oxygen demand, ammonia, phosphate, and chlorophyll *a* was not as good, to some extent due to inadequacies in the data sets.

4. QUAL-II was much easier to apply than WQRRS. QUAL-II handles both hydraulics and quality in a single application, while WQRRS requires two separate computer runs. The WQRRS quality model currently is limited to five withdrawals. Consequently, the Yakima River had to be modeled as seven separate simulations, rather than the two required for QUAL-II. Also, WQRRS results are sensitive to initial conditions if the simulation period is shorter than the total time of travel through the system. Therefore, unless dynamic flow must be simulated, use of QUAL-II is recommended.

INTRODUCTION

Description of the Study Area

The Yakima River drains 15 700 km^2 of south-central Washington (fig. 1). Its headwaters, in the northwestern part of the basin, are in the Cascade Mountains, where peaks reach elevations above 2000 m. From the outlet of Keechelus Lake, it flows 345 km to its confluence with the Columbia River at Richland. The basin includes national forest, rangeland, irrigated agricultural land, and most of the Yakima Indian Reservation. Much of the basin is rural, with population centered along the major river valleys. The economy is based primarily on agriculture, although food processing and lumber are also important industries.

The western third of the basin is rugged and forested. Annual precipitation on the mountain crest averages more than 2500 mm, with 75 percent occurring as snow. Mean annual temperature is only 4 °C. This area contributes 90 percent of the basin's runoff, which averages 3.75×10^9 m^3 per year. Approximately 30 percent of this runoff is regulated by five USBR reservoirs, which were constructed between 1910 and 1932 to provide irrigation water to the lower valleys.

The climate of the lower basin, downstream from the city of Yakima, is arid to semiarid. Average annual precipitation ranges from 170 to 200 mm and mean temperature is approximately 11 °C. During the irrigation season, river discharge below Sunnyside Diversion Dam, near Parker, is dominated by agricultural return flows.

Yakima River Basin Water Enhancement Project

Development of irrigation systems in the basin began in the mid-19th-century. In 1981, diversions above Kiona were being provided to 172 000 ha of pasture

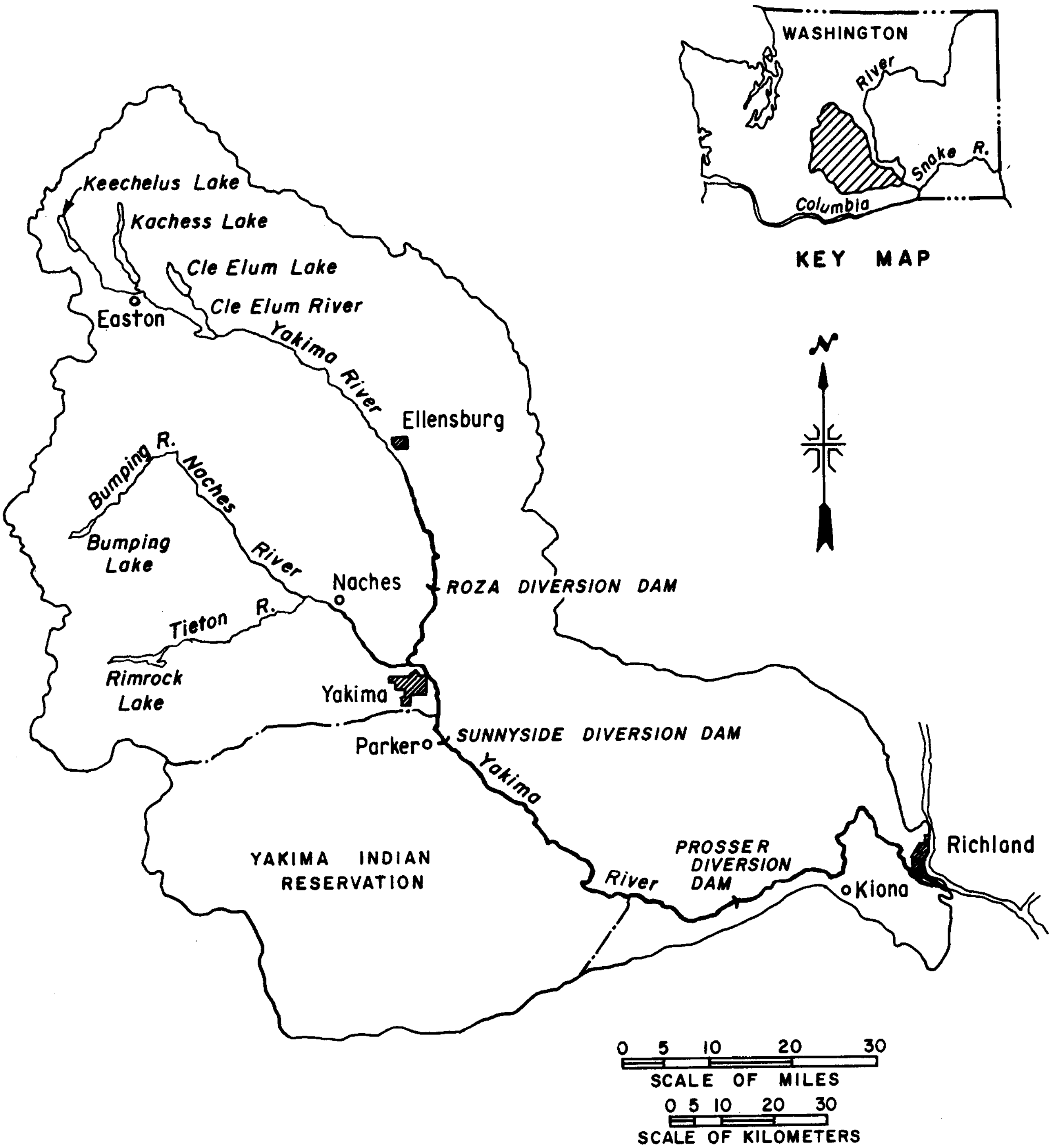

Figure 1. — Map of Yakima River Basin, Washington.

and cultivated land. Even with a 1.32 x 10^9 m^3 reservoir storage capacity, shortage conditions existed during 3 of the 7 years between 1973 and 1979. During this same time the Yakima Indians were demanding a greater share of the supply for irrigation on their reservation and for instream flows to restore spawning and rearing habitat for anadromous fish. Also, wasteload increases associated with urban growth were causing severe water quality degradation in the lower Yakima River. In order to resolve these problems, the State of Washington developed the Yakima River Basin Water Enhancement Plan. This called for a study of alternatives, including both structural and nonstructural measures, for dealing with conflicts arising because of water shortage conditions. Federal participation in planning of the Yakima River Basin Water Enhancement Project was authorized under Public Law 96-162, December 28, 1979. A joint study involving the USBR and the State Department of Ecology was initiated in April 1981.

Need for Water Quality Modeling

One objective of the Enhancement Project is to provide minimum flows to attain adequate water quality. The study team was interested in obtaining a predictive tool to evaluate water quality impacts of Project alternatives. At the same time, the USBR Division of Planning Technical Services in Denver was interested in obtaining a test data set for comparison of two streamflow transport models: the EPA QUAL-II model and the COE WQRRS (Water Quality for River-Reservoir Systems) model. Therefore, a model application project was undertaken jointly by the Yakima Study Team and the Division of Planning Technical Services in the summer of 1981. Four data collection surveys were made between August 1981 and November 1982. Chemical analyses were performed by the USBR Pacific Northwest Regional Laboratory. The models were calibrated and verified on the USBR CYBER computer at the Engineering and Research Center in Denver. These two aspects of the study, data base development and model application, are reported separately in the following sections. The models are then evaluated and compared based on calibration/verification results. The calibrated models were made available to the Yakima Study Team for use in project planning.

DATA BASE DEVELOPMENT

Data for calibration and verification of the selected water quality models were compiled from several sources. Hydrologic and climatic data along with physical descriptive information were available from existing reports and routine data collection. In addition, four synoptic water quality surveys were conducted during the summer and autumn of 1981 and 1982.

Available Data

Data available on the Yakima River Basin includes published reports, NOAA (National Oceanic and Atmospheric Administration) records, USGS (U.S. Geological Survey) maps, and unpublished cross-sectional surveys and rating tables. Main stem discharge between the headwater reservoirs and the town of Kiona is continuously recorded at 11 locations (fig. 2). An additional 11 recording gages are located on major tributaries and diversion canals. Seventeen of these 22 stations are polled remotely at 2-hour intervals as part of the Columbia River Operational Hydromet Management System. Gages are maintained by the USGS and USBR. Data collected at these gages, stage-velocity-discharge data from the gage sites, and rating tables were available from the Yakima Project Office.

Climatological data for determination of simulation model input were taken from several locations in the basin (fig. 3). Stations at Stampede Pass and Yakima are maintained by NOAA. Available records include: wet and dry bulb temperatures, windspeed, and sky cover, all at 3-hour intervals; and once-daily station pressure [1]*. Additional temperature data were available for NOAA stations at Cle Elum, Ellensburg, Wapato, Sunnyside, Prosser, and Richland. Solar radiation data were obtained for the Hanford station, maintained by Battelle Laboratories for the Nuclear Regulatory Commission.

* Numbers in brackets refer to entries in the bibliography.

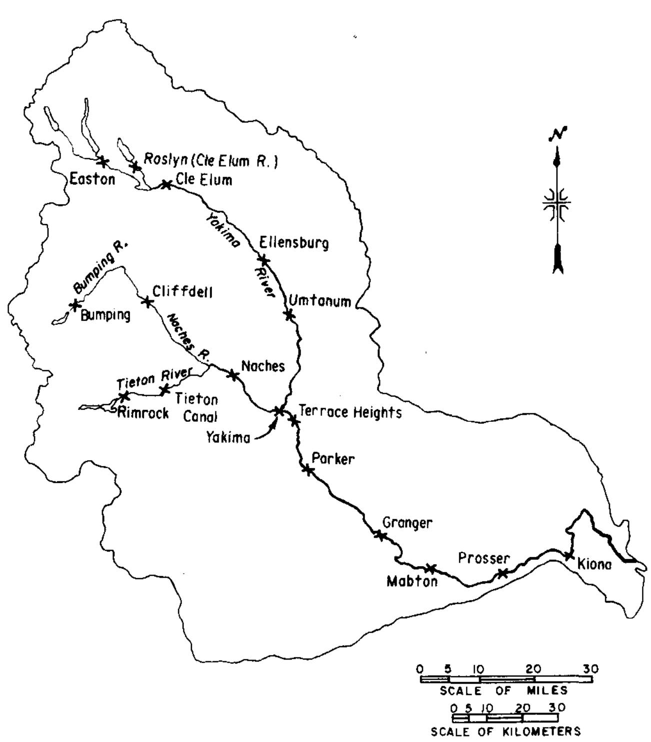

Figure 2. — Headwater and target site sampling locations.

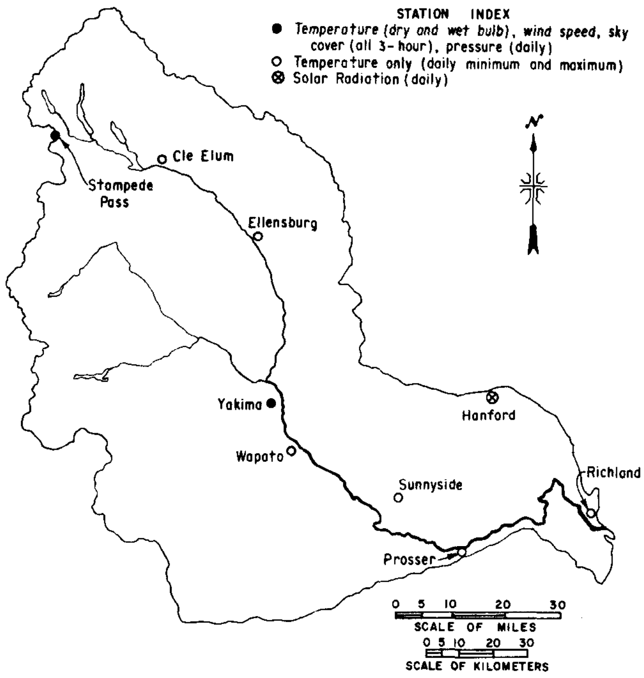

Figure 3. — Climatological data measurement stations.

Physical description of the basin was derived from USGS topographic maps and two river basin inventories [2, 3]. Cross-section surveys were obtained from the COE Seattle office. These covered the main stem between the Kiona and Easton gages, excluding Umtanum Canyon, and the Naches River from its confluence with the Yakima to the Naches gage. Cross-section surveys were made at intervals which varied from 0.1 mile (0.16 km) to 1.5 miles (2.4 km).

Synoptic Surveys

Four synoptic surveys were undertaken in order to collect data necessary for calibration and verification of the models. Synoptic sampling covers a large area in a short time period. Conversely, routine sampling covers a long time period at a single site. Surveys of the Yakima Basin were conducted during the irrigation season when flows were low (August) and the post-irrigation period (October or November) for 2 years (1981 and 1982). These periods were chosen because they were identified by project personnel as critical times for water quality and because streamflows were approximately steady-state, as required by the simulation models. Preliminary analysis of the first year's data indicated that flow was not quite constant in August due to fluctuating release rates from a diversion dam upstream of the Easton gage. Therefore, the second year's survey was designed to consider travel time from the headwaters to Parker, where the major source of streamflow changes from headwater flow to irrigation return flow. Main stem sampling was timed so samples were obtained from approximately the same parcel of water as it traveled down the channel.

The synoptic surveys involved measurement of stage, temperature, DO (dissolved oxygen), and EC (electroconductivity or specific conductance) at all point source inflows and gage sites on the main stem from Easton to Kiona and the Bumping-Tieton-Naches tributaries below Bumping and Rimrock Reservoirs. For withdrawals, only stage was measured. Stage heights were read from existing staff gages. DO measurements were made with YSI meters and a Hydrolab Model 6000, which were all air-calibrated at the project office. Conductivity measurements were made using Beckman Solubridges and the Hydrolab, calibrated with standard KCl solutions of 147, 500, and 1413 μS/cm. Temperature was measured with laboratory-calibrated field thermometers. One of these used in the October 1981 survey was found to be defective, and a constant error was subtracted from all affected measurements.

In addition, samples were collected and analyzed for ammonia-, nitrite-, and nitrate-nitrogen; orthophosphate; chlorophyll *a*; BOD (biochemical oxygen demand); and chloride ion. At the Yakima Project Office a portion of the sample for chlorophyll *a* measurement was filtered through a fiberglass filter, which was then placed in a desiccator with silica gel desiccant, and frozen. The remainder of the sample was refrigerated and sent to Boise in light-excluding containers for laboratory analyses. For the 1982 surveys, a portion of the sample was fixed with sulphuric acid for later ammonia analysis. Another portion was filtered through a membrane filter; analyses performed on this portion included nitrate, nitrite, orthophosphate, and chloride.

Stage data were converted to discharge values by Yakima Project Office personnel using rating tables corrected for channel conditions at the time of the surveys. Chemical analyses were performed at the Pacific Northwest Region Laboratory in Boise, Idaho, using methods listed in table 1. Reduced data were tabulated by regional personnel. Unsampled municipal and industrial effluent data for the survey periods were obtained from the Washington State Department of Ecology in order to complete point source information.

APPLICATION OF QUAL-II

Background

QUAL-II is a one-dimensional, multiparameter, streamflow transport simulation model. It was developed by WRE (Water Resources Engineers) based on the Texas Water Development Board's QUAL-I Model. In 1977, WRE further modified the model for the SEMCOG (Southeast Michigan Council of Governments). This "SEMCOG" version was adapted by EPA [8, 9] and has been widely applied in pollution control and waste load allocation studies.

Table 1. — Laboratory methods for sample analyses.

Parameter	Description of method	Reference and page
Chloride	Potentiometric	[4] 306
Ammonia	Specific ion electrode	[5] 17
Nitrate	Auto analyzer	[6]
Nitrite	Auto analyzer	[6]
Dissolved oxygen	Azide modification	[4] 443
	Membrane electrode	[4] 450
Orthophosphate	Auto analyzer	[7]
Biochemical oxygen demand	Air incubation	[4] 543
Chlorophyll *a*	Trichromatic	[4] 1030

QUAL-II can simulate the spatial distribution of the following quality parameters along a stream channel:

1. Temperature
2. DO
3. BOD
4. Ammonia
5. Nitrate
6. Phosphorus
7. Chlorophyll *a*
8. Coliform bacteria
9. Three user-defined conservative parameters
10. One user-defined nonconservative parameter

Any combination of parameters may be selected for simulation. Input and output may be specified in either inch-pound or SI metric units.

The model may be operated in either a steady-state or quasi-dynamic mode. Steady-state simulation uses a fully implicit finite difference solution. Dynamic operation allows simulation of diurnal fluctuations in temperature, dissolved oxygen, and algal growth. For dynamic simulation, meteorological data are input for 3-hour time intervals. Hydrologic and quality inputs, however, remain fixed for the entire period of simulation. Therefore, the model is not completely dynamic.

Acquisition and Modification of the Model

The version of QUAL-II used in this study was obtained from the EPA Research Laboratory, Athens, Georgia, in March 1980. It was corrected according to the EPA errata dated February 1980, and subsequently modified as recommended by the National Council of the Paper Industry for Air and Stream Improvement [10]. Early in the present study, additional modifications were made. Most of these involved changes in output information and format or correction of nonfatal compiler diagnostics.

One major change was made to bring consistency to the value of total daily solar radiation used in steady-state temperature and algae simulation. Calculations of average light intensity and initialization of algal growth rate in the main program were shifted to follow calls to the temperature subroutines. This was done to allow use of the solar radiation value estimated in subroutine HEATER if a measured value is unavailable. HEATER itself was also modified to calculate solar radiation only if a nonpositive value is read from data group 1A or local climate data cards (table 2). If total daily solar radiation (in langleys) is entered on card 6 of data group 1A or in columns 31-40 of the Local Climate card, this value will be used in all calculations involving temperature and algae. If *both* entered values are zero or negative, solar radiation will be computed as described in reference [8]. This computed value will then be used in all temperature and algae calculations. If a solar radiation value is entered, data on cards 11, 12, and 14 in data group 1 are not involved in temperature calculation and, therefore, will have no effect on model calibration.

Initial Input Evaluation

When QUAL-II is applied in the steady-state mode, it is necessary that a balance exist between inflow and outflow water volumes. The first step in developing this flow balance is to compare the sum of headwater flow, point source inflows, and withdrawals with gaged flow at various points in the system[1]. Shortages in the water balance are attributed to diffuse source inflow, or in QUAL-II terminology, incremental inflow. During the irrigation season, diffuse source return flow occurs in the Kittitas Valley above Ellensburg, and along the lower main stem below Parker. Water budget shortages at the Cle Elum, Ellensburg, Granger, Mabton, Prosser, and Kiona gages were, therefore, reduced by addition of incremental inflow. The resultant water budgets for the 1981 surveys are given in figures 4 and 5.

[1]August streamflow at the Easton gage was affected by fluctuating release volume from the Easton Diversion Dam. Therefore, the daily average headwater flow was computed as the sum of inflows minus the Kittitas Canal withdrawal from Lake Easton.

Table 2. - QUAL-II input file organization.

Data Group	Card Number(s)	Input Item(s)
Title	1-15	Run identification, Parameter selection
1	1-6	Input-output options
	7-10	Stream system descriptors
	11	Latitude and longitude
	12	Standard meridian and day of year
	13	Dalton evaporation coefficients
	14	Elevation, radiation attenuation
1A	1	O_2 uptake by N oxidation
	2	O_2 production and uptake by algae
	3	N and P content of algae
	4	Algae growth and respiration rates
	5	N and P half-saturation constants
	6	Light half-saturation constant Total daily solar radiation
2	1 per reach	Reach identification and length
3	1 per reach	Flow augmentation data
4	1 per reach	Computational element flags
5	1 per reach	Discharge coefficients (or trapezoidal channel characteristics) Roughness coefficient
6	1 per reach	BOD decay and settling rates Reaeration option and coefficients
6A	1 per reach	Chlorophyll *a* to algae ratio Algae settling rate NH_3 and NO_2 oxidation rates Benthos source rates for NH_3 and PO_4
6B	1 per reach	Benthos source rate for BOD Coliform decay rate Light extinction coefficient Nonconservative decay rate
7, 7A	1 per reach	Initial conditions
8, 8A	1 per reach	Incremental inflow data
9	1 per junction	Junction location
10, 10A	1 per headwater	Headwater data
11, 11A	1 per source or withdrawal	Input and withdrawal data
Local climate	1 (steady state) or 1 per time step (dynamic)	Climate data

Once a reasonable hydrologic balance was achieved, the QUAL-II input files could be developed. The first step was to break the entire channel system into reaches and computational elements. An element length of 1 mile (1.6 km) was selected to provide adequate resolution without exceeding the limits of the model. This resulted in 262 elements in the system. QUAL-II is programmed to accept up to 500 elements; however, the operational limit to ensure accuracy of the numerical solution has been found to be 250 [11]. The channel system was, therefore, divided, at the Parker gage, into an upper basin unit of 188 elements and a lower basin unit of 74 elements. Simulation of the system then involved two separate model applications, with output from the first (above Parker) providing input for the second (below Parker).

This structure also allowed specification of different climatic conditions in the upper and lower basins.

The system was divided into homogeneous reaches based on changes in channel slope and surface topography. Reaches longer than 10 miles (16 km) were further subdivided so no reach exceeded 10 computational elements. Since the model dimensions allow a maximum of 20 elements per reach, limiting reach length to 10 miles (16 km) provided an option to reduce the element size to 0.5 mile (0.8 km).

The next step was to develop a data set including the headwater, inflow, and climate data; system prototype description; and initial estimates of model coefficients. The latter are constants involved in mathematical representation of physical and chemical processes affecting quality parameters.

Initial coefficient evaluation was made using recommended values from the QUAL-II User's Manual [9]

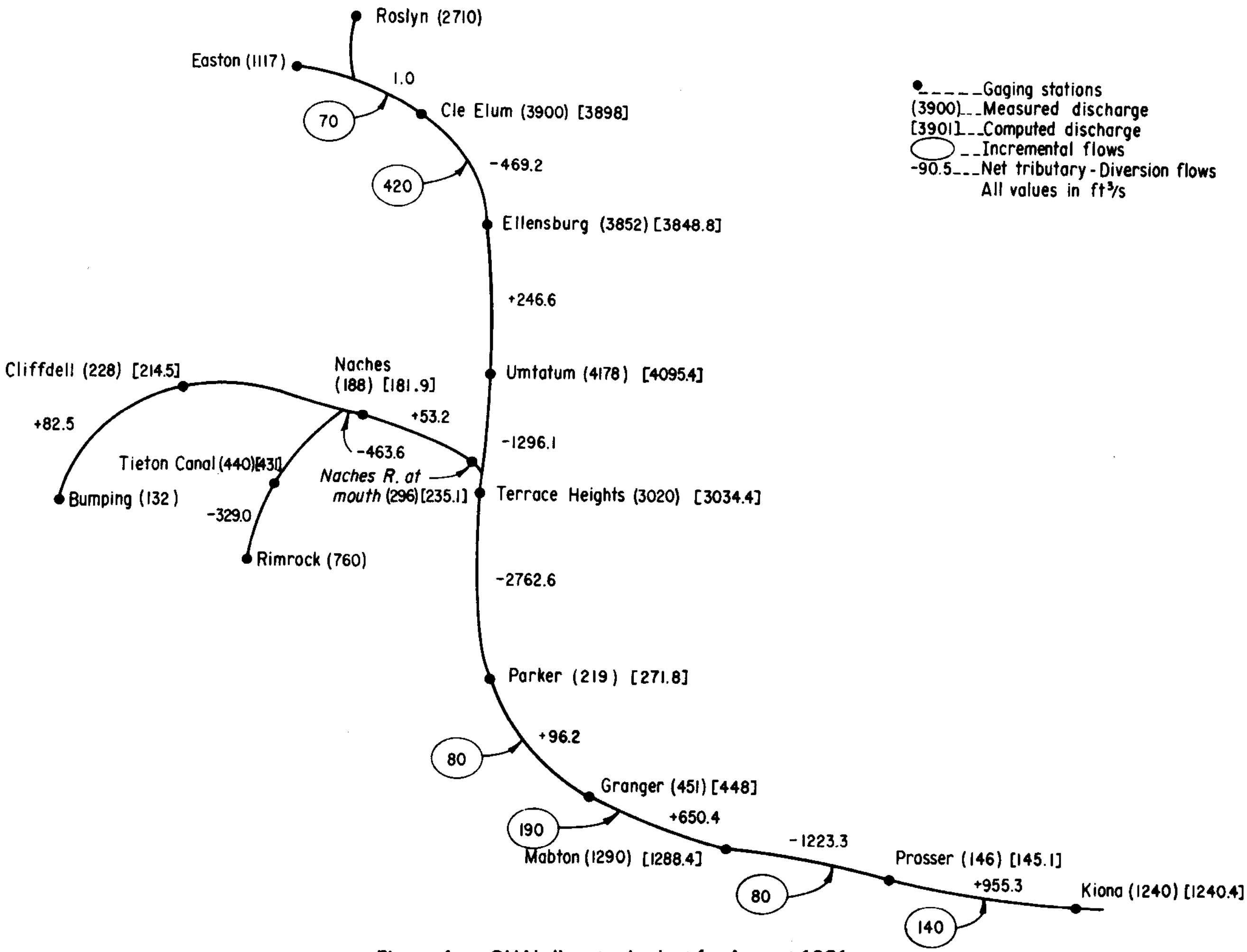

Figure 4. — QUAL-II water budget for August 1981.

and techniques and data compiled by Zison, et al. [12].

Coefficients are divided into two groups: variable by reach, and constant for the entire system. Nonvariable coefficients are entered in data groups 1 and 1A (table 2). Data on group 1 cards 11, 12, and 14 are used to estimate solar radiation for temperature simulation. Since a solar radiation value was entered in group 1A, estimation was unnecessary and, although values were entered on the group 1 cards, they were not used by the model. Therefore, the only coefficients required in data group 1 were those involved in the Dalton Evaporation Rate Equation:

$$E = (a \times b\, W)(e_s - e_a) \qquad (1)$$

where E = evaporation rate
a = empirical constant
b = empirical constant
W = windspeed
e_s = saturated vapor pressure of the water surface
e_a = vapor pressure of the air

The empirical constants a and b have been evaluated in a variety of studies. The normally recommended values are: a = 0 ft/(h • in Hg) [m/(s•mbar)] and b = 2.72 x 10^{-4} ft/(in Hg • mi) [1.27 x 10^{-9} $mbar^{-1}$] ([8], p. 46, and [12], p. 52). These values can be varied to adjust temperature during calibration.

Group 1A coefficients were evaluated as described in table 3. These values were assumed to apply to the entire system, both above and below Parker, and for both the summer and autumn simulations. The only value subject to change during calibration is the specific algal growth rate (see reference [9], p. 73).

Spatially variable coefficients are entered by reach in data groups 5, 6, 6A, and 6B (table 2). Group 5 consists of hydraulic data. Two options are available to describe stream hydraulics: (1) discharge coefficients and (2) cross-section geometry. For simulation of the Yakima River, discharge coefficients were used. These relate velocity, V, and depth, D, as functions of discharge, Q:

$$V = aQ^b \qquad (2)$$

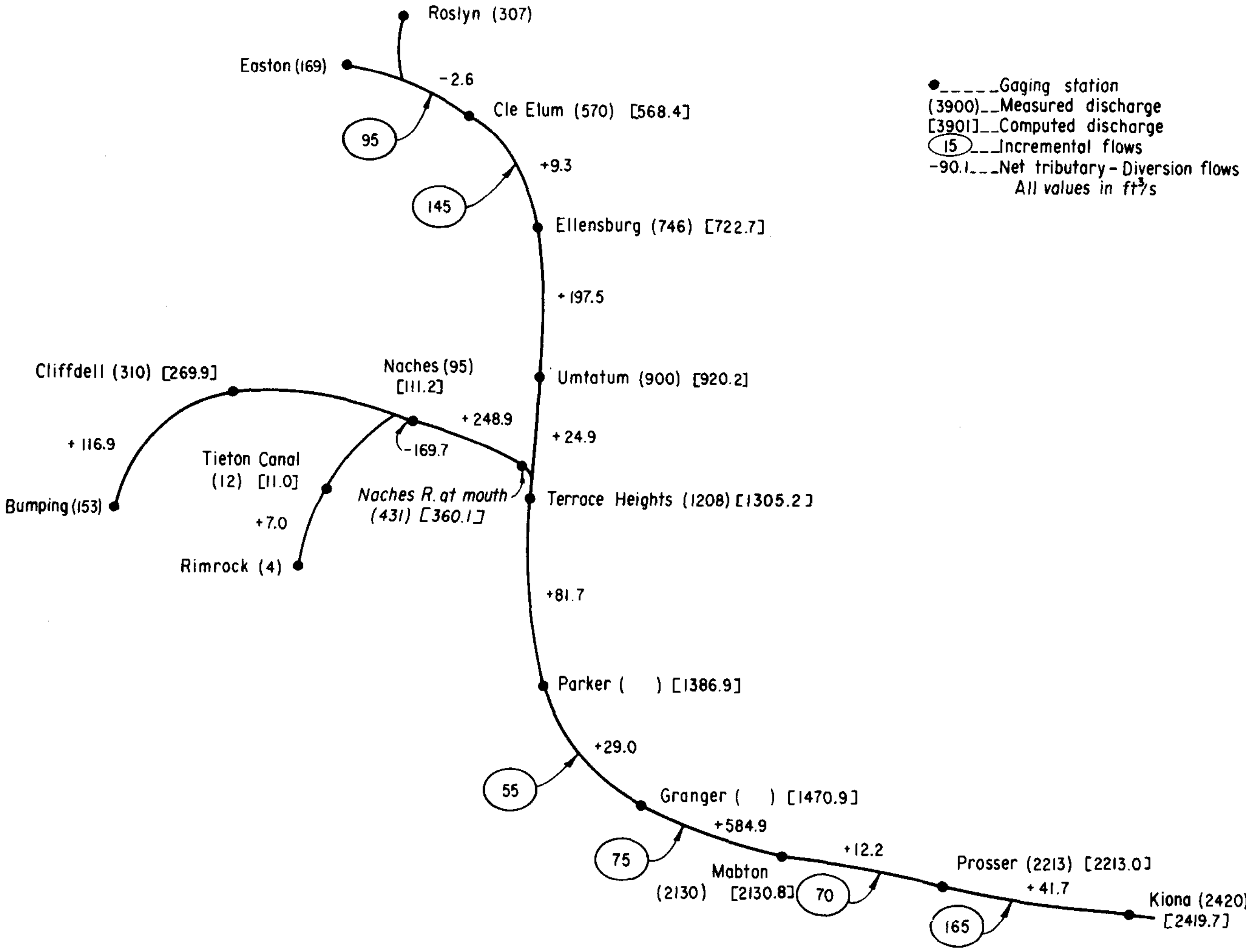

Figure 5. — QUAL-II water budget for October 1981.

$$D = \alpha Q^{\beta} \tag{3}$$

Values were calculated from data provided by the USBR Yakima Project Office for gage locations within the study area. Model reaches were associated with gage locations as shown in table 4. Velocity coefficients were determined by nonlinear regression of actual velocity and discharge data. For determination of depth coefficients, values were taken at regular intervals from the most recent rating tables. Usually, an adjustment was necessary to convert stage above an arbitrary datum to actual stream depth. Exponents b and β and were compared to criteria given by Krenkel and Novotny [13] (pp. 314-316):

$$b + \beta \cong 1.0 \tag{4}$$

$$0 \leq \beta \leq 0.6 \tag{5}$$

$$0.4 \leq b \leq 1.0 \tag{6}$$

Predicted depths and velocities were also checked in QUAL-II output to identify unreasonable variations between reaches. Suspicious values were replaced by averaging coefficients from the adjacent upstream and downstream stations. In such a case, exponents b and β were calculated as simple mean values. Coefficients a and α were calculated using logarithmic transformations; for example:

$$\log\ (a_i) = \frac{\log (a_{i-1}) + \log (a_{i+1})}{2} \tag{7}$$

where the subscripts indicate reach order.

Data group 5 also includes roughness coefficient, n, values. These were taken from Barnes [14] by comparison with photographs taken during the sampling survey.

Velocities and depths calculated from water budget discharge and data group 5 hydraulic coefficients were

Table 3. - Evaluation of QUAL-II data group 1A coefficients.

Coefficient	Value	Reference and page	Remarks
O_2 uptake by NH_3 oxidation	3.5 mg O/mg N	[12] 108	
O_2 uptake by NO_2 oxidation	1.2 mg O/mg N	[12] 108	Average of Boise and North Fork Kings Rivers
O_2 produced by algal growth	1.6 mg O/mg algae	[9] 11	
O_2 uptake by algae	2.0 mg O/mg algae	[9] 11	
N content of algae	0.085 mg N/mg algae	[12] 267	Average of Boise and North Fork Kings Rivers
P content of algae	0.015 mg P/mg algae	[12] 267	Average of Boise and North Fork Kings Rivers
Maximum algae specific growth rate	2.25 day^{-1}	[12] 266	Average of San Joaquin, North Fork Kings (cold water) and Boise (not readily grazed, not fast settling phytoplankton) Rivers
Algae respiration rate	0.1 day^{-1}	[12] 278	Average of San Joaquin, Boise, and North Fork Kings (cold water, active algae) Rivers
N half saturation constant	0.30 mg/L	[9] 11	Midpoint of given range
P half saturation constant	0.04 mg/L	[9] 11	
Light half saturation constant	0.03 langley/min	[9] 11	

used to calculate several additional coefficients in data groups 6 and 6A (table 2). First, the BOD decay constants, K_d, were calculated based on an empirical study of Bansal cited by Zison, et al. [12] (p. 172). Bansal related K_d to the ratio of the Reynolds and Froude numbers:

$$\log\left(\frac{K_d D^2}{\nu}\right) = -8.543 + 1.383 \log\left(\frac{\rho VD/\mu}{V/(gD)^{1/2}}\right) \quad (8)$$

where K_d = BOD decay rate, base e, s^{-1}
D = stream depth, ft (m)
V = stream velocity, ft/s (m/s)
ν = kinematic viscosity, 1.091×10^{-5} ft^2/s at 68 °F ($1.014 \times 10^{-6} m^2/s$ at 20 °C)
ρ = mass density of water, 1.936 $slugs/ft^3$ at 68 °F (997.8 kg/m^3 at 20 °C)
μ = dynamic viscosity, 2.112×10^{-5} $lb\text{-}s/ft^2$ at 68 °F (1.011×10^{-3} Pa at 20 °C)
g = gravitational acceleration, 32.174 ft/s^2 (9.807 m/s^2)

Equation 8 was modified from that given in reference [8] in order to correct the dimensionality of the left-hand side and to properly express the Froude number. Note that K_d must be converted to day^{-1} for entry into data group 6.

Reaeration rate is calculated internally by QUAL-II using the method specified in data group 6. As suggested in the QUAL-II User's Manual [9], the Tsivoglou-Wallace Method was selected. The empirical coefficient was initially set at the suggested default value of 0.0524 ft^{-1} (0.172 m^{-1}) and adjusted during calibration. Energy slope was computed internally using Manning's equation. Reaeration over Prosser Dam was set at a constant value of 10 day^{-1} for August (low flow) and 20 day^{-1} for October (high flow). These values were adjusted during calibration to fit observed DO concentrations below the dam.

The ratio of chlorophyll *a* to algal biomass in data group 6A could not be evaluated based on literature or field data. It was arbitrarily set at 75, the midpoint of the range given in the User's Manual [9] (p. 11), for all reaches. A sensitivity analysis was performed to determine the effect of this assumption on QUAL-II output values. The lower basin simulation using August 1981 data was used in the analysis. Because maximum chlorophyll *a* concentrations were contained in this data set, changes to input parameters should exhibit their greatest impact. The chlorophyll *a* to algae ratio was varied between 50 and 100, or ± 33 percent

Table 4. - Gage-reach association for assignment of discharge coefficients.

Reach No.	Associated gage site	Coefficient determination	
Above Parker			
1-3	Easton	Depth: Velocity:	rating table data (4 of 11 available samples)
4	Roslyn	Depth: Velocity:	rating table, -3.6 ft (-1.1 m) adjustment data
5-10	Ellensburg	Depth: Velocity:	rating table, -27.5 ft (-8.4 m) adjustment data
11		Depth: Velocity:	average of Ellensburg and Umtanum average of Ellensburg and Umtanum
12-14	Umtanum	Depth: Velocity:	rating table, -29 ft (-8.8 m) adjustment average of Ellensburg and Terrace Heights
15-16	Bumping	Depth: Velocity:	rating table, -1 ft (-0.3 m) adjustment data
17		Depth: Velocity:	average of Bumping and Cliffdell average of Bumping and Cliffdell
18-20	Cliffdell	Depth: Velocity:	rating table, -26 ft (-7.3 m) adjustment data
21-22	Rimrock	Depth: Velocity:	rating table, -1 ft (-0.3 m) adjustment data
23-25	Tieton Canal	Depth: Velocity:	average of Rimrock and Naches average of Rimrock and Naches
26-27	Naches	Depth: Velocity:	rating table, -10 ft (-3.0 m) adjustment data
28-30	Parker	Depth: Velocity:	rating table, -1 ft (-0.3 m) adjustment data
Below Parker			
1-2		Depth: Velocity:	average of Parker and Granger average of Parker and Granger
3-7	Granger	Depth: Velocity:	rating table, -3 ft (-0.9 m) adjustment data
8	(Prosser Diversion Dam backwater)	Depth: Velocity:	constant, 6 ft (1.8 m) 0.0003 times flow
9-12	Prosser	Depth: Velocity:	rating table, -9 ft (-2.7 m) adjustment data

of the assumed value. The corresponding changes in output chlorophyll *a* concentrations were -0.10 to +0.06 μg/L (-0.5 to +0.3 percent). The maximum relative change for any constituent was 0.7 percent, for ammonia-nitrogen. The model was therefore considered insensitive to the chlorophyll *a* to algae ratio and no attempt was made to determine the actual value.

Also in group 6A, the ammonia and nitrite oxidation rates were initially set at one and five times the BOD decay rate, respectively, as recommended in the User's Manual [9] (p. 11).

The light extinction coefficient (λ) in data group 6B was calculated using an exponential decay function:

$$L_d = Le^{-\lambda d} \qquad (9)$$

where L = light intensity at the surface (langley/min)
L_d = light intensity at depth d

For all reaches, the light intensity at 10 feet (3 m) was assumed to be 10 percent of the surface value. Solving equation 9 for λ then yields a value of 0.23 ft^{-1}

($0.75\ m^{-1}$). The sensitivity analysis described above was used to determine the impact of this assumption. The depth of 10 percent surface light intensity was varied from 5 to 20 feet (-50 to +100 percent). Chlorophyll *a* was the only constituent significantly affected. Changes in average concentration ranged from -1.3 to 0.8 µg/L (-10.7 to +6.3 percent). This was considered in interpretation of model results.

All other coefficient values in data groups 6, 6A, and 6B were set at zero.

The next few data groups deal with initial conditions, incremental inflows, headwater flows, and point source inflows and withdrawals. Initial conditions are unimportant in the steady-state solution, other than the requirement that initial temperature is set greater than freezing. Temperature was, therefore, initialized at 55 °F (12.8 °C) and all other parameter values were set at zero.

Incremental inflow volumes were computed in the flow balancing procedure, described previously. The source of this incremental inflow is assumed to be ground water, and quality parameters were evaluated accordingly. Temperature was set at mean annual air temperature, interpolated between stations if necessary. DO was set at zero. EC, chloride, and nitrate were initially approximated by measured values in surrounding point sources and adjusted during calibration. Other quality parameters were considered insignificant in incremental flow.

Headwater and point source data were obtained from the synoptic survey results, as described earlier. Unknown BOD concentrations at Roslyn and Rimrock and chlorophyll *a* concentrations at Easton and Rimrock were set equal to known values at nearby headwater gage sites. Unknown BOD values for point source inflows were similarly estimated based on data from nearby sources. In all cases, 60-day BOD values were used as a measure of ultimate BOD, which is the required input for QUAL-II. If 60-day BOD was not measured, it was estimated from the 5-day value. Chlorophyll *a* concentrations for the Roza, Wapatox, and Chandler power return flows, if unknown, were estimated as the sampled value at the nearest gage site above the diversion point. Other unknown point source chlorophyll *a* concentrations were estimated based on measurements made during the verification sampling. In most cases, field EC values were entered. Laboratory values were used if field values were below the detection limit, or seemed unreasonable. Occasional missing values in municipal and industrial effluent data were estimated by averaging known values from upstream and downstream effluent sources. All parameter concentrations reported as below detection limits were assigned a value of zero. Point loads or withdrawals which occurred at intervals less the one computational element (1 mile [1.6 km]) had to be combined and entered as a single source. Combined point load quality parameter values were computed as flow-weighted averages.

The final input group includes climate data. For steady-state simulation, average values for the simulation period are required. In this study, average climate input was calculated from calendar day data for the sampling dates. For the area above Parker, input values were computed using Stampede Pass, Cle Elum, Ellensburg, and Yakima data (see fig. 3). Values for the area below Parker were computed using Yakima, Wapato, Sunnyside, Prosser, and Richland data. Dry bulb temperatures were averaged from minimum and maximum readings at all stations. Relative humidity, cloud cover, and windspeed were determined by averaging 3-hour readings, available for Yakima and Stampede Pass. Average cloud cover was based only on sunrise to sunset values. Wet bulb temperatures were read from standard charts based on dry bulb temperature and relative humidity. Atmospheric pressure input was based on daily values available for Yakima and Stampede Pass. Solar radiation input for both the upper and lower areas were computed from Hanford data. Reported values were modified to account for differences in cloud cover between Hanford and the study area:

$$SR = \left(\frac{1 - 0.65\, CC^2}{1 - 0.65\, CC_H^2} \right) SR_H \qquad (10)$$

where SR and CC are solar radiation and cloud cover in the study area;
SR_H and CC_H are reported solar radiation and cloud cover at Hanford.

Equation 10 was based on the dampening effect of cloudiness on solar radiation described by Roesner et. al [8] (p. 43). QUAL-II climatological input values are listed in table 5.

Calibration

QUAL-II simulation results for the initial input sets are displayed in tables 6 and 7. QUAL-II predictions are compared to observed data at 13 target gage sites. RMSE (root-mean-square errors) are calculated as follows:

$$\mathrm{RMSE} = \left[\frac{\Sigma_i (P_i - O_i)^2}{n} \right]^{1/2} \qquad (11)$$

where P_i = predicted value at site i
O_i = observed value at site i
n = number of observations

The model was calibrated by changing coefficient values in order to minimize these errors.

Table 5. - QUAL-II climatological input values and derivation data sources.

Simulation Date	Simulation Area	Dry bulb temperature °F (°C)	Wet bulb temperature °F (°C)	Cloud cover	Atmos. pressure in Hg (mbar)	Wind-speed ft/s (m/s)	Solar radiation (langleys/d)
8-81	Above Parker	74.4 (23.6)	59.2 (15.1)	0.39	27.3 (924.5)	11.1 (3.4)	540
	Below Parker	77.0 (25.0)	63.1 (17.3)	.35	28.6 (968.5)	11.2 (3.4)	551
8-82	Above Parker	70.4 (21.3)	57.7 (14.3)	.05	27.3 (924.5)	9.1 (2.8)	548
	Below Parker	73.8 (23.2)	61.7 (16.5)	.08	28.7 (971.9)	13.5 (4.1)	555
10-81	Above Parker	49.1 (9.5)	45.6 (7.6)	.81	26.9 (911.0)	13.1 (4.0)	160
	Below Parker	50.9 (10.5)	46.2 (7.9)	.90	28.6 (968.5)	5.9 (1.8)	131
11-82	Above Parker	38.7 (3.7)	35.1 (1.7)	.83	27.6 (934.7)	14.0 (4.3)	151
	Below Parker	44.4 (6.9)	40.6 (4.8)	.68	28.9 (978.7)	5.3 (1.6)	146

A quality calibration procedure for QUAL-II is described in the User's Manual [9] (pp. 67 to 74). This includes the recommended order of coefficient adjustments for fitting model predictions to observed values. This procedure was followed in calibration of temperature, DO, nutrients, and the conservative parameters, EC and chloride. However, a standard calibration was not possible for BOD or chlorophyll *a* due to deficiencies in the survey data.

Separate calibrations were made using the August and October 1981 data. Actual calibration was accomplished in seven steps:

1. EC and chloride were fit by adjusting incremental inflow values. These normally had to be increased, which is reasonable because the irrigation returns which comprise this inflow are normally more saline than the surface flows used in making the original estimates.

2. Temperature calibration was restricted somewhat because solar radiation values were specified on input rather than computed internally. This limits effective adjustment to the evaporation coefficients and the incremental inflow temperatures. Since these coefficients apply to all reaches, their adjustment is useful only if temperatures at target sites are either all greater or all less than observed values. Since all target temperatures were low for the October simulations, the evaporation coefficient, BE, was reduced above and below Parker. Slight adjustments to this coefficient were also made for both August simulations to reduce overall error. Incremental inflow temperatures were also adjusted, although this had a significant impact only on the August simulation below Parker, where incremental flows comprise a significant fraction of total discharge.

3. BOD data at target gage sites were sparse, so DO errors also were considered in calibration of this parameter. For the August data set, BOD decay coefficients generally were increased for reaches above the city of Yakima and decreased for downstream reaches. For October, coefficients generally were decreased for main stem reaches above Yakima and increased both downstream and on the Naches tributaries.

4. Lack of point source data presented a major problem to chlorophyll *a* calibration, especially in the upper reaches, where concentration is controlled by inflow (and probably sloughing of periphyton and macrophytes) rather than growth rate. Point source concentrations initially were estimated based on measurements during verification sampling. Values for major inflows were adjusted during calibration to fit main stem target concentrations.

5. Following chlorophyll *a* calibration, predicted nutrient concentrations were not affected significantly by adjustment of other coefficients. This was probably due to the low concentrations at

Table 6. - QUAL-II simulation results, using initial coefficient values, compared to observed data, August 1981.

Site		Flow (m^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	Chl. *a* (µg/L)	EC (µS/cm)	Cl^- (mg/L)
Cle Elum	Observed	110.4	19.0	8.3	2.0	0.00	0.02	0.000	0.4	50	0.0
	Predicted	110.4	19.1	8.3	2.2	.00	.01	.000	.5	61	.1
Ellensburg	Observed	109.1	17.0	8.8	-1.0	.00	.10	.006	.9	77	.0
	Predicted	109.0	18.7	8.3	1.8	.00	.02	.000	.4	73	.2
Umtanum	Observed	118.3	18.0	8.2	2.2	.00	.08	.000	1.4	85	.0
	Predicted	116.0	18.9	8.4	2.0	.00	.07	.012	.8	89	.5
Cliffdell	Observed	6.5	18.5	8.4	-1.0	.01	.02	.000	.4	70	.0
	Predicted	6.1	20.9	8.1	2.1	.00	.01	.003	.5	68	.2
Tieton Canal	Observed	12.5	15.0	8.3	-1.0	.04	.02	.002	.4	85	2.1
	Predicted	12.2	13.2	9.6	2.6	.02	.01	.000	.7	85	1.4
Naches	Observed	5.3	19.0	8.0	-1.0	.01	.02	.000	.5	90	.7
	Predicted	5.2	17.7	8.7	2.3	.02	.01	.001	.7	89	1.3
Confluence	Observed	8.4	18.5	8.7	2.6	.01	.06	.009	2.6	115	2.1
	Predicted	6.7	20.5	8.2	3.2	.03	.12	.004	1.2	115	1.9
Terrace Hgts.	Observed	85.5	19.0	8.0	-1.0	-2.00	.08	.014	1.6	87	.7
	Predicted	85.9	19.8	8.1	2.3	.01	.08	.015	1.4	93	.6
Parker	Observed	6.2	19.0	8.3	2.8	.03	.17	.040	2.3	90	.7
	Predicted	7.7	20.0	8.1	2.6	.08	.13	.063	1.4	110	.9
Granger	Observed	12.8	20.8	7.4	-1.0	.01	.56	.027	8.0	181	2.8
	Predicted	12.7	22.1	6.2	1.8	.05	1.05	.074	2.3	152	2.7
Mabton	Observed	36.5	22.9	8.7	-1.0	.02	1.19	.066	9.6	263	4.3
	Predicted	36.5	22.3	6.3	2.0	.02	1.64	.089	5.6	244	4.4
Prosser	Observed	4.1	24.7	7.5	-1.0	.13	1.15	.110	17.0	336	6.0
	Predicted	4.1	23.5	7.3	11.8	.24	1.72	.151	17.5	271	4.6
Kiona	Observed	35.1	25.0	9.5	4.7	.03	1.22	.064	14.5	336	7.1
	Predicted	35.1	23.9	8.0	4.0	.02	1.32	.065	19.9	303	5.7
Root-mean-square error		0.9	1.4	1.0	0.5	0.04	0.25	0.024	2.5	23	0.7

-1.0 = missing data; -2.00 = unreliable data.
Sites with observed parameter values of zero are not included in error computation for that parameter.

most target gage sites. Some improvement was achieved by modifying NH_3 and NO_2 oxidation rates within a range of ±20 percent of the initial estimate. Nitrate concentrations in incremental inflow were also adjusted.

6. Final DO calibration was accomplished by adjusting the Tsivoglou-Wallace reaeration constant with a range of ±15 percent of the default value. In general, values for October above Parker were increased and those below Parker were decreased. August values were mostly unchanged. User-specified reaeration over Prosser Diversion Dam was increased for the August simulation. For October, Prosser Dam reaeration was changed from user-specified to internally computed using the Tsivoglou-Wallace Formula.

Tables 8 and 9 display calibration results for the August and October 1981 survey data.

Table 7. - QUAL-II simulation results, using initial coefficient values, compared to observed data, October 1981.

Site		Flow (m^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	Chl. *a* (μg/L)	EC (μS/cm)	Cl^- (mg/L)
Cle Elum	Observed	16.1	9.0	10.8	-1.0	-2.00	0.01	0.000	0.5	67	1.4
	Predicted	16.1	8.8	9.5	1.8	.01	.02	.000	.8	66	1.0
Ellensburg	Observed	21.1	11.8	11.0	-1.0	.00	.08	.008	.8	100	1.4
	Predicted	20.5	8.9	9.8	1.3	.01	.04	.001	.6	96	1.6
Umtanum	Observed	25.5	10.7	11.3	-1.0	.02	.17	.032	3.4	160	3.2
	Predicted	26.1	9.4	10.3	1.7	.01	.19	.018	2.2	147	2.5
Cliffdell	Observed	8.8	9.3	10.1	-1.0	.01	.00	.002	.8	55	1.1
	Predicted	7.6	8.1	10.5	2.9	.02	.01	.006	1.0	65	.8
Tieton Canal	Observed	.3	9.8	10.1	-1.0	.01	.01	.012	.9	120	2.8
	Predicted	.3	8.8	9.1	2.0	.02	.02	.003	.5	104	2.9
Naches	Observed	2.7	10.8	9.5	-1.0	.02	.01	.002	1.3	70	1.8
	Predicted	2.2	8.6	10.4	2.7	.02	.01	.006	.7	71	1.2
Confluence	Observed	12.2	-2.0	11.2	2.8	.01	.09	.005	4.1	130	2.0
	Predicted	10.2	9.8	10.0	2.8	.02	.15	.013	1.5	99	2.1
Terrace Hgts.	Observed	34.2	10.5	10.8	-1.0	.03	.12	.020	7.5	265	2.0
	Predicted	37.0	9.3	10.2	2.2	.03	.19	.018	2.1	140	2.6
Parker	Observed	-2.0	10.0	9.0	-1.0	.05	.26	.052	6.0	185	5.0
	Predicted	39.3	9.4	10.1	2.5	.11	.27	.085	2.1	166	3.2
Granger	Observed	-2.0	12.2	7.4	-1.0	.16	.34	.050	8.2	230	6.4
	Predicted	41.7	9.6	10.4	2.3	.10	.45	.089	2.1	176	3.5
Mabton	Observed	60.3	12.8	9.8	-1.0	.03	1.12	.067	7.7	260	8.2
	Predicted	60.3	10.5	9.8	2.6	.09	1.24	.096	4.8	270	6.2
Prosser	Observed	62.7	13.8	7.9	-1.0	.12	1.61	.076	5.6	335	8.9
	Predicted	62.7	10.4	10.0	3.1	.09	1.40	.097	5.0	285	6.8
Kiona	Observed	68.5	12.8	8.2	-1.0	.04	1.31	.067	11.4	280	7.4
	Predicted	68.0	10.5	9.9	2.7	.08	1.60	.090	5.0	314	8.0
Root-mean-square error		1.1	2.02	1.4	0.0	0.04	0.12	0.020	3.3	43	1.4

-1.0 = missing data; -2.00 = unreliable data.
Sites with observed parameter values of zero are not included in error computations for that parameter.

Verification

Data from the August and November 1982 surveys were used to verify the calibrated model. All coefficients and incremental inflow quality values were set at their calibrated values. Headwater and point source discharge and quality values were set at 1982 observed values. Incremental inflow volumes were recomputed to fit the 1982 water budgets (figs. 6 and 7). The model was then run without further input modification. Results were compared to 1982 observed values for target sites (tables 10 and 11).

APPLICATION OF WQRRS

Background

The WQRRS Model consists of three separate models: the reservoir model, the stream hydraulics model,

Table 8. — QUAL-II calibration results compared to observed data, August 1981.

Site		Flow (m^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	Chl. *a* (μg/L)	EC (μS/cm)	Cl^- (mg/L)
Cle Elum	Observed	110.4	19.0	8.3	2.0	0.00	0.02	0.000	0.4	50	0.0
	Predicted	110.4	19.0	8.3	2.2	.00	.02	.000	.5	60	.1
Ellensburg	Observed	109.1	17.0	8.8	-1.0	.00	.10	.006	.9	77	.0
	Predicted	109.0	18.4	8.2	1.8	.00	.10	.000	.4	72	.1
Umtanum	Observed	118.3	18.0	8.2	2.2	.00	.08	.000	1.4	85	.0
	Predicted	116.0	18.6	8.5	2.0	.00	.14	.012	.8	88	.4
Cliffdell	Observed	6.5	18.5	8.4	-1.0	.01	.02	.000	.4	70	.0
	Predicted	6.1	20.1	8.2	2.2	.00	.01	.003	.5	68	.2
Tieton Canal	Observed	12.5	15.0	8.3	-1.0	.04	.02	.002	.4	85	2.1
	Predicted	12.2	13.9	9.4	2.5	.02	.01	.000	.6	85	1.4
Naches	Observed	5.3	19.0	8.0	-1.0	.01	.02	.000	.5	90	.7
	Predicted	5.2	18.6	8.5	2.2	.01	.01	.001	.7	89	1.3
Confluence	Observed	8.4	18.5	8.7	2.6	.01	.06	.009	2.6	115	2.1
	Predicted	6.7	19.9	8.2	3.2	.03	.12	.004	1.2	115	1.9
Terrace Hgts	Observed	85.5	19.0	8.0	-1.0	-2.00	.08	.014	1.6	87	.7
	Predicted	85.9	19.4	8.2	2.3	.01	.13	.015	1.4	92	.5
Parker	Observed	6.2	19.0	8.3	2.8	.03	.17	.040	2.3	90	.7
	Predicted	7.7	19.6	8.2	2.6	.08	.18	.063	1.4	109	.9
Granger	Observed	12.8	20.8	7.4	-1.0	.01	.56	.027	8.0	181	2.8
	Predicted	12.7	21.8	6.9	2.0	.05	.68	.074	1.9	187	2.9
Mabton	Observed	36.5	22.9	8.7	-1.0	.02	1.19	.066	9.7	263	4.3
	Predicted	36.5	23.0	6.8	2.1	.02	1.26	.089	5.1	287	4.5
Prosser	Observed	4.1	24.7	7.5	-1.0	.13	1.15	.110	17.0	336	6.0
	Predicted	4.1	24.3	7.5	11.5	.24	1.25	.152	15.3	326	5.4
Kiona	Observed	35.1	25.0	9.5	4.7	.03	1.22	.064	14.5	336	7.1
	Predicted	35.1	24.4	8.2	4.2	.02	1.21	.065	20.0	335	7.3
Root-mean-square error		0.9	0.9	0.8	0.4	0.04	0.06	0.024	2.7	10	0.4

-1.0 = missing data; -2.00 = unreliable data.
Sites with observed parameter values of zero are not included in error computations for that parameter.

and the stream quality model. The reservoir model and the stream hydraulics model can be executed, analyzed, and interpreted separately or as part of a basin analysis. Data from the stream hydraulics model must be transferred to the stream quality model before the latter can be run. The models were developed by various contractors employed by the COE Hydrologic Engineering Center to combine the concepts of an ecological simulation model developed by Chen and Orlob [15] with the reservoir and river models to provide a tool that could be used to simulate water quality throughout a regulated or unregulated river basin. Data are transferred between the models by disk files or magnetic tapes. The stream hydraulics model can be used above and below applications of the reservoir model, and several sequential reaches of a river can be simulated. Only the stream hydraulics and quality models will be discussed because the reservoir model was not used in this study.

Table 9. — QUAL-II calibration results compared to observed data, October 1981.

Site		Flow (m^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	Chl. *a* (μg/L)	EC (μS/cm)	Cl^- (mg/L)
Cle Elum	Observed	16.1	9.0	10.8	-1.0	-2.00	0.01	0.000	0.5	67	1.4
	Predicted	16.1	9.2	9.3	1.8	.01	.01	.000	.8	68	1.3
Ellensburg	Observed	21.1	11.8	11.0	-1.0	.00	.08	.008	.8	100	1.4
	Predicted	20.5	9.8	9.5	1.3	.01	.07	.001	.6	104	1.6
Umtanum	Observed	25.5	10.7	11.3	-1.0	.02	.17	.032	3.4	160	3.2
	Predicted	26.1	10.0	10.1	1.7	.01	.22	.018	2.2	153	2.5
Cliffdell	Observed	8.8	9.3	10.1	-1.0	.01	.00	.002	.8	55	1.1
	Predicted	7.6	8.0	10.6	2.9	.02	.01	.006	.9	65	.8
Tieton Canal	Observed	.3	9.8	10.1	-1.0	.01	.01	.012	.9	120	2.8
	Predicted	.3	9.0	9.0	2.0	.02	.02	.003	.4	104	2.9
Naches	Observed	2.7	10.8	9.5	-1.0	.02	.01	.002	1.3	70	1.8
	Predicted	3.2	8.6	10.5	2.7	.02	.01	.006	.7	71	1.2
Confluence	Observed	12.2	-2.0	11.2	2.8	.01	.09	.005	4.1	130	-2.0
	Predicted	10.2	10.1	10.0	2.8	.02	.15	.013	1.5	99	2.1
Terrace Hgts.	Observed	34.2	10.5	10.8	-1.0	.03	.12	.020	7.5	265	-2.0
	Predicted	37.0	9.8	10.1	2.2	.03	.21	.018	2.1	144	2.6
Parker	Observed	-2.0	10.0	9.0	-1.0	.05	.26	.052	6.0	185	5.0
	Predicted	39.3	9.8	10.0	2.5	.11	.28	.085	2.1	170	3.2
Granger	Observed	-2.0	12.2	7.4	-1.0	.16	.34	.050	8.2	230	6.4
	Predicted	41.7	10.1	10.5	2.3	.10	.35	.089	2.2	186	3.9
Mabton	Observed	60.3	12.8	9.8	-1.0	.03	1.12	.067	7.7	260	8.2
	Predicted	60.3	11.0	9.9	2.6	.09	1.17	.096	5.1	271	6.6
Prosser	Observed	62.7	13.8	7.9	-1.0	.12	1.61	.07	5.62	290	7.2
	Predicted	62.7	11.1	9.7	3.0	.10	1.49	.097	5.5	290	7.2
Kiona	Observed	68.5	12.8	8.2	-1.0	.04	1.31	.067	11.4	280	7.4
	Predicted	68.0	11.3	9.6	2.6	.08	1.44	.090	5.7	309	7.7
Root-mean-square error		1.1	1.6	1.4	0.0	.03	.06	.020	3.2	40	1.2

-1.0 = missing data; -2.00 = unreliable data
Sites with observed parameter values of zero are not included in error computations for that parameter.

Twenty-six different parameters can be simulated with the models, including two types of phytoplankton, three different fishes, two benthic algaes, and five types of suspended solids, as well as temperature, nutrients, and coliform bacteria. These parameters may be simulated, held constant, or not simulated by omitting them from the data set. Temperature must be included in all simulations because practically all of the other parameters are temperature-dependent. Some of the parameters are not simulated very accurately but are included for complete representation of the ecosystem.

Stream Hydraulics Program

A stream is represented in the model as a series of connected elements as shown in figure 8. The length of the computational elements can vary within each reach. The program can handle up to 105 nodes (boundaries between adjacent elements). The river is assumed to be one-dimensional, gradually varied flow which has the same properties as a uniform flow of the same velocity and hydraulic radius.

The hydraulics program accepts either cross section data or data that describe elevation, area, hydraulic

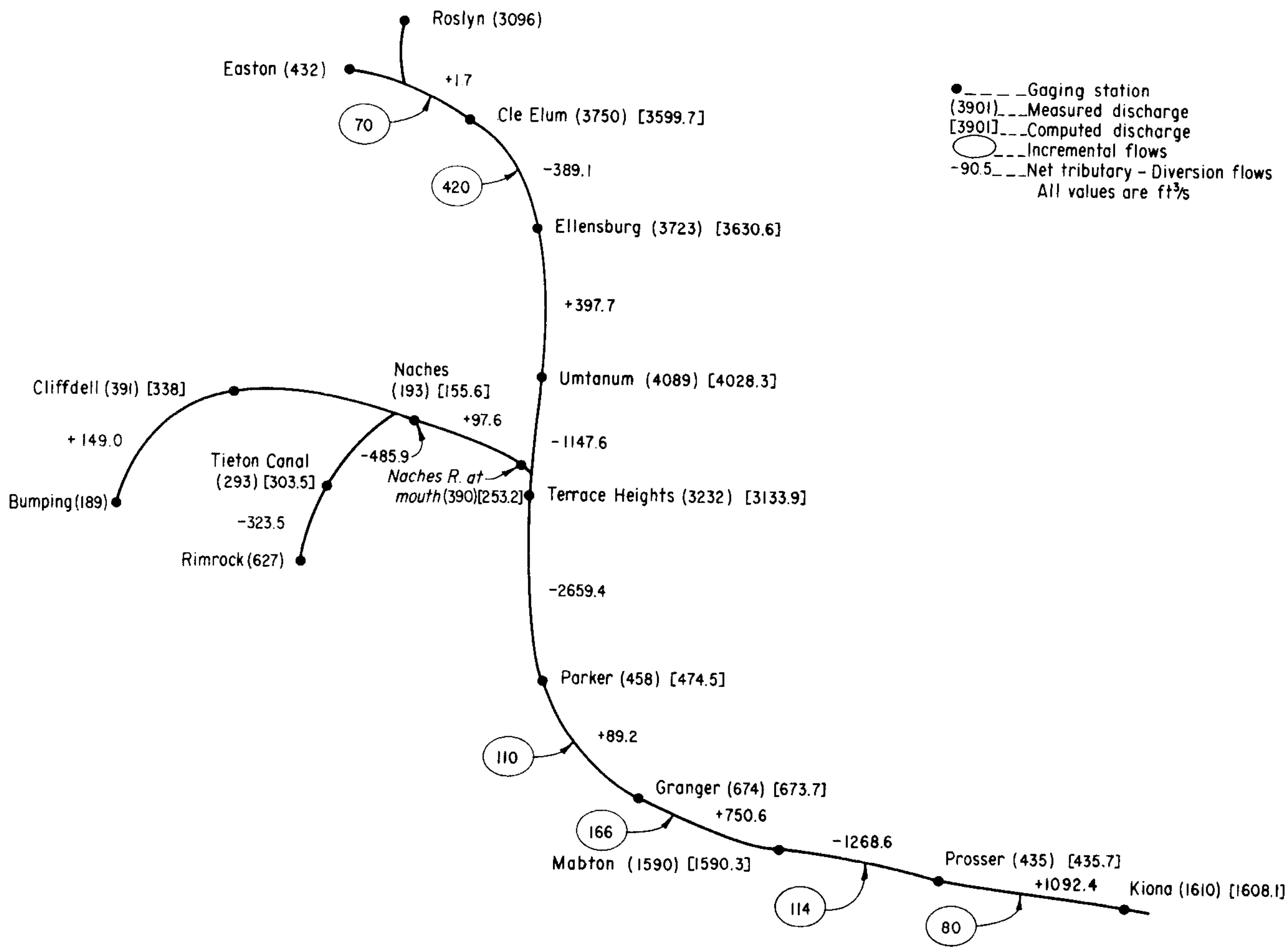

Figure 6. — QUAL-II water budget for August 1982.

radius, width, and friction factor as a function of flow. A program called GEDA accepts cross section data for irregular intervals and will generate values for equally spaced elements.

Six different methods of routing are available in the model. These are: (1) backwater, (2) St. Venant, (3) kinematic wave, (4) stage-discharge relationship, (5) Muskingum routing, and (6) modified Puls. Backwater computations were used where cross section data were available and the stage-discharge relationships were used where good cross section data did not exist. All the sections were set up for steady flow.

Stream Water Quality Program

Data from the stream hydraulics program is combined with headwater, tributary, and withdrawal records in the quality module to provide a record of water quality along the stream at each computational element. Printed output can be obtained at any multiple of the computational element. The model can simulate 25 tributaries and five withdrawals. Incremental flows into or from the stream may be specified in any element. Concentrations of the parameters being simulated must be specified for these incremental inflows.

The principal biological and chemical constituents considered in the water quality module are:

- Fish
- Aquatic insects associated with the substrate
- Benthic insects associated with the substrate
- Zooplankton
- Phytoplankton
- Benthic algae
- Detritus
- Organic detritus (settled detritus)
- Inorganic suspended solids
- Inorganic sediment
- Dissolved phosphate
- Total inorganic carbon
- Dissolved ammonia as nitrogen
- Dissolved nitrites as nitrogen

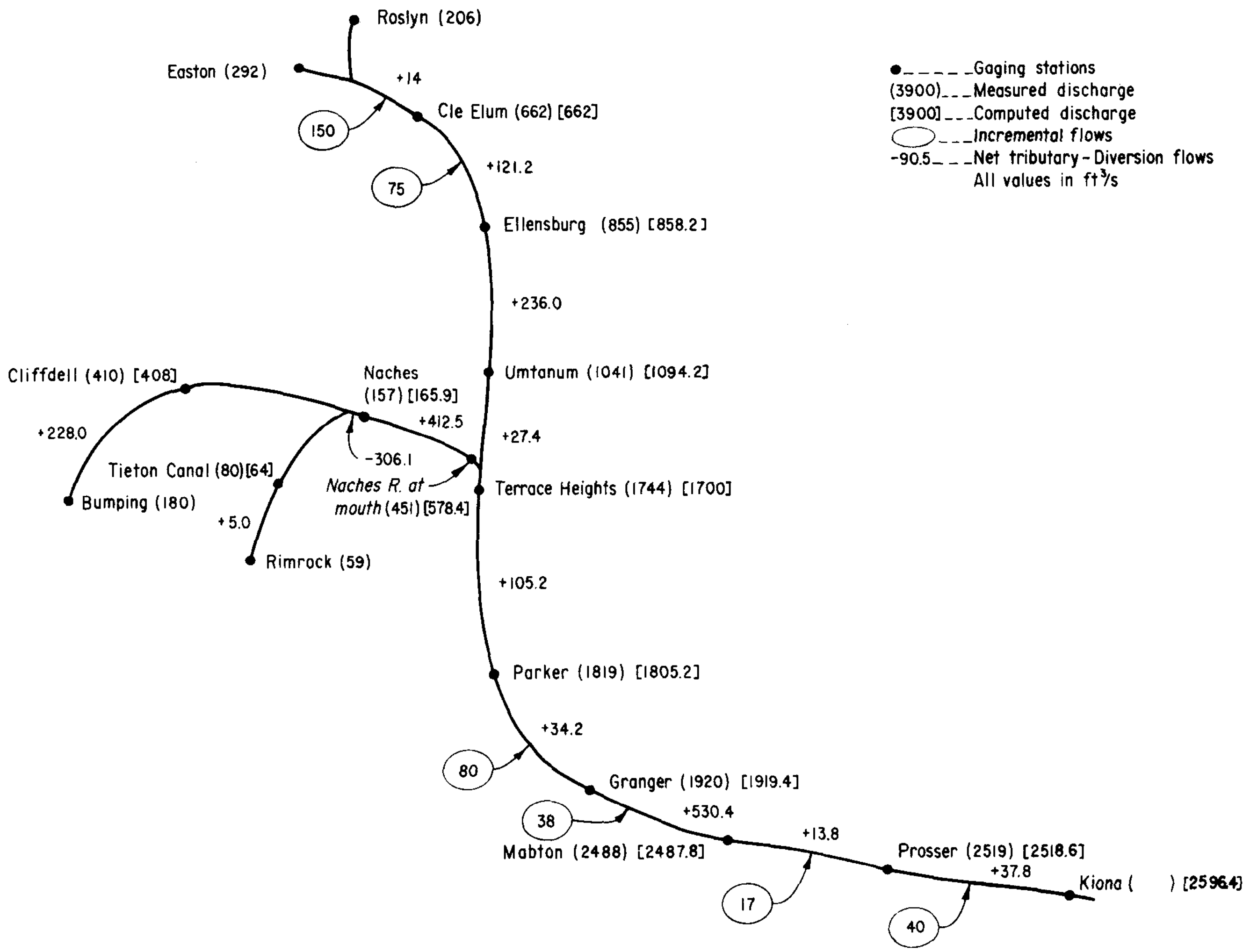

Figure 7. — QUAL-II water budget for November 1982.

- Dissolved nitrates as nitrogen
- Dissolved oxygen
- Biochemical oxygen demand
- Coliform bacteria
- Total alkalinity as $CaCO_3$
- Total dissolved solids
- pH
- Unit toxicity

The ecological processes within the quality model are centered around benthic algae and aquatic insects to form the base of the food chain. Relationships between the various components of the food chain are shown in figure 9. Basic processes which influence the components are shown in table 12. All of these processes are simulated in the model as mass balances with appropriate source and sink terms. For further details the reader is referred to the appendixes of reference [16].

With the exception of temperature, which must be included, any combination of parameters can be selected for simulation. Thus a user can tailor the parameters modeled to fit the problem being studied. However, care should be exercised because unrealistic situations can be created by not having the correct relationships in the model. All parameters except alkalinity, TDS, and unit toxicity are associated with one or more rate coefficients which modify growth, rate of decay, or chemical change. The complex physical and ecological processes are represented in the model by empirical relationships, first order decay reactions, or simplified diffusion processes. Coefficient values are set in the model, but because these values are functions of climate, location, time of day, and the type and level of pollution, they should be modified to reflect the system being modeled. Field data should be used to evaluate the coefficients, but if unavailable, values obtained from the literature or the values in the WQRRS Manual [16] can be used with caution.

Model output includes both a table listing the input data, initial conditions, and final concentrations at specified times for each computational element, and a data plot file with concentrations for all parameters

Table 10. — QUAL-II verification results compared to observed data, August 1982.

Site		Flow (m^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	Chl. *a* (µg/L)	EC (µS/cm)	Cl^- (mg/L)
Cle Elum	Observed	106.2	14.3	9.2	2.0	0.01	0.01	0.001	1.0	57	0.0
	Predicted	101.9	15.4	9.0	2.4	.01	.03	.000	.9	50	.0
Ellensburg	Observed	105.4	15.3	9.6	2.9	.01	.04	.001	.9	88	.0
	Predicted	102.8	15.7	8.8	2.0	.01	.10	.000	.8	64	.0
Umtanum	Observed	115.8	16.2	9.2	3.0	.01	.11	.003	1.4	90	.0
	Predicted	114.1	16.2	8.9	2.1	.01	.20	.011	1.3	91	.3
Cliffdell	Observed	11.1	14.3	9.7	3.2	.01	.00	.001	2.7	41	.0
	Predicted	9.6	17.0	8.8	1.9	.01	.01	.004	.7	37	.0
Tieton Canal	Observed	8.3	14.2	9.4	2.0	.00	.00	.000	.7	50	1.1
	Predicted	8.6	13.6	9.5	2.5	.01	.01	.000	.3	49	1.1
Naches	Observed	5.5	17.8	8.9	2.4	.00	.00	.002	.5	54	.7
	Predicted	4.4	18.7	8.5	2.0	.01	.01	.002	.6	46	.7
Confluence	Observed	11.0	22.1	9.4	3.2	.01	.04	.002	2.0	93	1.4
	Predicted	7.2	20.3	8.2	2.3	.00	.18	.012	1.3	91	1.4
Terrace Hgts.	Observed	91.5	17.8	10.7	-1.0	.01	.10	.004	2.8	95	.0
	Predicted	88.8	17.8	8.6	2.6	.01	.18	.010	1.9	95	.5
Parker	Observed	13.0	20.6	8.8	3.5	.04	-2.00	.092	4.2	130	2.1
	Predicted	13.4	18.5	8.5	2.7	.08	.29	.059	1.9	115	.8
Granger	Observed	19.1	19.0	6.8	4.0	.06	.45	.012	6.4	170	3.2
	Predicted	19.1	19.8	7.8	2.1	.08	.46	.046	2.1	185	2.4
Mabton	Observed	45.0	21.2	7.8	3.3	.03	1.20	.051	3.9	270	4.3
	Predicted	45.0	21.1	7.6	2.3	.04	1.06	.056	4.1	276	4.2
Prosser	Observed	12.3	23.4	7.8	4.4	.01	.93	.074	9.4	293	5.7
	Predicted	12.3	21.8	8.0	5.6	.12	1.01	.076	5.4	305	5.3
Kiona	Observed	45.6	25.1	10.6	6.7	.01	1.00	.041	8.0	295	6.4
	Predicted	45.5	22.3	8.2	3.9	.03	1.00	.040	9.1	296	6.2
Root-mean-square error		2.0	1.5	1.1	1.3	.04	.08	.014	1.9	10	.6

-1.0 = missing data; -2.00 = unreliable data.
Sites with observed parameter values of zero are not included in error computations for that parameter.

at each reach for each time interval used in the simulation. The latter can be interfaced with a plot routine to provide graphs of parameter concentration as a function of distance along the channel.

General Input Data

Stream reaches. — The WQRRS Model was applied to the Yakima River from Easton to river mile 43.3, below Prosser. Because the model is limited to five withdrawals, the river had to be modeled as eight separate simulations for various reaches. These reaches are shown on figure 10. Reach division was determined by number of withdrawals and changes in the hydraulic characteristics of the stream. Element lengths were constant within each reach, but varied from 0.5 mile (0.8 km) to 1.5 mile (2.5 km) between reaches.

Table 11. — QUAL-II verification results compared to observed data, November 1982.

Site		Flow (m^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	Chl. *a* (μg/L)	EC (μS/cm)	Cl^- (mg/L)
Cle Elum	Observed	18.8	6.5	11.5	2.0	0.00	0.00	0.001	0.9	41	0.7
	Predicted	18.8	6.8	9.8	1.7	.00	.00	.002	1.3	53	.9
Ellensburg	Observed	24.2	7.5	12.6	3.0	.00	.13	.007	1.9	84	.7
	Predicted	24.3	5.6	11.3	1.5	.00	.03	.002	1.0	76	.9
Umtanum	Observed	29.5	6.8	12.3	2.7	.00	.18	.002	5.6	127	2.0
	Predicted	31.0	5.7	11.6	1.9	.01	.21	.013	2.4	141	2.0
Cliffdell	Observed	11.6	4.2	11.3	2.7	.00	.00	.009	3.3	82	.4
	Predicted	11.6	3.3	12.3	2.1	.00	.00	.009	1.3	59	.1
Tieton Canal	Observed	2.3	6.4	11.8	2.7	.00	.00	.011	.9	92	1.1
	Predicted	1.8	5.4	11.2	1.8	.01	.00	.005	1.8	86	1.2
Naches	Observed	4.5	5.0	11.9	-1.0	.01	.00	.007	.8	78	.5
	Predicted	4.7	3.2	12.3	2.0	.01	.00	.010	1.2	66	.4
Confluence	Observed	12.8	6.0	13.3	2.1	.00	.06	.008	1.1	103	1.4
	Predicted	16.4	4.2	12.0	2.0	.01	.16	.016	1.3	89	1.0
Terrace Hgts.	Observed	49.4	6.8	12.7	-1.0	.01	.08	.002	6.4	120	1.8
	Predicted	48.1	4.7	11.8	2.0	.01	.20	.015	2.1	129	1.8
Parker	Observed	51.5	7.2	11.4	3.0	.05	.16	.052	5.2	147	3.2
	Predicted	51.1	4.8	11.8	2.3	.08	.29	.067	2.1	154	2.4
Granger	Observed	54.4	8.0	9.7	3.9	.01	.25	.052	11.2	164	4.3
	Predicted	54.4	5.5	12.0	2.1	.08	.35	.065	2.1	176	3.0
Mabton	Observed	70.5	8.7	9.8	3.5	.02	.93	.067	4.8	240	5.7
	Predicted	70.5	6.8	11.3	2.3	.07	1.07	.073	3.9	242	4.7
Prosser	Observed	71.3	8.8	10.3	5.9	.10	1.23	.079	6.5	310	6.7
	Predicted	71.3	6.8	11.3	2.7	.08	1.16	.076	4.2	248	4.9
Kiona	Observed	-2.0	8.8	11.4	2.7	.02	1.11	.065	10.2	280	6.7
	Predicted	73.5	6.9	11.4	2.5	.07	1.20	.074	4.4	259	5.3
Root-mean-square error		1.2	1.8	1.2	1.3	.04	.10	.009	3.6	21	.8

-1.0 = missing data; -2.00 = unreliable data.
Sites with observed parameter values of zero are not included in error computations for that parameter.

Cross section data was furnished by the Seattle District of the Corps of Engineers for all reaches except those in Umtanum Canyon and upstream of Ellensburg. For these two reaches stage-discharge relationships were used in the hydraulic computations. Otherwise, backwater computation was used. Manning's *n* values were based on USGS data at the gaging stations and from travel time studies. Some *n* values were changed to obtain continuity of depth and velocity between reaches when the slopes changed between reaches.

Initially, the cross section or stage-discharge data were put directly into the stream hydraulics program, but two problems occurred: (1) the program failed if any element length exceeded 0.5 mile (0.8 km) in length, and (2) the computed water surface became lower than the bottom of the channel when the slope of the channel decreased from one element to the next downstream element. Modifications were made in the computer code to solve both of these problems. Similar modifications have been made to the utility program called GEDA. This program creates values at

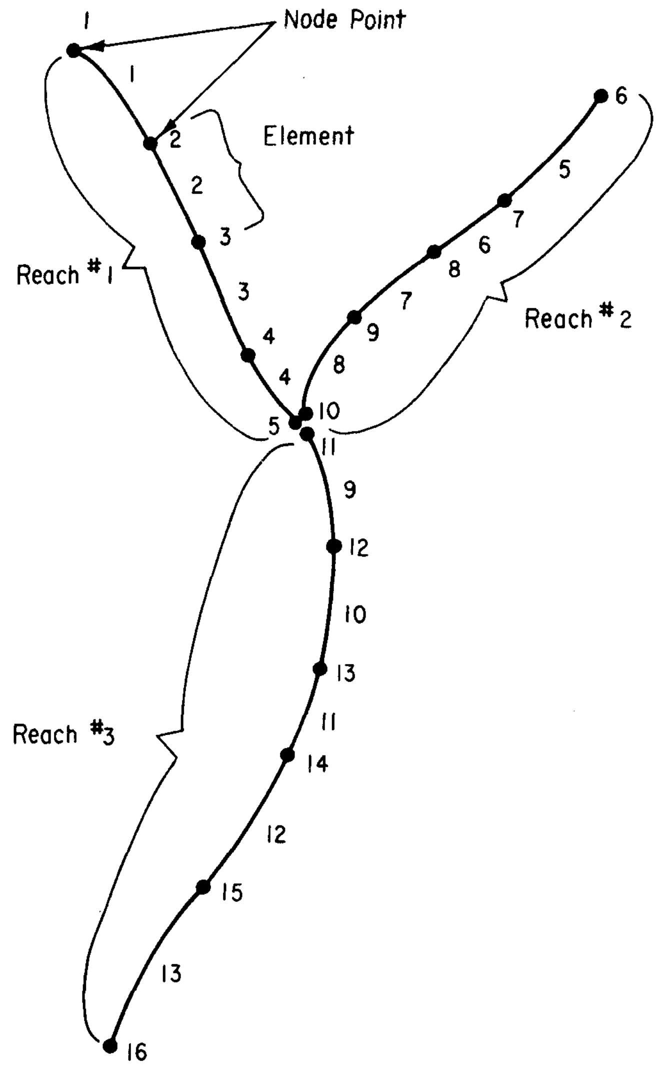

Figure 8. — Model representation of a river used in the WQRRS model.

regular intervals from variably spaced cross sections. Also, the GEDA program has an algorithm to follow the slope of the cross section data, thus eliminating the problem of the water surface becoming lower than the channel bottom.

Water budget. — A hydraulic balance between inflows and outflows is necessary for the steady-state assumption with either the backwater or stage-discharge computations. A hydraulic budget was developed by computing the flows at the gaged points. Differences between computed and measured flows were minimized by adding or subtracting water from the river on a distributed basis. These differences in discharge result mainly from subsurface return flows or increases in bank storage. The headwater boundary condition at Easton was computed the same way as mentioned in the QUAL-II discussion, except that for August 1981 additional flow was added to obtain a water balance at Cle Elum.

Figures 11 and 12 show the hydraulic budgets, including distributed flows for the 1981 and 1982 irrigation season surveys. Return flows are indicated in the Kittitas Valley above Ellensburg and below Parker for August 1981. Water was lost from the channel around Yakima.

Budgets for the nonirrigation season are shown on figures 13 and 14. These indicate that return flows were occurring in the Kittitas Valley above and below the Ellensburg gage and below Parker.

Measured flows for the Naches River at Yakima were used in all four water budgets.

Parameters modeled. — Temperature, dissolved oxygen, BOD, electrical conductivity, nitrate, nitrite, ammonia, and phosphate were modeled. Electrical conductivity was treated as a conservative parameter. Chlorophyll *a* was not modeled because the food chain in the stream model is based on benthic algae rather than phytoplankton, and no general relationships exist between chlorophyll *a* and benthic algae. Estimates of benthic algae can be obtained by placing substrate in the stream and observing growth over a

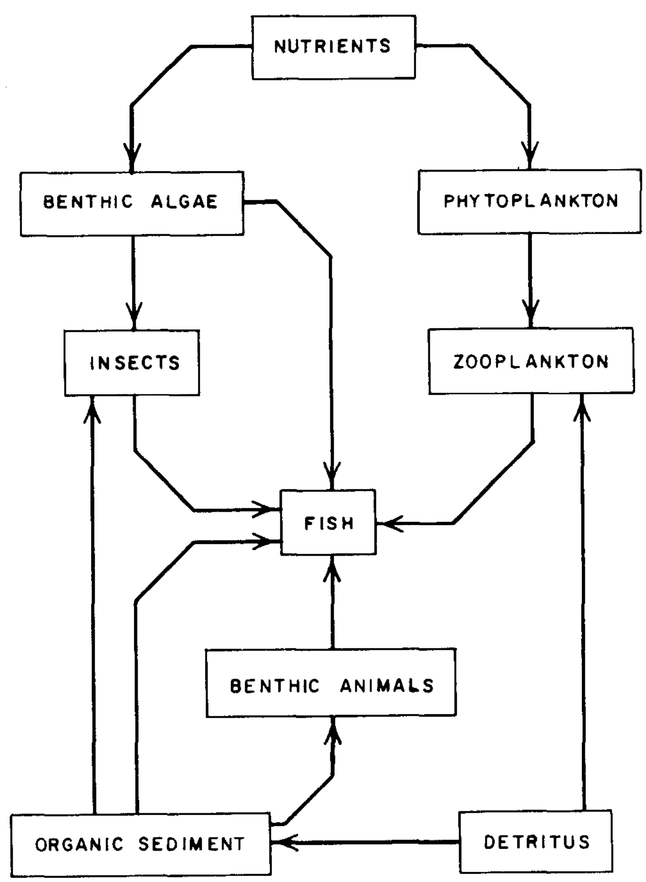

Figure 9. — Food chain relationships within the WQRRS stream model (after Smith [16]).

Table 12. — Basic processes in the WQRRS model (after Smith) [16].

Constituent	Conservative constituent	Advected[1] and diffused	Exchange through air-water interface	Rates are temp. dependent	Mass increased by: Growth	Mass increased by: By-products of other constituents	Mass decreased by: Mortality or settling	Mass decreased by: Respiration	Mass decreased by: Grazed or consumed by	Mass decreased by: Decay
Temperature		X	X							
BOD		X		X						X
Coliforms		X		X						X
Fish (three types)				X	X		X	X	Man	
Insects				X	X		X	X	Fish	
Benthos				X	X		X	X	Fish	
Zooplankton		X		X	X		X	X	Fish	
Phytoplankton (two types)		X		X	X		X		Zooplankton	
Benthic Algae (two types)				X	X		X	X	Insects and fish	
Detritus		X		X		X	X		Zooplankton	X
Phosphorous		X		X		X			Algae	
Ammonia		X		X		X			Algae	X
Nitrite		X		X		X				X
Nitrate		X		X		X			Algae	
Total Carbon		X	X	X		X			Algae	
Organic Sediment				X		X			Fish and benthos	X
Alkalinity	X	X								
TDS	X	X								
Oxygen		X	X	X		X			Decay[2]	
Suspended Solids		X		X			X			
Inorganic Sediment						X				
Toxicity	X	X								

[1]Advected and diffused between segments and advected into and out of the system by inflow and outflow waters.
[2]Consumed with decay of BOD, sediment, detritus, ammonia, nitrite, and biota respiration.

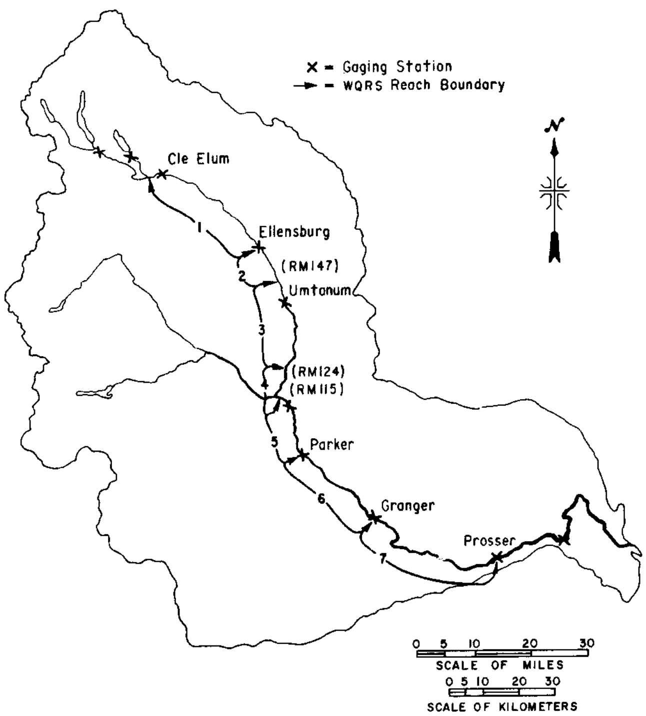

Figure 10. — Reach division used for WQRRS simulation of the Yakima River.

period of time. Numerous sites would need to be established and observed over several months. Benthos sampling is very time consuming and costly and could not be accomplished as part of the sampling program. Consequently, no benthic data were obtained. Unlike phytoplankton, benthic algae grow slowly and have only a minor effect on dissolved oxygen and nutrients. Therefore, exclusion of benthic algae is not expected to significantly affect simulation of other parameters.

Recommended model coefficients were used initially and were modified to improve agreement between the model results and observed data. Table 13 shows the initial (recommended) and final (calibrated) values of these coefficients. The model was not sensitive to changes in thermal capacity of the bed or to the conduction coefficient and was not very sensitive to changes in the evaporation coefficients. Atmospheric turbidity had the greatest effect on temperatures. Final 1981 calibration values were used for verification runs with 1982 data.

Meterological Data

Dry bulb temperature was available at the following stations: (1) Cle Elum, (2) Ellensburg, (3) Yakima, (4) Wapato, (5) Sunnyside, and (6) Prosser.

The remaining meteorological data (cloud cover, pressure, windspeed, and relative humidity) were obtained from stations at Stampede Pass, Yakima, and Hanford. These data were used to obtain the meteorological input values applicable to each of the reaches, as shown in table 14. Cloud cover data were the average of the 3-hour observations from sunrise to sunset as shown in table 14 with the following exceptions:

(1) Cloud cover values for the reach below Granger for October 1981 used Hanford data.

(2) Cloud cover values for the Easton to Ellensburg reach for August 1982 used Yakima data only.

(3) Average cloud cover for Yakima and Stampede Pass was used for the Ellensburg to Rm 147 reach for August 1982.

Windspeed and relative humidity were the average of the 3-hour data from sunrise to sunset. Wet bulb data were computed from dry bulb, relative humidity, and pressure data for each reach. Table 15 shows the input meteorological data used in the model for both years.

The WQRRS Model computes the solar radiation based on longitude, latitude, cloud cover, and atmospheric turbidity. Computed solar radiation was compared to values from both the Smithsonian meterological tables and results from a different reservoir quality model (CE-QUAL-R1 [17]). There was excellent agreement between these values and those computed from WQRRS.

Calibration

Data for 1981 were used as a calibration set and the 1982 data were used to verify the calibration. Separate calibrations were set up for August and October 1981.

First the hydraulics program was run with the water balances shown in figures 11 and 13, then the water quality simulation was run. The only adjustment required for the hydraulic model was the *n* values were changed at the boundaries of adjacent reaches to maintain the correct velocity and depth. When the slope changed in the middle of the reach, no adjustments were required to maintain continuity of velocity and depth.

Quality runs used the recommended coefficients except for evaporation, atmospheric turbidity, bed conduction, and reaeration coefficients. Heat exchange at the water surface was obtained by a heat budget which relies on the gradients of temperature, vapor pressure, and evaporation coefficients. The O'Connor-Dobbins Reaeration Formula was used in the model simulations. The reaeration coefficient

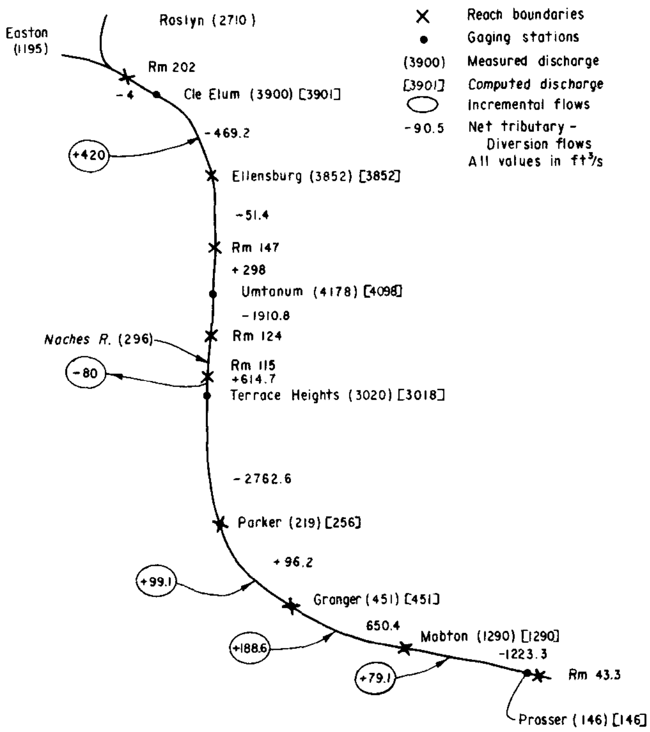

Figure 11. — WQRRS water budget for August 1981.

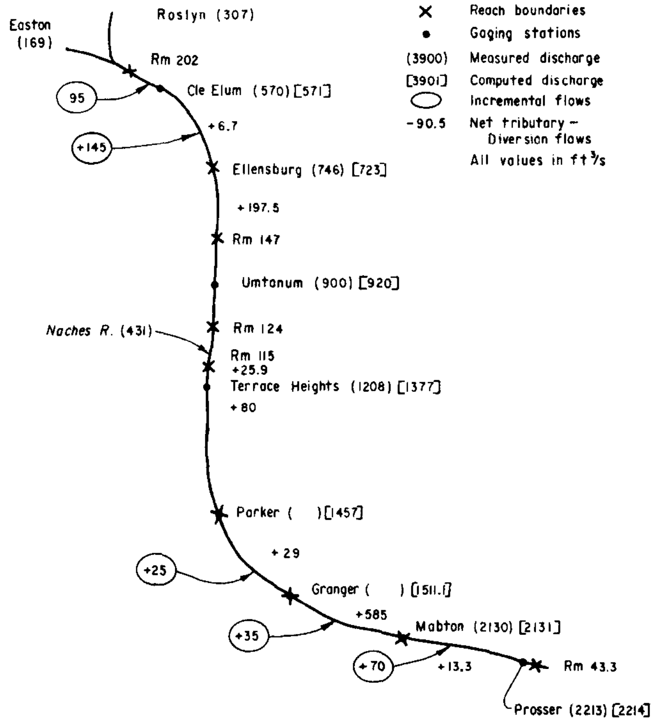

Figure 13. — WQRRS water budget for October 1981.

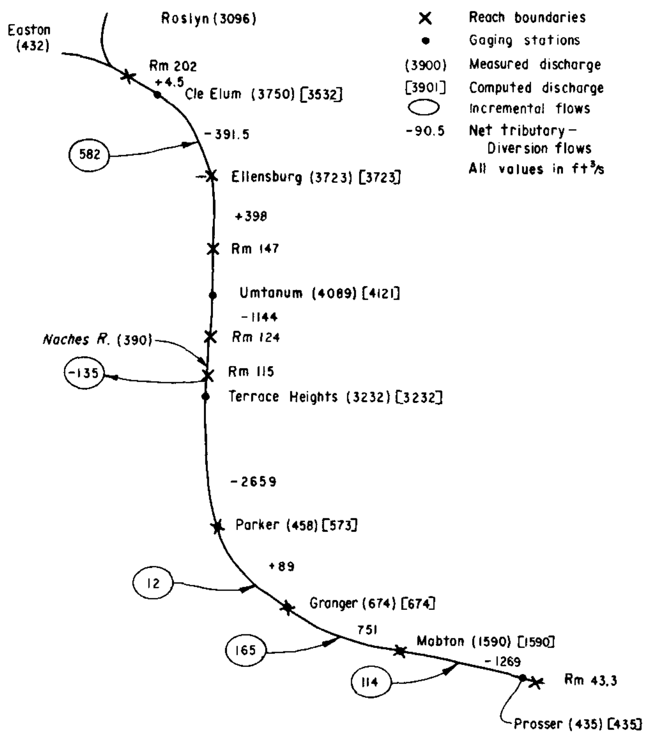

Figure 12. — WQRRS water budget for August 1982.

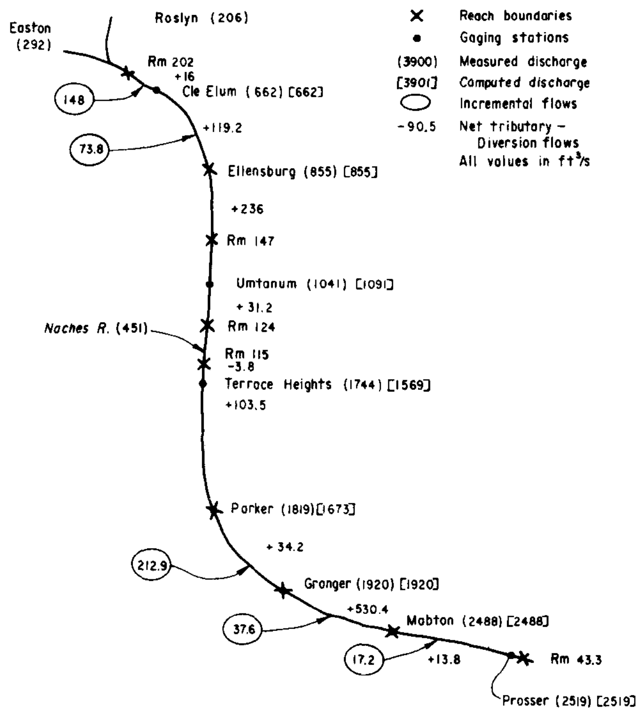

Figure 14. — WQRRS water budget for November 1982.

Table 13. — Recommended (R) and calibrated (C) WQRRS coefficient values.

Reach		Evaporation AA	Evaporation BB	Atmospheric turbidity	Conduction coefficient	Thermal capacity of bed
		m/(s•bar)	mbar		kCal/(m•s•°C)	m
August 1981 and 1982 Simulations						
Easton to	R	0	1.5×10^{-9}	2-5	-	-
Ellensburg	C	0	2.0×10^{-9}	3	0.05	0.5
Ellensburg to	R	0	1.5×10^{-9}	2-5	-	-
Rm 147	C	0	2.0×10^{-9}	3	.05	.5
Rm 147 to	R	0	1.5×10^{-9}	2-5	-	-
Rm 124	C	0	2.0×10^{-9}	3	.05	.5
Rm 124 to	R	0	1.5×10^{-9}	2-5	-	-
Rm 115	C	0	2.0×10^{-9}	3	.05	.5
Rm 115 to	R	0	1.5×10^{-9}	2-5	-	-
Parker	C	0	2.0×10^{-9}	3	.05	.5
Parker to	R	0	1.5×10^{-9}	2-5	-	-
Granger	C	0	1.0×10^{-9}	1	.05	1.0
Granger to	R	0	1.5×10^{-9}	2-5	-	-
below Prosser	C	0	1.0×10^{-9}	1	.05	1.0
October 1981 and November 1982 Simulations						
Easton to	R	0	1.5×10^{-9}	2-5	-	-
Ellensburg	C	0	1.0×10^{-9}	2	.05	.5
Ellensburg to	R	0	1.5×10^{-9}	2-5	-	-
Rm 147	C	0	1.0×10^{-9}	2	.05	.5
Rm 147 to	R	0	1.5×10^{-9}	2-5	-	-
Rm 124	C	0	1.0×10^{-9}	2	.05	.5
Rm 124 to	R	0	1.5×10^{-9}	2-5	-	-
Rm 115	C	0	1.0×10^{-9}	2	.05	.5
Rm 115 to	R	0	1.5×10^{-9}	2-5	-	-
Parker	C	0	1.0×10^{-9}	2	.05	.5
Parker to	R	0	1.5×10^{-9}	2-5	-	-
Granger	C	0	1.0×10^{-9}	1	.05	1.0
Granger to	R	0	1.5×10^{-9}	2-5	-	-
below Prosser	C	0	1.0×10^{-9}	1	.05	1.0

Rm = River mile

computed by the program for each computational element was a function of the depth and velocity for that element.

Because the total simulation time period was greater than the travel time for flow through any reach, simulation results for the final time intervals are independent of initial conditions and, therefore, may be considered steady state values. However, the simulation period was less than the overall travel time from Easton to Prosser. In this situation, initial conditions for upstream reaches can affect final results for downstream reaches. This impact is minimized if initial conditions approximate steady state values.

Therefore, initial conditions were set at observed values for the gage site within or nearest to each reach, since these were the expected steady state values. The problem could also have been alleviated by increasing the time of simulation to a value greater than the overall travel time through the system. User's of WQRRS must be aware that major errors may result if improper estimates of initial conditions are used.

Model results were written to an output file on an hourly interval and data were then processed by a program which averaged the data for each day. Tables 16 and 17 compare observed data to the daily

Table 14. — Stations averaged for WQRRS climatological input.

Reach	Dry bulb temperature	Cloud cover, pressure, windspeed, relative humidity
Easton to Ellensburg	Cle Elum and Ellensburg	Stampede Pass and Yakima
Ellensburg to Rm 147	Ellensburg	Yakima
Rm 147 to Rm 124	Ellensburg and Yakima	Yakima
Rm 124 to Rm 115	Yakima	Yakima
Rm 115 to Parker	Yakima and Wapato	Yakima
Parker to Granger	Wapato	Yakima
Granger to below Prosser	Wapato, Sunnyside, and Prosser	Yakima

Table 15. — Climatological input for WQRRS simulations.

Date	Reach number	Cloud cover	Dry bulb temp. (°F)	Wet bulb temp. (°F)	Pressure (in Hg)	Wind (m/hr)	Wind (ft/s)	Relative humidity (%)
08-18-81	1	0.39	72.5	58.0	27.3	7.56	11.08	40.9
	2	.35	72.0	59.0	28.6	7.63	11.19	46.5
	3	.35	74.7	62.0	28.6	7.63	11.19	46.5
	4	.35	77.5	64.0	28.6	7.63	11.19	46.5
	5	.35	77.8	64.0	28.6	7.63	11.19	46.5
	6	.35	78.0	64.0	28.6	7.63	11.19	46.5
	7	.35	76.8	63.0	28.6	7.63	11.19	46.5
10-28-81	1	.81	50.25	46.0	26.92	8.91	13.1	77.7
	2	.625	51.00	45.0	28.35	12.24	17.95	64.9
	3	.625	50.25	44.0	28.35	12.24	17.95	64.9
	4	.625	49.50	44.0	28.35	12.24	17.95	64.9
10-29-81	5	.90	46.75	43.0	28.61	4.03	5.91	70.7
	6	.90	50.00	45.0	28.61	4.03	5.91	70.7
	7	.80	49.83	45.0	28.61	4.03	5.91	70.7
08-25-82	1	.075	69.0	57.0	27.33	8.16	11.97	47.7
08-26-82	2	.063	73.0	60.0	28.66	5.33	7.81	48.9
	3	.025	71.8	59.0	28.66	5.33	7.81	48.9
	4	.025	70.5	59.0	28.66	5.33	7.81	48.9
	5	.025	73.3	60.0	28.66	5.33	7.81	48.9
08-25-82	6	.075	73.5	61.0	28.71	9.21	13.51	50.4
	7	.075	73.0	61.0	28.71	9.21	13.51	50.4
11-02-82	1	.500	38.0	35.0	27.74	11.03	16.17	73.3
	2	.325	39.5	36.0	29.26	6.50	9.53	70.9
11-03-82	3	.975	40.8	37.0	29.06	3.60	5.28	66.1
	4	.975	43.0	38.0	29.06	3.60	5.28	66.1
	5	.975	42.5	38.0	29.06	3.60	5.28	66.1
11-04-82	6	.675	43.0	39.0	28.89	3.60	5.28	72.5
	7	.675	44.2	40.0	28.89	3.60	5.28	72.5

averages and the hourly data nearest the time of day when the data were collected for August and October 1981. The first line associated with each station is the observed data. The second line is the hourly data nearest the time of data collection and the third line is the daily average.

Verification

Data from August and November 1982 surveys were used to verify the model calibration. Flow balances were established for the 1982 data and are shown in figures 12 and 14. Headwater, point discharge, and

Table 16. — WQRRS calibration results compared to observed data, August 1981.

Station	Time		Flow (ft^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	EC (μS/cm)
Cle Elum	1430	O	3900	19.0	8.3	0.3	<0.01	0.02	<0.001	50
	1400	P	3930	19.4	9.0	.33	.005	.01	.000	61
	Ave.	P	3930	18.9	9.0	.33	.005	.01	.000	61
Ellensburg	1030	O	3852	17.0	8.8	—	<0.01	<0.01	.006	77
	1000	P	3854	18.5	8.9	.32	.005	.028	.001	74
	Ave.	P	3854	18.8	8.8	.32	.005	.028	.001	74
Umtanum	746	O	4178	18.0	8.2	.4	<0.01	<0.08	<0.001	85
	800	P	4101	18.2	9.0	.39	.006	.082	.013	91
	Ave.	P	4101	18.9	9.0	.39	.006	.082	.013	91
Terrace	608	O	3020	19.0	8.0	—	.11	.08	.014	87
Heights	600	P	3020	19.0	8.7	.49	.013	.085	.015	94
	Ave.	P	3020	19.5	8.7	.49	.013	.085	.015	94
Parker	655	O	219	19.0	8.3	.8	.03	.17	.040	90
	700	P	261	18.9	8.7	.68	.084	.129	.064	112
	Ave.	P	261	19.9	8.7	.70	.084	.129	.064	111
Granger	715	O	451	20.8	7.4	—	.01	.17	.027	181
	700	P	453	20.8	7.4	.61	.06	.617	.070	176
	Ave.	P	453	21.7	7.3	.61	.06	.622	.071	178
Mabton	1100	O	1290	22.9	8.7	—	.02	.56	.066	263
	1100	P	1298	21.5	7.9	.77	.044	.973	.084	221
	Ave.	P	1298	21.2	7.9	.77	.043	.988	.085	223
Prosser	1345	O	145	24.7	7.5	—	.13	1.15	.110	336
	1400	P	149	24.1	8.0	1.30	.078	.69	.081	283
	Ave.	P	149	21.9	8.1	1.30	.079	.69	.081	281

O = observed
P = predicted

concentrations were set to 1982 observed values and the model was then run. The results of these simulations are compared to the 1982 observed data in tables 18 and 19. These tables have the same organization as explained for the 1981 results.

DISCUSSION

Comparison of Simulation Results

Calibration and verification results of WQRRS and QUAL-II simulations are displayed graphically, along with observed values, in figures 15 through 21. The plotted lines are the steady-state solution given by QUAL-II and the 24-hour average for the last day of simulation with WQRRS. Several general observations can be made concerning the plots:

- Few major differences are apparent between results of the 2 models.
- Model results for both August and October-November are of similar accuracy.
- Simulation of temperature, DO, and nitrate is generally more accurate than that of ammonia, phosphate, BOD, and chlorophyll *a*.

The following sections present specific observations for each parameter.

Temperature. — Results of both models for the August simulations were very good, but QUAL-II lost some accuracy in the October and November simulations. WQRRS simulations used a meteorological data set interpolated for each reach; Qual-II used only two meteorological data sets: one above Parker and one below Parker. Differences in input data along the river were compensated for during August, when air temperature is greater than water temperature at all sampling sites, and the river gains heat throughout its length. For such conditions simulated temperature is easily fit by adjusting the evaporation coefficients. In October and November, the upper reaches are losing heat and the lower reaches gaining. Below Mabton, temperature is nearly constant. In this situation, errors in air temperature and solar radiation input values are difficult to compensate for by parameter adjustment.

Table 17. — WQRRS calibration results compared to observed data, October 1981.

Station	Time		Flow (ft^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	EC (μS/cm)
Cle Elum	1152	O	570	9.0	10.8	—	0.49	0.01	0.000	67
	1200	P	566	9.6	10.1	1.58	.01	.04	.000	77
	Ave.	P	566	9.4	10.1	1.58	.01	.04	.000	77
Ellensburg	1435	O	746	11.8	11.0	—	.00	.08	.008	100
	1500	P	723	10.0	10.9	1.30	.01	.07	.001	105
	Ave.	P	723	10.9	10.9	1.30	.01	.07	.001	105
Umtanum	1555	O	900	10.7	11.3	—	.02	.17	.032	160
	1600	P	921	10.3	11.2	1.41	.01	.22	.018	154
	Ave.	P	921	10.1	11.2	1.34	.01	.21	.018	153
Terrace	1715	O	1208	10.5	10.8	—	.03	.12	.020	265
Heights	1700	P	1378	10.2	11.2	1.77	.02	.18	.016	152
	Ave.	P	1378	10.0	11.2	1.75	.02	.18	.017	151
Parker	1020	O		10.0	9.0	—	.05	.26	.052	185
	1000	P	1459	9.8	11.1	2.00	.10	.25	.082	177
	Ave.	P	1459	10.0	11.1	2.00	.11	.24	.081	177
Granger	1125	O		12.2	7.4	—	.16	.34	.050	230
	1100	P	1512	10.8	10.9	1.89	.11	.29	.091	202
	Ave.	P	1512	10.6	10.9	1.89	.11	.29	.091	202
Mabton	1440	O	2130	12.3	9.8	—	.03	1.12	.067	260
	1500	P	2135	12.4	10.1	1.31	.10	1.08	.080	284
	Ave.	P	2135	12.2	10.1	1.35	.10	.08	.081	284
Prosser	1240	O	2213	13.8	7.9	—	.12	1.61	.076	335
	1300	P	2216	12.9	9.8	1.85	.11	1.16	.074	327
	Ave.	P	2216	12.7	9.8	1.86	.11	1.15	.075	325

O = observed
P = predicted

DO and BOD. — Accuracy of DO simulation is greatly influenced by that of BOD. Unfortunately, BOD data in 1981 were inadequate for proper calibration. Therefore, BOD decay rates were set to default values or adjusted to fit simulated DO to observed targets. This led to inaccurate verification results, especially for QUAL-II. BOD loading for wastewater treatment plants was not measured directly, but taken from monthly averages reported to the Washington State Department of Ecology. This may account for the relative inaccuracy of DO simulation downstream of the basin's major sewage treatment plant, below the city of Yakima at river kilometer 175. This is particularly apparent in the October 1981 results. In future model applications, synoptic sampling should include all known waste-load sources. BOD analysis should be performed such that ultimate carbonaceous BOD can be determined for all point sources and target gage sites.

Although not as significant as errors in BOD loading, inaccurate temperature simulation also affects DO results. Simulated temperatures were generally less than observed values for the lower Yakima River in October and November. This would artificially elevate DO concentrations and may have contributed to the DO errors indicated in figure 16.

Errors in algae simulation may also affect DO predictions. However, sensitivity analysis performed for summer conditions in the lower basin indicates this effect was not important. A 1-μg/L change in chlorophyll *a* resulted in approximately a 0.01 mg/L change in DO. The maximum verification error for chlorophyll *a* is 9.1 μg/L, so the impact of chlorophyll *a* simulation errors on DO is less than 0.1 mg/L at any gate site. Also, most DO errors are negatively correlated with chlorophyll *a* errors and would increase if chlorophyll *a* predictions were improved.

Ammonia. — Both models gave similar results and were moderately accurate in calibration and verification with August data. As with BOD, ammonia simulation below river kilometer 175 was adversely affected by inadequate treatment plant data. October and November simulation accuracy was poor. This was due in part to attempting to fit the models to wildly oscillating, possibly erroneous data in the October calibration, particularly below kilometer 175.

Table 18. — WQRRS verification results compared to observed data, August 1982.

Station	Time		Flow (ft³/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	EC (μS/cm)
Cle Elum	915	O	3750	14.3	9.2	0.7	0.01	0.01	0.001	57
	900	P	3566	15.5	9.9	1.07	.01	.01	.000	51
	Ave.	P	3566	15.1	9.9	1.07	.01	.01	.000	51
Ellensburg	1200	O	3723	15.8	9.4	1.4	.01	.06	.001	88
	1200	P	3725	16.4	9.3	.95	.01	.04	.001	72
	Ave.	P	3725	16.0	9.3	.95	.01	.04	.001	72
Umtanum	1130	O	4089	16.2	9.2	1.5	.01	.11	.003	90
	1100	P	4123	16.7	9.6	.98	.01	.14	.012	97
	Ave.	P	4123	16.7	9.5	.98	.01	.14	.012	97
Terrace	1425	O	3232	17.8	10.7	1.0	.01	.10	.004	95
Heights	1400	P	3234	18.8	9.3	1.23	.01	.13	.009	99
	Ave.	P	3234	18.2	9.3	1.23	.01	.13	.009	99
Parker	1552	O	458	20.6	8.8	1.1	.04	1.30	.092	130
	1600	P	573	19.9	9.2	1.32	.08	.24	.056	118
	Ave.	P	573	18.7	9.3	1.32	.08	.24	.056	118
Granger	841	O	674	19.0	6.8	1.3	.06	.45	.012	170
	900	P	674	20.4	8.5	1.23	.09	.46	.053	144
	Ave.	P	674	21.4	8.5	1.23	.09	.46	.053	144
Mabton	1140	O	1590	21.2	7.8	1.2	.03	1.20	.051	270
	1200	P	1591	21.9	8.0	1.09	.05	1.05	.059	243
	Ave.	P	1591	21.6	8.0	1.08	.05	1.05	.059	243
Prosser	1425	O	435	23.4	7.8	1.7	.01	.93	.074	293
	1400	P	435	24.4	7.8	1.44	.06	.99	.059	325
	Ave.	P	435	22.6	7.8	1.45	.06	1.00	.059	327

O = observed
P = predicted

Nitrate. — Despite the poor fit to ammonia data, prediction of nitrate concentration is quite good. In the Yakima River, nitrate is more dependent on agricultural return flow sources than on municipal wastewater. Thus, the uncertainty in treatment plant effluent data has less impact on nitrate than on ammonia. Also, there is a difference in scale. Nitrate concentrations are normally an order of magnitude greater than ammonia and therefore appear to fit better graphically, even though the standard errors for nitrate prediction may be greater than those for ammonia (see tables 7 through 10 above).

Orthophosphate. — Orthophosphate prediction has the same problems as that of ammonia. It is highly influenced by wastewater treatment plant data and observed concentrations are both low and, in some cases, wildly fluctuating. The latter is particularly true for the August 1982 sampling. Thus, graphical fit is poor, though absolute standard error is small. Overestimation of orthophosphate in simulation of the lower basin may be related to underestimation of algae growth, which would affect nutrient uptake. Also, observed concentrations of orthophosphate in the lower basin could have been affected by adsorption of orthophosphate on suspended sediment. The Yakima River is very turbid in its lower reaches. Adsorption on sediment may be a significant sink for orthophosphate not considered by the model.

Chlorophyll a. — Chlorophyll *a* is reported on QUAL-II output as an indicator of phytoplankton. WQRRS reports phytoplankton directly. Since field data were available only for chlorophyll *a*, WQRRS predictions are not shown in figure 21. Calibration of QUAL-II for this parameter was hindered by inadequate point source inflow data. Most values had to be estimated based on 1982 measurements. Consequently, prediction errors were ascribed to data inadequacies, and model adjustments were kept to a minimum. Goodness-of-fit varies widely over the length of the river. In the upstream reaches, chlorophyll *a* is probably more related to periphyton and point source inflow than phytoplankton. Concentrations are low and fit is generally good. In the lower reaches, phytoplankton growth becomes the dominant chlorophyll source. Concentrations are higher, and model fit varies from good to poor. Fit is better for the August simulations, when temperature is warmer and lower reach velocities slower, giving growth simulation a

Table 19. — WQRRS verification results compared to observed data, November 1982.

Station	Time		Flow (ft^3/s)	Temp. (°C)	DO (mg/L)	BOD (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	PO_4 (mg/L)	EC (μS/cm)
Cle Elum	1033	O	664	6.5	11.5	1.00	<0.01	<0.01	0.001	41
	1100	P	654	7.2	10.4	.92	.01	.05	.002	64
	Ave.	P	654	7.3	10.4	.92	.01	.05	.002	64
Ellensburg	1350	O	855	7.5	12.6	1.20	<0.01	.13	.007	84
	1400	P	855	5.9	12.3	.86	.01	.05	.002	82
	Ave.	P	855	5.4	12.3	.86	.01	.05	.002	82
Umtanum	1538	O	1042	6.8	12.2	1.35	<0.01	.17	.006	127
	1600	P	1092	6.0	12.5	1.04	.01	.23	.013	132
	Ave.	P	1092	5.8	12.5	1.04	.01	.23	.013	132
Terrace Heights	1040	O	1746	6.8	12.7	1.00	.01	.08	.002	120
	1100	P	1570	5.9	12.6	1.05	.01	.19	.013	130
	Ave.	P	1570	5.9	12.6	1.05	.01	.19	.013	130
Parker	1150	O	1820	7.2	11.4	1.00	.05	.16	.052	147
	1200	P	1685	6.3	12.4	1.33	.08	.26	.068	153
	Ave.	P	1685	6.2	12.4	1.34	.09	.26	.068	153
Granger	825	O	1922	8.0	9.7	1.70	.01	.25	.052	164
	800	P	1921	7.4	11.2	1.22	.08	.28	.061	277
	Ave.	P	1921	7.7	11.2	1.20	.08	.28	.061	280
Mabton	1150	O	2491	8.7	9.8	1.40	.02	.93	.067	240
	1200	P	2492	8.8	10.9	1.36	.08	.97	.069	310
	Ave.	P	2492	8.7	11.0	1.35	.08	.97	.069	311
Prosser	920	O	2519	8.8	10.3	2.60	.10	1.23	.079	310
	900	P	2521	8.5	11.2	1.92	.08	.97	.068	318
	Ave.	P	2521	8.7	11.2	1.93	.08	.97	.069	317

O = observed
P = predicted

greater influence than advection.

Predictions are generally low for all simulations of the lower basin. This could be due to faulty assumption of parameter values. As shown by the sensitivity analysis described previously, the light extinction depth significantly influences prediction of chlorophyll *a*. However, the extinction coefficient value assumed in this application is probably small, considering the high turbidity of the lower river. Therefore, any logical adjustment to the light extinction coefficient would not improve the fit of chlorophyll *a*.

Underestimation of chlorophyll *a* in the lower basin may also be associated with underestimation of nutrient uptake. This may explain errors in prediction of orthophosphate and ammonia. However, the sensitivity analysis indicates the magnitude of such an effect is probably small.

Suggestions for Model Use

The most popular use of streamflow transport models has been in wasteload allocation studies. A model is calibrated for a steady-state, low-flow period, and the impact of changing point source loading is determined in subsequent simulations. Headwater flows are kept constant. The intended application in the Yakima River Basin Water Enhancement Project is somewhat different. Here, changing headwater reservoir operation must be evaluated. Therefore, it is the headwater flows themselves that will be varied to determine the impact of Enhancement Project alternatives on downstream water quality. The problem with such an application is that changes in headwater flow may affect the point sources. Withdrawals may increase or may have to be reduced. Consequently, incremental and point source inflows which include agricultural return flows would be affected. The magnitude of all these impacts for any given change in headwater flow is uncertain. Therefore, modifications to point source and incremental inflow data, while expected qualitatively, are difficult to justify quantitatively. Unless adequate justification can be made, it is recommended that the point source and incremental inflow quantity and quality values in the calibration and verification data set be kept constant. One case where changes may be justified is for wastewater treatment plant effluent. As pointed out above, average monthly values were used, and may have

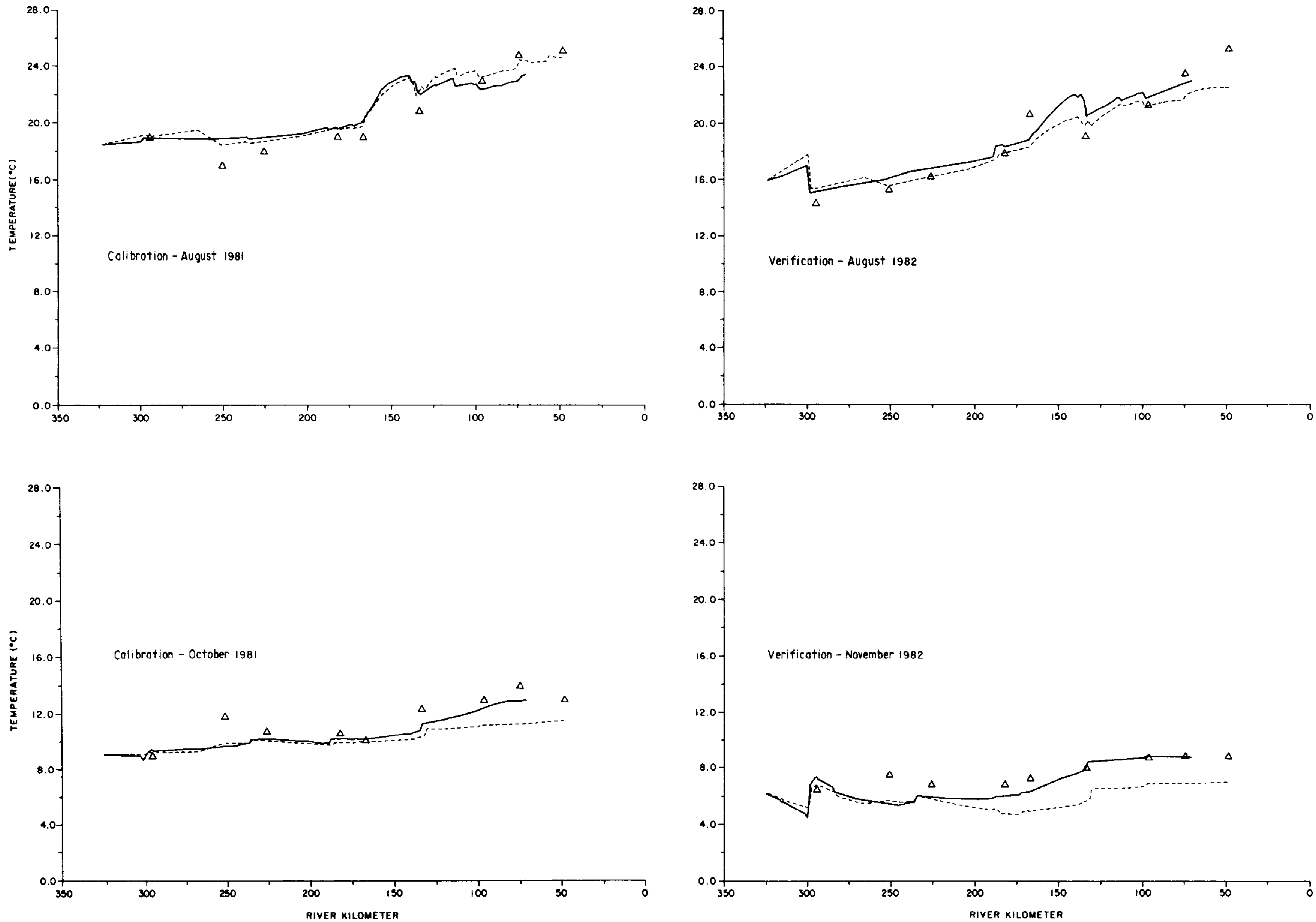

Figure 15. — Predicted vs. observed temperatures for the main stem Yakima River. (Δ = observed values, ——— = WQRRS prediction, ········ = QUAL-II prediction). Data collection locations, Δ, are, left to right: Cle Elum, Ellensburg, Untanum, Terrace Heights, Parker, Granger, Mabton, Prosser, and Kiona.

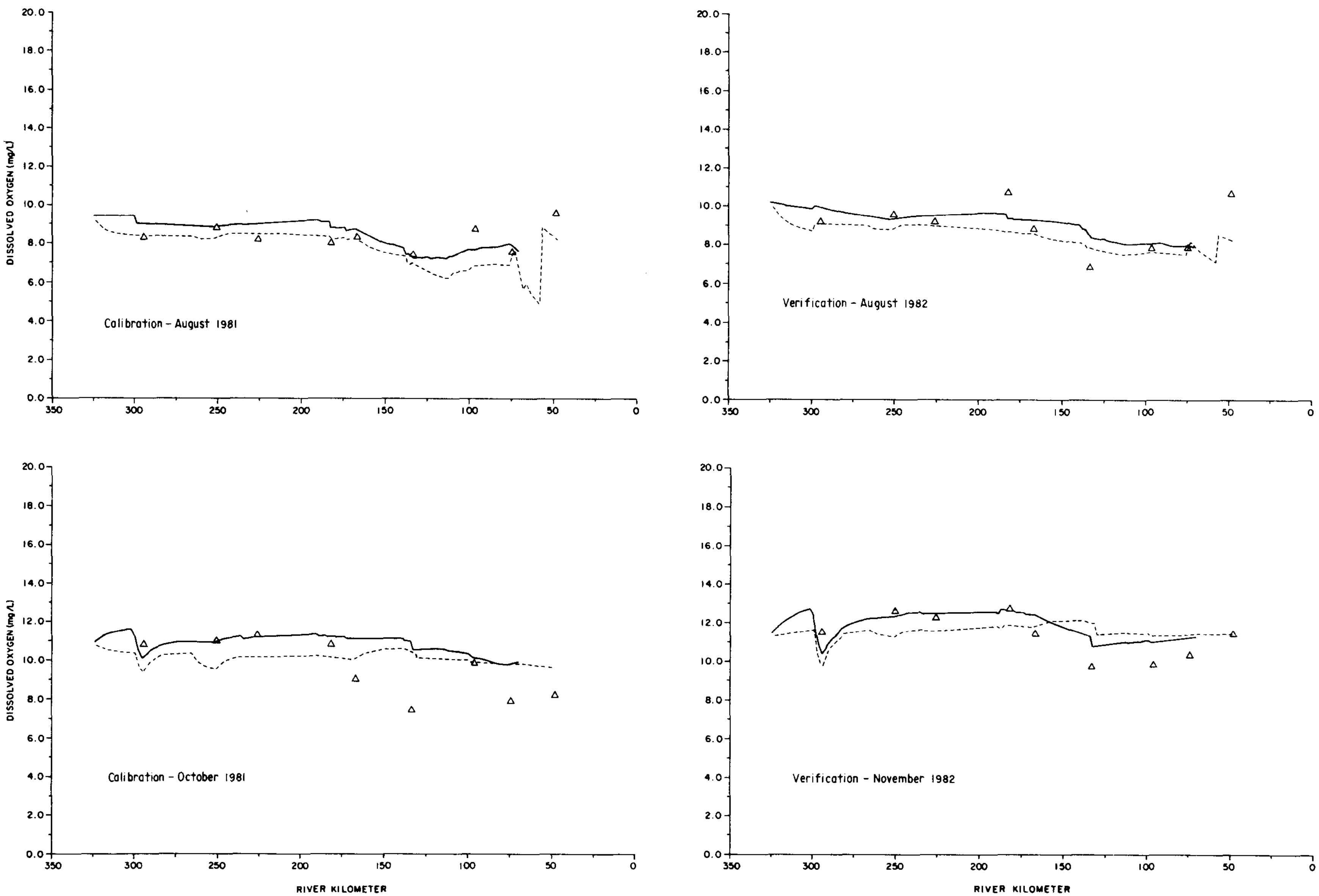

Figure 16. — Predicted vs. observed dissolved oxygen for the main stem Yakima River. (Δ= observed values, ———— = WQRRS prediction, ············ = QUAL-II prediction). Data collection locations, Δ, are, left to right: Cle Elum, Ellensburg, Untanum, Terrace Heights, Parker, Granger, Mabton, Prosser, and Kiona.

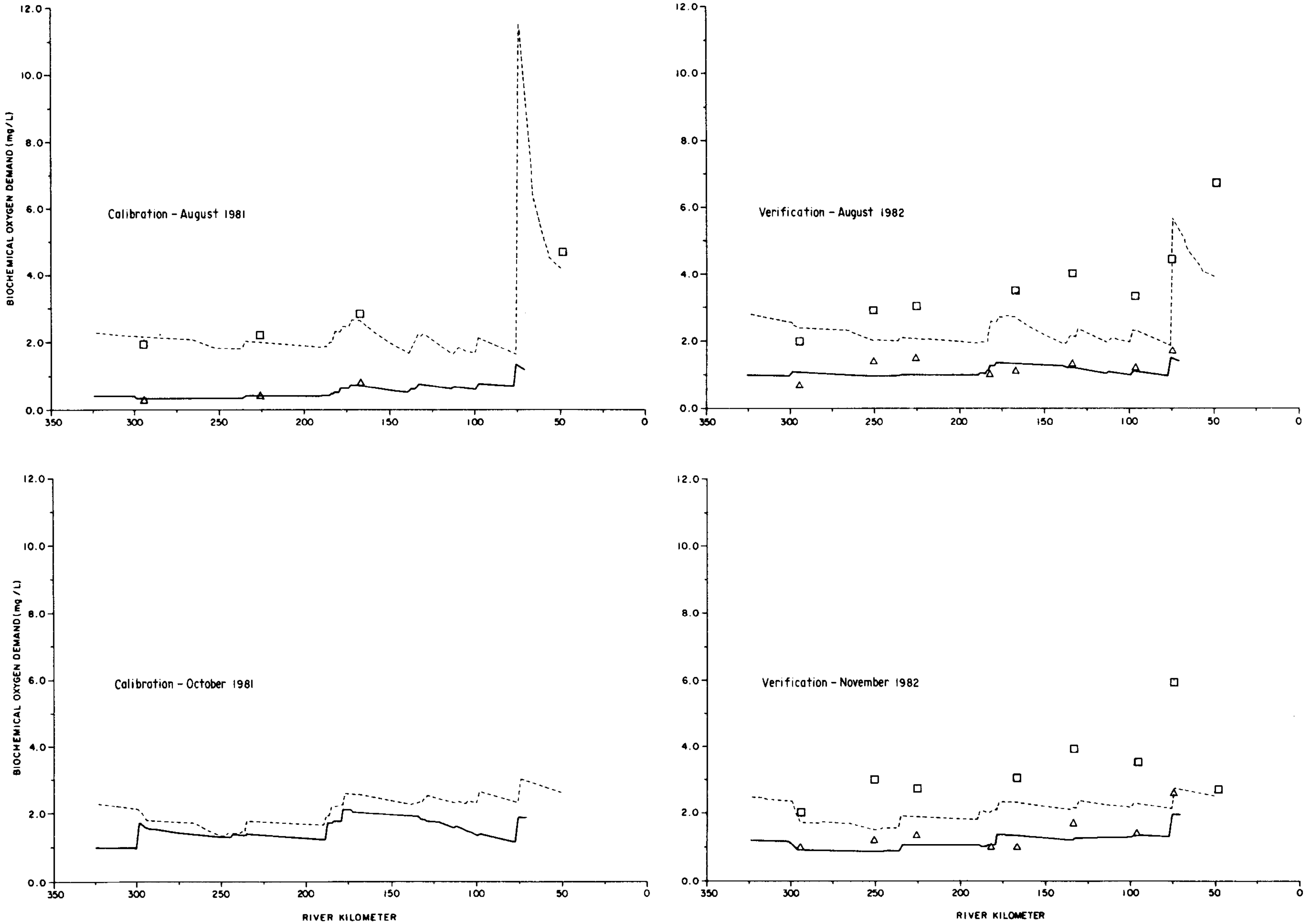

Figure 17. — Predicted vs. observed biochemical oxygen demand for the main stem Yakima River. (Δ = observed 5-day BOD, □ = observed 60-day BOD, ——— = WQRRS 5-day BOD, ·········· = QUAL-II ultimate BOD). Data collection locations, Δ, are, left to right: Cle Elum, Ellensburg, Untanum, Terrace Heights, Parker, Granger, Mabton, Prosser, and Kiona.

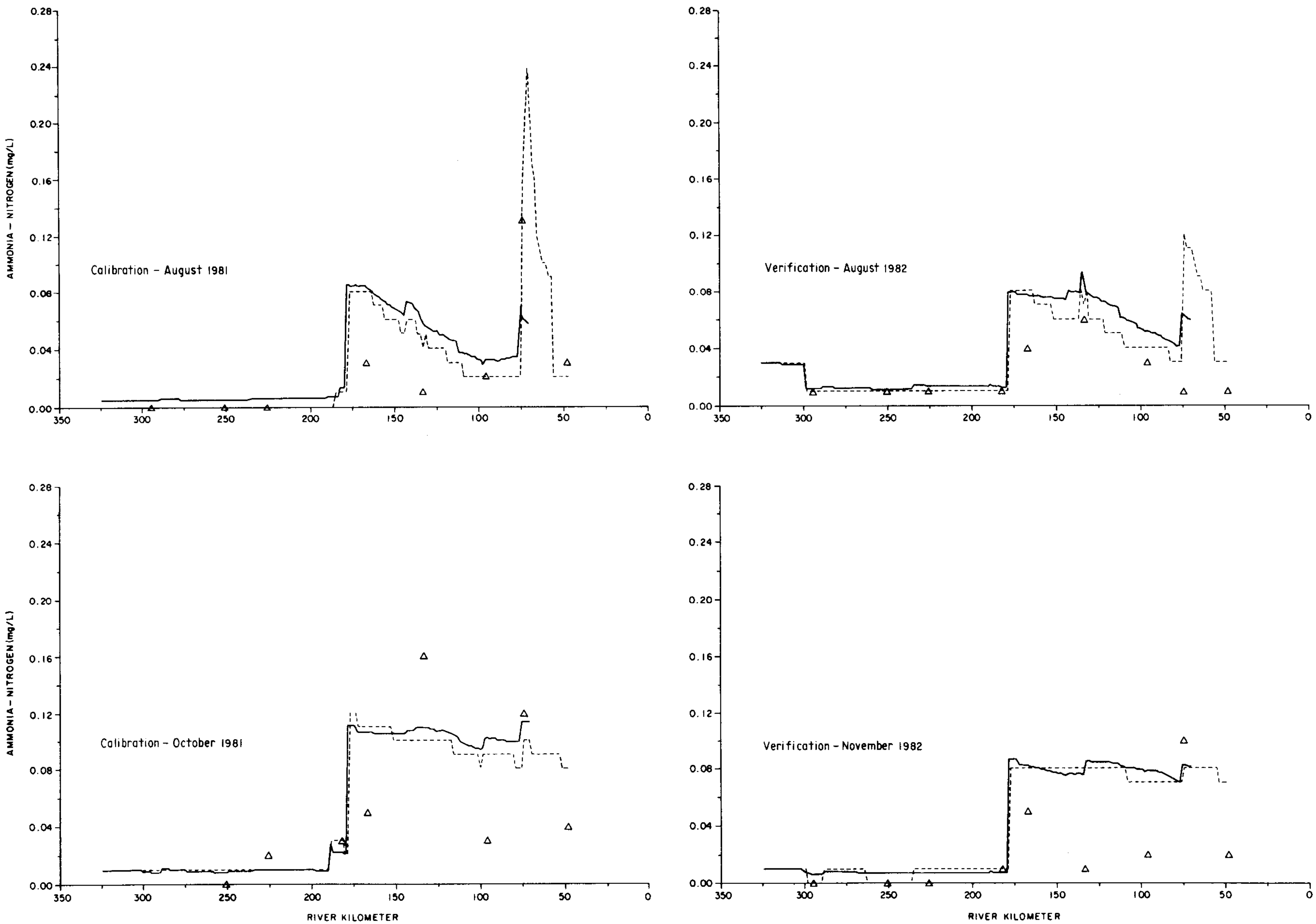

Figure 18. — Predicted vs. observed ammonia for the main stem Yakima River. (Δ = observed values, ———— = WQRRS prediction, ·············· = QUAL-II prediction). Data collection locations, Δ, are, left to right: Cle Elum, Ellensburg, Untanum, Terrace Heights, Parker, Granger, Mabton, Prosser, and Kiona.

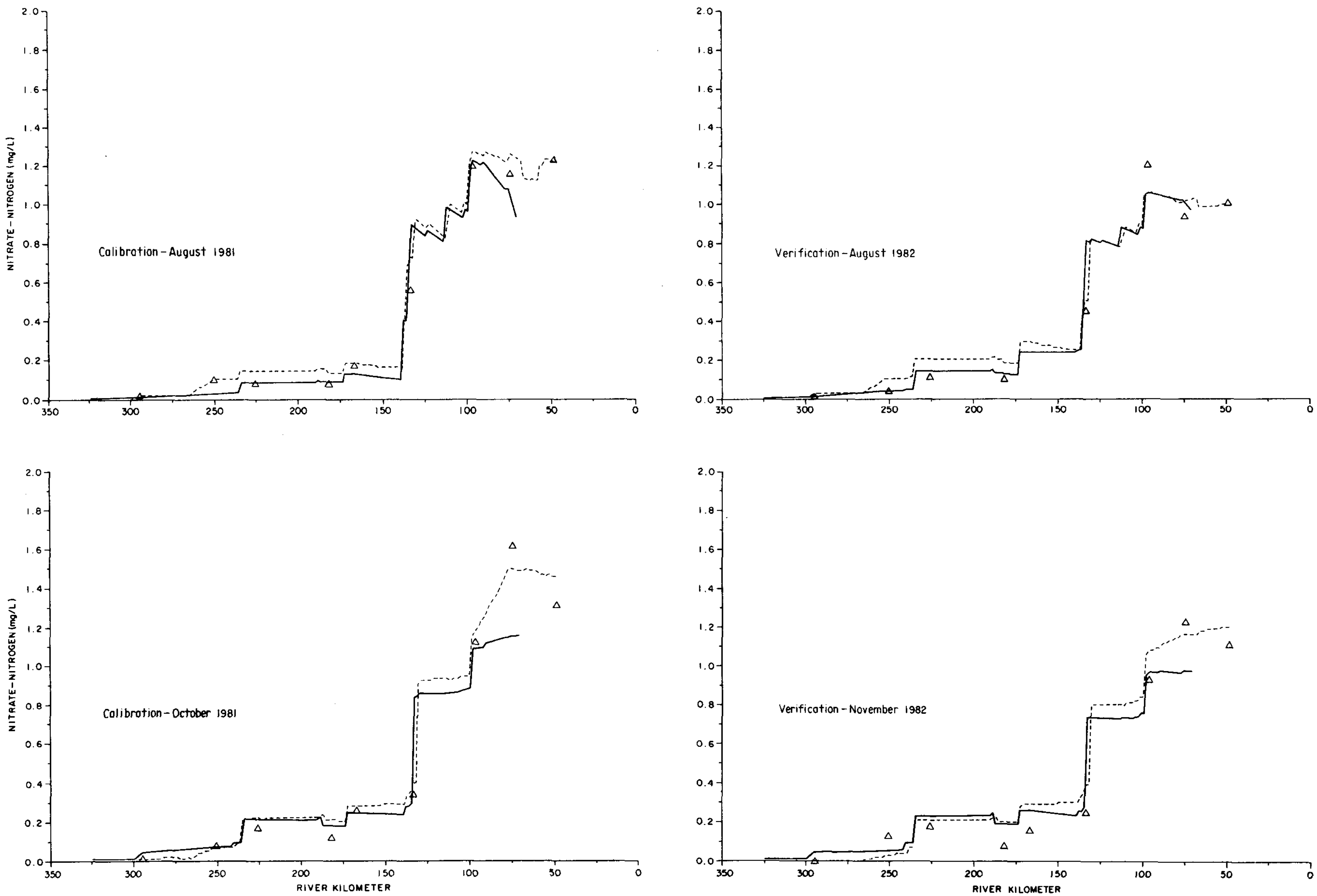

Figure 19. — Predicted vs. observed nitrate for the main stem Yakima River. (Δ = observed values, ———— = WQRRS prediction, ·········· = QUAL-II prediction). Data collection locations, Δ, are, left to right: Cle Elum, Ellensburg, Untanum, Terrace Heights, Parker, Granger, Mabton, Prosser, and Kiona.

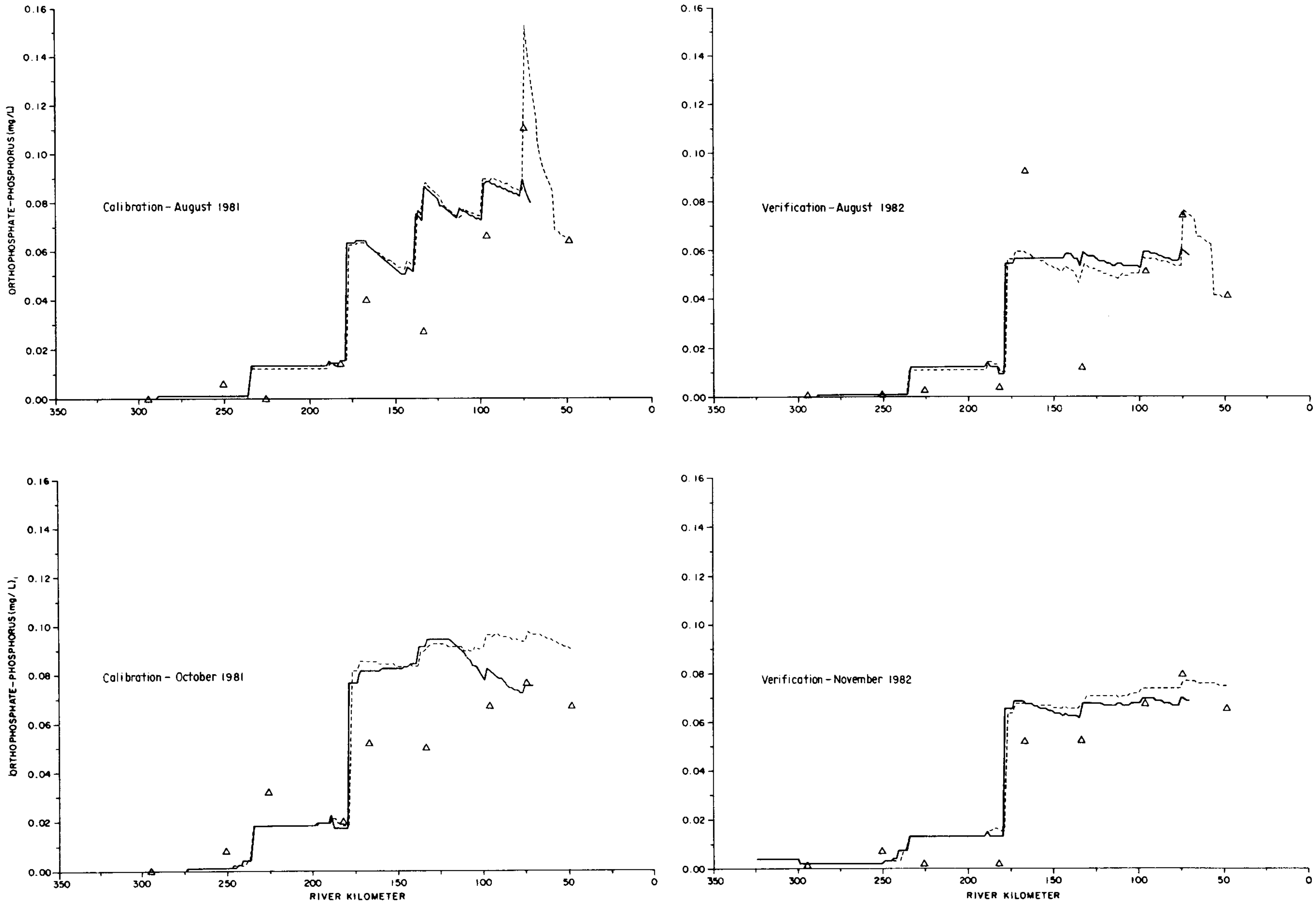

Figure 20. — Predicted vs. observed phosphate for the main stem Yakima River. (Δ = observed values, ———— = WQRRS prediction, ········ = QUAL-II prediction). Data collection locations, Δ, are, left to right: Cle Elum, Ellensburg, Untanum, Terrace Heights, Parker, Granger, Mabton, Prosser, and Kiona.

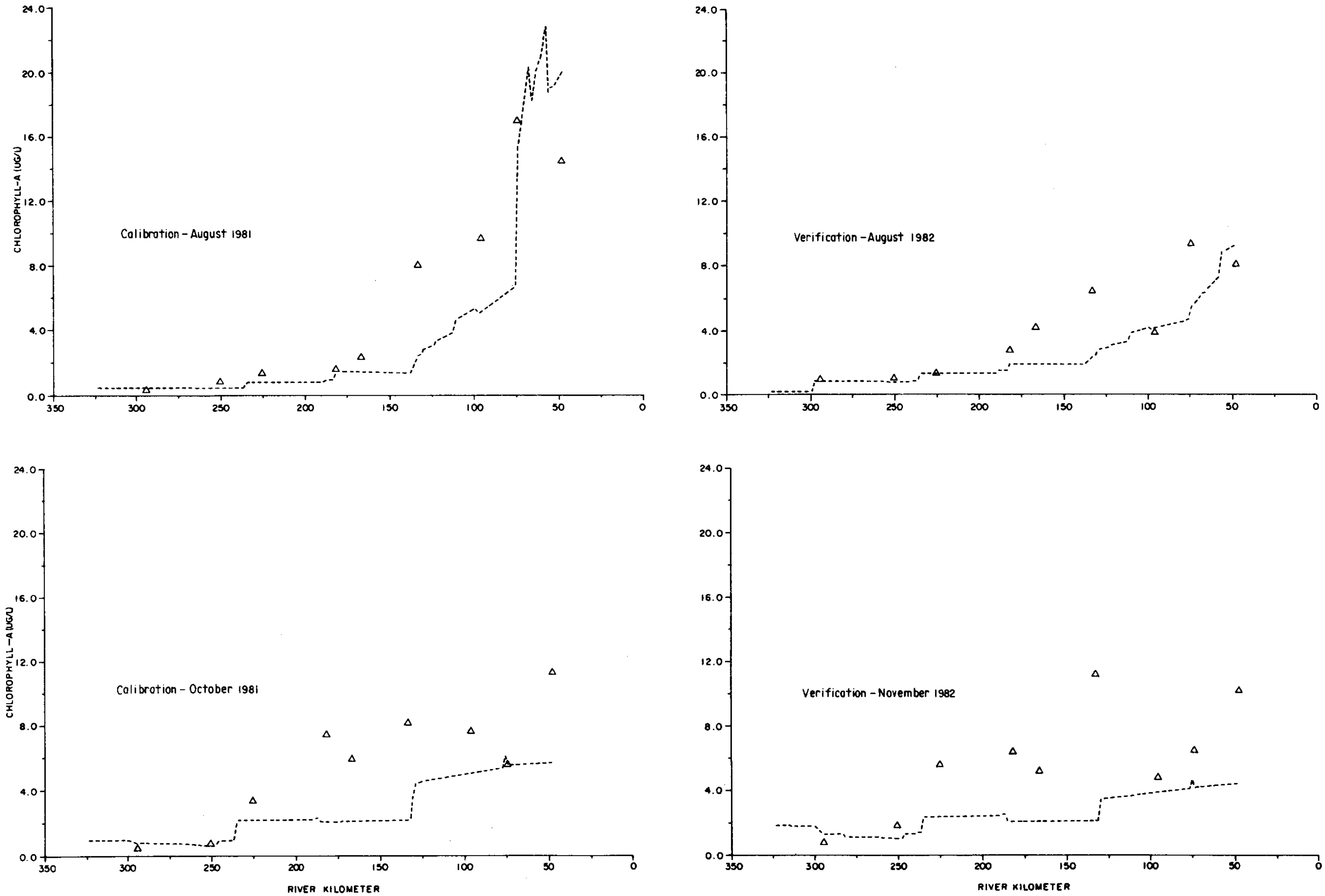

Figure 21. — Predicted vs. observed chlorophyll *a* for the main stem Yakima River. (Δ = observed values, ... = QUAL-II prediction). Data collection locations, Δ, are, left to right: Cle Elum, Ellensburg, Untanum, Terrace Heights, Parker, Granger, Mabton, Prosser, and Kiona.

adversely affected goodness-of-fit for several water quality parameters. Expected values of plant effluent volume and quality for the simulation time period could be determined and substituted into the data sets.

Results of simulation of project alternatives must be evaluated in light of any assumptions made concerning potential changes in withdrawals or inflows. The prediction accuracy of each parameter, as discussed above, must also be considered. The quantity which should be evaluated for each parameter is the relative change from present conditions. For QUAL-II simulations, the significance of such changes can be determined using the root-mean-square error values given in tables 8 through 13.

Because QUAL-II and WQRRS give similar results, either would be adequate for studying project alternatives. However, QUAL-II is recommended for ease of application.

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