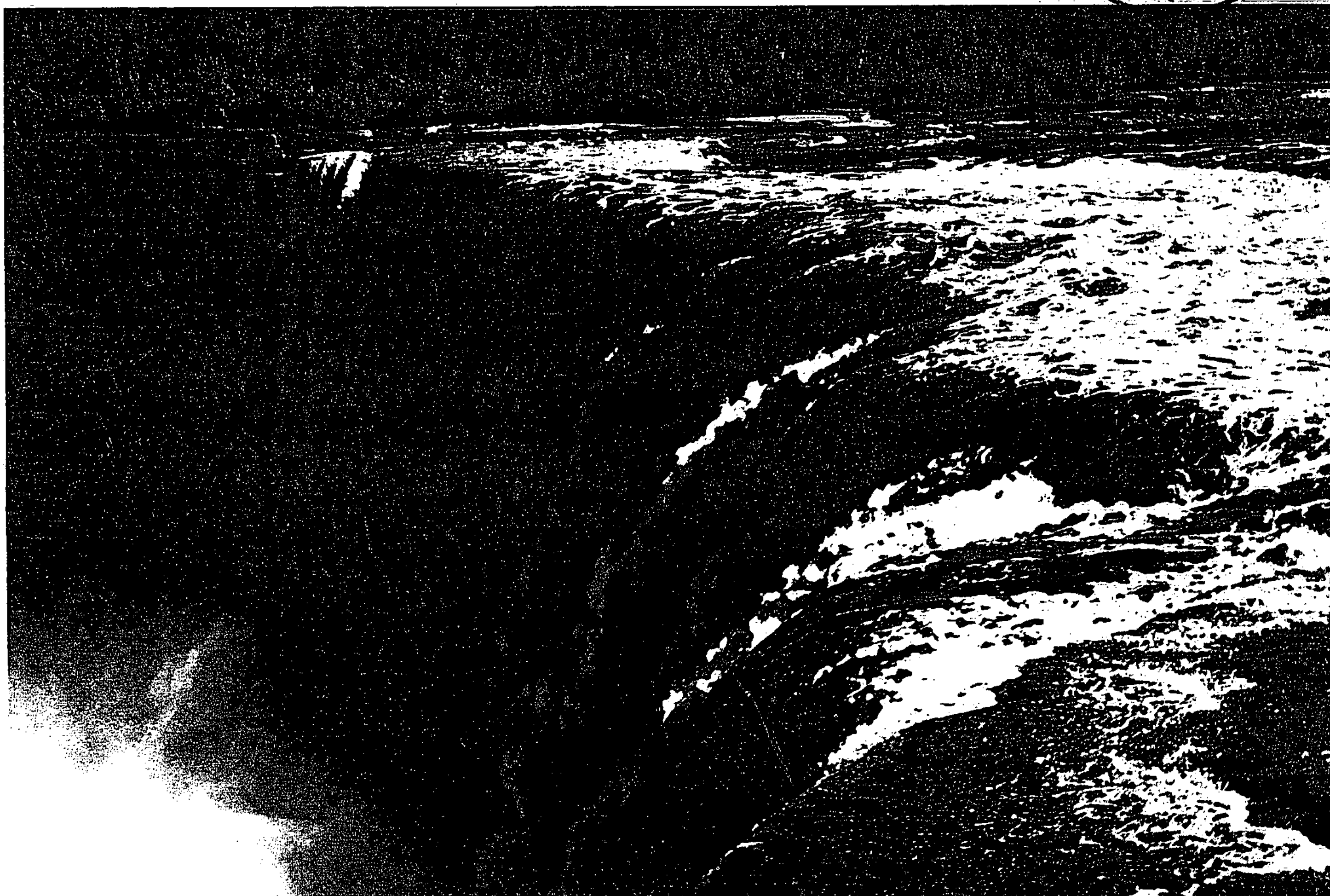
Dissolved Oxygen Modelling of the St. Croix River, Maine—New Brunswick

Millard [illegible] and Thomas A. [illegible]



TECHNICAL BULLETIN NO. 121

INLAND WATERS DIRECTORATE,
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ATLANTIC REGION,
WATER QUALITY BRANCH,
MONCTON, NEW BRUNSWICK, [illegible]

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MONCTON, NEW BRUNSWICK, 1981

Canada

Cat. No. En 36-503/121E

ISBN 0-662-11936-3

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Abstract

Mathematical modelling techniques have been applied to study the dissolved oxygen concentration in the lower reach of the St. Croix River. A hydraulic routing model, HEC-2, was used to describe the flow regime, and the WATQUAL model was used to simulate dissolved oxygen levels under different conditions of temperature, flow and biological oxygen demand. The results indicate that waste loading to the river should be restricted during periods of high temperature and minimum river discharge in order to permit fish migration.

Résumé

Des techniques de modélisation mathématique ont été appliquées à l'étude de la teneur en oxygène dissous du cours inférieur de la rivière Ste-Croix. Un modèle d'écoulement hydraulique, le HEC-2, a servi à décrire le régime d'écoulement de la rivière tandis que le modèle WATQUAL a permis de simuler la teneur en oxygène dissous pour diverses conditions de température, de débit et de demande biologique d'oxygène. Les résultats de l'étude indiquent qu'il faudrait réduire la charge des eaux usées versées dans la rivière lorsqu'il fait très chaud et lorsque le débit est minimal, afin de permettre la migration du poisson.

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1. INTRODUCTION

The St. Croix River for the last few decades has been receiving a pollutant load composed of organic fibres and dissolved organic compounds from the Georgia-Pacific paper mill in Woodland, Maine. This pollutant input, together with the building of dams and other control structures, has had an adverse impact on fish migration. In the last few years, however, secondary effluent treatment at the paper mill has improved the water quality of the river, and the building and reparation of fishways have reopened access so that it may now be feasible to reintroduce sea-run salmon. The purpose of this study is to determine whether the dissolved oxygen (DO) concentration in the river below the paper mill will be sufficiently high to sustain salmon migration.

Too high a biological oxygen demand (BOD) load or too low a river discharge would cause DO levels to become unsuitable for fish passage. Unfortunately, determination of safe loads cannot be measured experimentally in the river owing to the strains that would be placed on the ecosystem. An alternate approach, described here, is to mathematically model the factors which affect DO levels in the St. Croix River, especially variations in effluent discharge and river level. For this study a mathematical model describing the DO profile in the river was developed by the Systems Division of the Water Planning and Management Branch (Ottawa), using Water Quality Branch (Atlantic Region) data.

The use of mathematical models to simulate ambient conditions represents an important step in understanding and appreciating the factors governing impact assessment. More importantly, however, a model may be an expedient way to test the viability of a theory or to establish a responsible operating schedule for pollutant discharge. The aim of this study was to use mathematical modelling techniques to determine the BOD loads which could be discharged into the St. Croix River under various conditions while still providing a safe environment for fish passage. This paper discusses the use of the water quality model WATQUAL and how its results can be applied to managing the water quality of the St. Croix River.

2. STUDY AREA

The St. Croix River forms the international boundary between Canada and the United States for approximately 113 kilometres. The river drains much of York and Charlotte counties in New Brunswick, and Washington county in Maine. In most of the watershed, and for the upper 100 km of the river, the water quality is pristine.

The Georgia-Pacific paper mill in Woodland, Me., at the point where it discharges effluent into the river, marks the upstream end of the reach causing concern in the river. The 14 km long section, between Woodland, Me., and Milltown, N.B., is sparsely inhabited, with settlements at Upper Mills, N.B. and Baring, Me., 9 km from the effluent discharge. The river banks throughout this stretch are generally heavily wooded, allowing limited access to the water. There are no major tributaries along the study reach, although three small streams - Strachan Brook, Mohannas Creek and Magurrewock River enter the river below Upper Mills-Baring (Figure 2.1).

Flows as high as 529 m^3/s (18 665 cfs) and as low as 17 m^3/s (610 cfs) have been recorded in the study reach. Since 1975, the annual mean discharge at Baring has been 76 m^3/s (2 680 cfs). Georgia-Pacific, which controls discharges in the study area, operates under a permit allowing a minimum discharge of 23 m^3/s (807 cfs). Under non-spring flow conditions, the river width in the study area varies between 30 and 90 m (100-300 ft) and reaches depths of up to 4 m (13 ft).

The river bottom is mainly gravel in the fast-flowing sections, with organic detritus accumulations in pools and protected areas. The major feature of the study area is a narrow, shallow channel beginning at Woodland and extending 5.5 km downstream. There are rapids (Bailey Rips) slightly more than halfway down this stretch. The river bends sharply after this channel and widens to include Haywood Island, where it becomes deeper and slower moving. The river narrows at Baring Rips for approximately 1.6 km, and drops 7 m in the area between Upper Mills and Baring. The river then widens into a slow-moving lake for approximately 3 km and finally narrows again until it reaches the downstream end of the study area at the Milltown International Bridge. Over the study reach, more than 30 islands divide the natural flow and form as many as three divided channels.

2.1 St. Croix Model System Configuration

The river system was divided into 30 reaches between 150 and 1200 metres long, based on work by the U.S. Corps of Engineers (2). Node points were assigned to surveyed cross sections at the limits of each reach. For example, Reach "1" lies between the cross section at chainage station 1000 and chainage station 2000. Reach 1 is also identified as the reach between Node 1 and Node 2 (Table 2-1). Figure 2-1 shows the St. Croix River divided into 30 reaches with 31 nodal points. Node 32 represents the river inflow, and Node 33 is the waste loading into the river system.

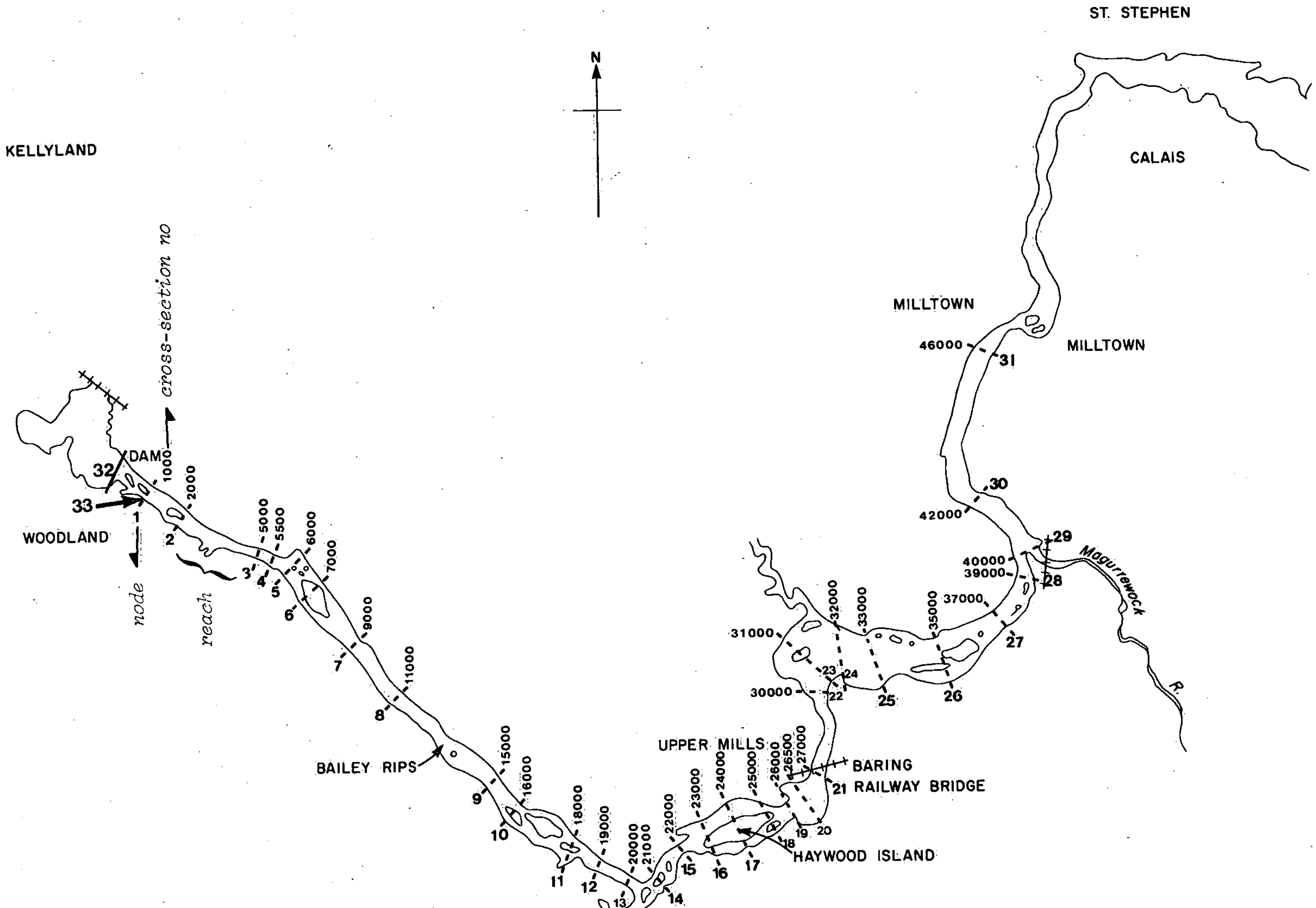

Figure 2-1. Map of study reach.

Table 2-1. Division of Study Reach

Reach	Node	Distance mi.	Distance km	Chainage stations
1	1 - 2	.189	.30	1000 - 2000
2	2 - 3	.568	.91	2000 - 5000
3	3 - 4	.095	.15	5000 - 5500
4	4 - 5	.095	.15	5500 - 6000
5	5 - 6	.189	.30	6000 - 7000
6	6 - 7	.379	.61	7000 - 9000
7	7 - 8	.379	.61	9000 - 11000
8	8 - 9	.758	1.21	11000 - 15000
9	9 - 10	.189	.30	15000 - 16000
10	10 - 11	.379	.61	16000 - 18000
11	11 - 12	.189	.30	18000 - 19000
12	12 - 13	.189	.30	19000 - 20000
13	13 - 14	.189	.30	20000 - 21000
14	14 - 15	.189	.30	21000 - 22000
15	15 - 16	.189	.30	22000 - 23000
16	16 - 17	.189	.30	23000 - 24000
17	17 - 18	.189	.30	24000 - 25000
18	18 - 19	.189	.30	25000 - 26000
19	19 - 20	.095	.15	26000 - 26500
20	20 - 21	.095	.15	26500 - 27000
21	21 - 22	.568	.91	27000 - 30000
22	22 - 23	.189	.30	30000 - 31000
23	23 - 24	.189	.30	31000 - 32000
24	24 - 25	.189	.30	32000 - 33000
25	25 - 26	.379	.61	33000 - 35000
26	26 - 27	.379	.61	35000 - 37000
27	27 - 28	.379	.61	37000 - 39000
28	28 - 29	.189	.30	39000 - 40000
29	29 - 30	.379	.61	40000 - 42000
30	30 - 31	.756	1.21	42000 - 46000
31	31 - 0	.0	.00	46000 (or end)
32	32 - 1	.0	.00	inflow
33	33 - 1	.0	.00	waste loading

3. METHODOLOGY

In order to simulate DO levels along the study reach, two models were used. The first was a hydraulic routing model which used river discharge values and channel geometry to simulate flow. The second was a DO-BOD model which used the hydraulic model results, cross-sectional flow areas, and surface width as inputs, together with BOD loadings, water temperature, benthic oxygen uptake values and organic matter decay rates, to predict DO levels.

3.1 Hydraulic Model

The hydraulic model used was the Hydrologic Engineering Center Model 2 (HEC-2) (1) developed by the U.S. Army Corps of Engineers. Input data for the model included the 31 cross sections surveyed in the Woodland to Milltown reach (2) in 1967. During this survey, soundings were made with a metal probe along the line of each cross section to establish the location and depth of the unconsolidated bottom deposits, and then the bottom topography was recorded.

Initial river discharges for the model calibration were obtained from Georgia-Pacific. A reaeration coefficient was calculated for the water quality model from the cross-sectional area, surface width, mean velocity and average depth of flow.

3.2 Water Quality Model

The water quality model chosen was WATQUAL (3,4). With this model DO profiles in the river channel were computed using HEC-2 results, effluent loadings, water temperatures and initial DO profiles. The basis of the model is a pollutant routing algorithm that uses the Streeter-Phelps formulation for the relationship between instream DO and BOD. Other factors included in the model are the rate of photosynthesis, sediment oxygen demand and various organic matter decay rates (Appendix A available from the authors). The other variables used were chosen from actual field measurements listed in Table 3-1.

Table 3-1. Water Surface Elevations at Cross-Sectional Transects

Cross Section	Surveyed date	Water surface elevations (ft above sea level, USGS datum)
1000	August 11, 1967	95.8
2000	August 08, 1967	92.5
5000	August 08, 1967	88.6
5500	August 08, 1967	88.4
6000	August 08, 1967	88.3
7000	August 04, 1967	85.8
9000	August 04, 1967	85.5
11000	August 04, 1967	85.3
15000	July 31, 1967	81.1
16000	July 31, 1967	80.85
18000	July 31, 1967	79.55
19000	July 31, 1967	79.3
20000	July 31, 1967	79.2
21000	August 02, 1967	78.4
22000	August 02, 1967	77.6
23000	August 02, 1967	77.25
24000	August 02, 1967	76.8
25000	August 03, 1967	76.65
26000	August 03, 1967	75.3
26500	August 09, 1967	74.6
27000	August 09, 1967	74.3
30000	July 26, 1967	65.6
31000	July 27, 1967	65.9
32000	July 28, 1967	65.6
33000	July 25, 1967	65.6
35000	July 24, 1967	65.5
37000	July 17, 1967	65.4
39000	July 17, 1967	65.4
40000	July 17, 1967	65.5
42000	July 18, 1967	65.3
46000	July 18, 1967	65.2

4. MODEL CALIBRATION

4.1 Hydraulic Model - HEC-2

4.1.1 Program Description

The purpose of using this model was to provide input data for the water quality model by calculating the cross-sectional areas and surface widths of each reach, which are needed to define river flows. The initial version of HEC-2 was modified to allow the use of additional options, to provide for future expansion and to simplify input preparation. Other changes were also made to increase the program's flexibility to handle a variety of water surface profile problems.

A computer package, Program XSECT (5), was programmed to generate HEC-2 control parameters. It used the surveyed cross sections (1) to calculate the number of profile points, and the distance between cross sections to generate these values in a format compatible with HEC-2. Plots of these cross sections can also be obtained from the Calcomp Plotter with this program.

A set of appendices, which provide (A) details of the WATQUAL program and its application to the Woodland-Milltown reach of the St. Croix River, (B) cross-sectional areas at St. Croix River nodes, and (C) HEC-2 model results, is available from the authors.

4.1.2 Calibration

The cross sections of the study reach were surveyed between July 17 and August 11, 1967, when water surface elevations were also recorded. The mean river discharge for that period was 51 m^3/s (1818 cfs) with a standard deviation of 7 m^3/s (250 cfs). This mean value was used to calibrate the HEC-2 model, with a known starting water level of 65.2 ft above sea level (USGS datum) at chainage station 46000 in Milltown. A tentative value for Manning's roughness coefficient of 0.035 was initially selected for the section of the St. Croix River under study. Figure 4-1 demonstrates the initial calibration showing the difference between the measured water surface profile and the HEC-2 calculated profile. Additional runs were made varying the Manning's "N" coefficient for every reach between Milltown and

Table 4-1. Refined Roughness Coefficients for Each Reach

Reach between cross section	Distance (ft)	Manning's N values
46000 - 40000	6000	.035
40000 - 39000	1000	.045
39000 - 31000	8000	.035
31000 - 30000	1000	.042
30000 - 27000	3000	.040
27000 - 26500	500	.025
26500 - *26400	100	.075
*26400 - 25000	1400	.070
25000 - 24000	1000	.090
24000 - 23000	1000	.040
23000 - 22000	1000	.083
22000 - 19000	3000	.063
19000 - 18000	1000	.040
18000 - 16000	2000	.050
16000 - 15000	1000	.080
15000 - *14000	1000	.045
*14000 - 9000	5000	.070
9000 - 6500	2500	.020
6500 - 5500	1000	.080
5500 - 5000	500	.025
5000 - 2000	3000	.044
2000 - 1000	1000	.060

* interpolated cross section

Woodland. Since the river bed became steeper and the water velocity increased rapidly between chainage stations 30000 and 27000 and between 26000 and 26500, additional cross sections were constructed by interpolation between known sections. The number of additional cross sections varied with the length of the reach and the steepness of the river bed. Table 4-2 lists the roughness coefficients obtained for each reach after calibration, and Figure 4-2 is a graphical representation of the final calibrated model showing the measured and calculated water surface profiles. The actual HEC-2 runs used in the WATQUAL model calibration are shown in Figure 4-3.

4.1.3 Validation

Figure 4-2 compares the measured surface water profile with the profile calculated by means of the HEC-2 model. The results demonstrate a good calibration in that the differences in magnitude between measured and calculated water elevation do not exceed 0.10 ft. This calibration is representative of actual field conditions when river discharge is approximately 51 m^3/s (1818 cfs).

An approximate starting elevation was used at station 46000 in order to carry out the HEC-2 runs. This assumption affects only the computed elevation between stations 46000 and 30000. Upstream from chainage station 27000 there is no hydraulic effect transferred because this was designated the control point in the river channel.

4.2 Water Quality Model - WATQUAL

4.2.1 Program Description

Program WATQUAL is a one-dimensional water quality simulation model designed to compute DO profiles in a river channel when the river water has been loaded with waste material exerting a biochemical oxygen demand. The program is a restructured, simplified version of the routing segment of a more complex water quality model developed by Acres Consulting Services and described in their report (3) of August 1971. The original model was condensed to the present form to permit easier application to isolated systems with real data and to facilitate calibration. This model uses hydraulic parameters from HEC-2, such as cross-sectional area and surface width, generates atmospheric reaeration, and combines these with effluent levels and decay rates of organic matter to estimate DO levels.

4.2.2 Calibration

The WATQUAL model was calibrated using water quantity and quality data assembled by the Water Quality Branch (6), summarized in Table 4-3. On seven sampling runs DO was measured near the American and Canadian shores and in the middle of the river with the results then averaged at each of five transects. Kellyland, a site above the mill which was used as a control, was only sampled on the Canadian side.

The first WATQUAL model simulations were done using measured BOD levels and an estimated value for the organic matter decay rate. Additional runs were made to adjust decay rates until the model's results satisfactorily simulated the measured field values. Figure 4-4 compares simulated DO levels with measured field values. Decay rate values, (K_r), after calibration are shown in Table 4-4 and Figure 4-5.

An important factor added to the original WATQUAL model was the oxygen demand generated by decomposing river sediments. Benthic oxygen demand, caused by respiration of sediment bacteria, was linked to water temperature by a mathematical equation based on oxygen uptake values calculated for the St. Croix River by Nolan and Johnson (7) (See Fig. 4-6).

The laboratory measurements of sediment oxygen demand showed a high average demand of 3.6 g O_2/m^2/day upstream near the effluent discharge and a decrease to 1 - 2 g O_2/m^2/day further downstream.

4.2.3 Validation

Figure 4-4 compares measured values of DO with DO calculated using the WATQUAL model. The results demonstrate a good calibration, since the differences in magnitude between the measured and computed DO levels do not exceed 1.0 ppm.

This calibration is representative of the actual laboratory measurement of DO depletion curves. Figure 4-5 shows that a plot of decay rate (K_r) against river discharge (Q) has an asymptotic trend. The high values of calibrated decay rate (K_r) are due to deoxygenation from

Table 4-2. Water Quantity and Quality Values Used in Calibrating WATQUAL Model

Date	River discharge*	5-day BOD loading*	Station	Temperature °C	Mean sectional DO (ppm)
28/08/80	15.5 m^3/sec	5900 kg/day	Kellyland	22.5	8.6
			Woodland	22.5	-
			Bailey Rips	22.5	-
			Haywood Is.	22.5	-
			Baring	22.5	-
			Milltown	22.5	0.0
24/06/80	32.6 m^3/sec	2287 kg/day	Kellyland	22.5	8.7
			Woodland	-	-
			Bailey Rips	-	-
			Haywood Is.	-	-
			Baring	23.0	7.6
			Milltown	23.0	5.9
27/02/80	53.6 m^3/sec	1555 kg/day	Kellyland	0.5	13.0
			Woodland	-	-
			Bailey Rips	-	-
			Haywood Is.	-	-
			Baring	-	12.9
			Milltown	-	12.8
02/10/79	36.6 m^3/sec	2486 kg/day	Kellyland	-	10.5
			Woodland	-	-
			Bailey Rips	-	-
			Haywood Is.	-	-
			Baring	8.6	8.8
			Milltown	8.2	8.4
21/08/79	80.0 m^3/sec	1552 kg/day	Kellyland	17.0	9.5
			Woodland	17.0	8.5
			Bailey Rips	17.0	8.5
			Haywood Is.	17.0	8.6
			Baring	17.0	8.0
			Milltown	17.5	7.7
12/07/79	68.9 m^3/sec	3081 kg/day	Kellyland	22.0	8.6
			Woodland	23.0	8.0
			Bailey Rips	24.0	7.2
			Haywood Is.	25.0	6.9
			Baring	23.0	6.4
			Milltown	21.5	6.8
05/06/79	338.2 m^3/sec	1980 kg/day	Kellyland	16.5	12.8
			Woodland	17.0	8.8
			Bailey Rips	-	-
			Haywood Is.	-	-
			Baring	15.1	9.2
			Milltown	15.1	9.2

* From measurements by Georgia-Pacific

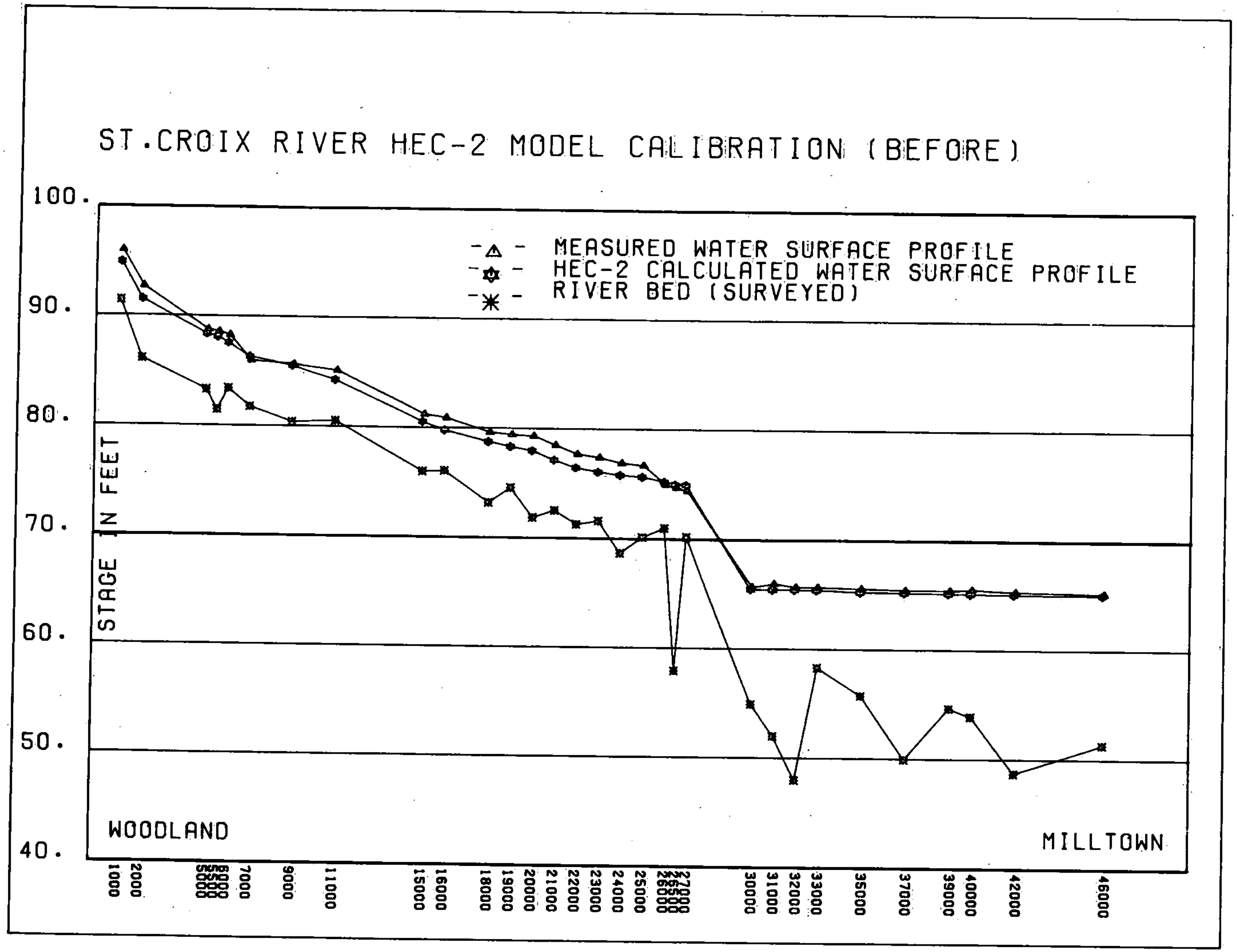

Figure 4-1. Initial HEC-2 model calibration. The numbers along the horizontal axis are chainage station numbers.

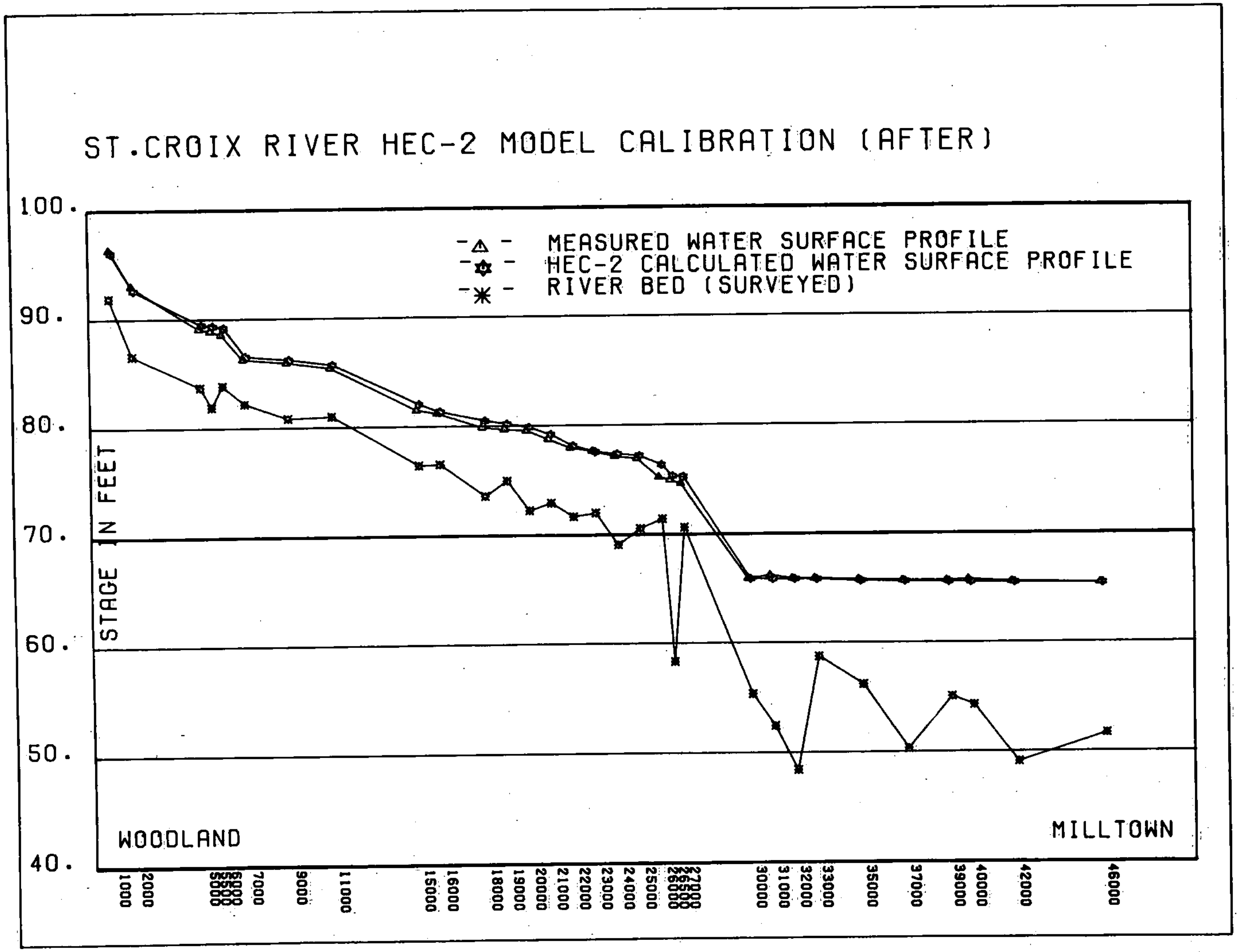

Figure 4-2. Final HEC-2 model calibration. The numbers along the horizontal axis are chainage station numbers.

St. Croix River, HEC-2 Model Run

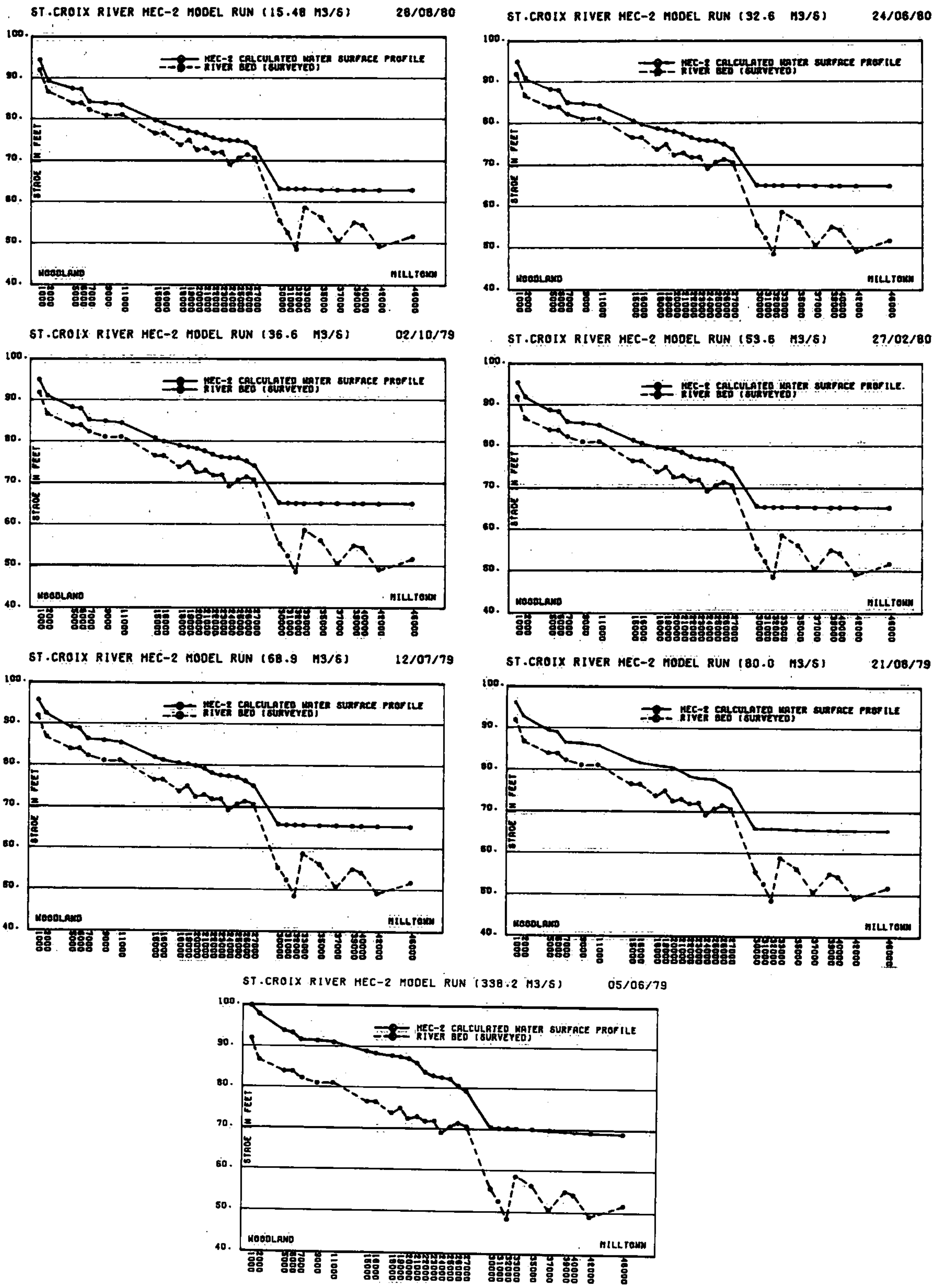

Figure 4-3. HEC-2 runs used to calibrate WATQUAL model.

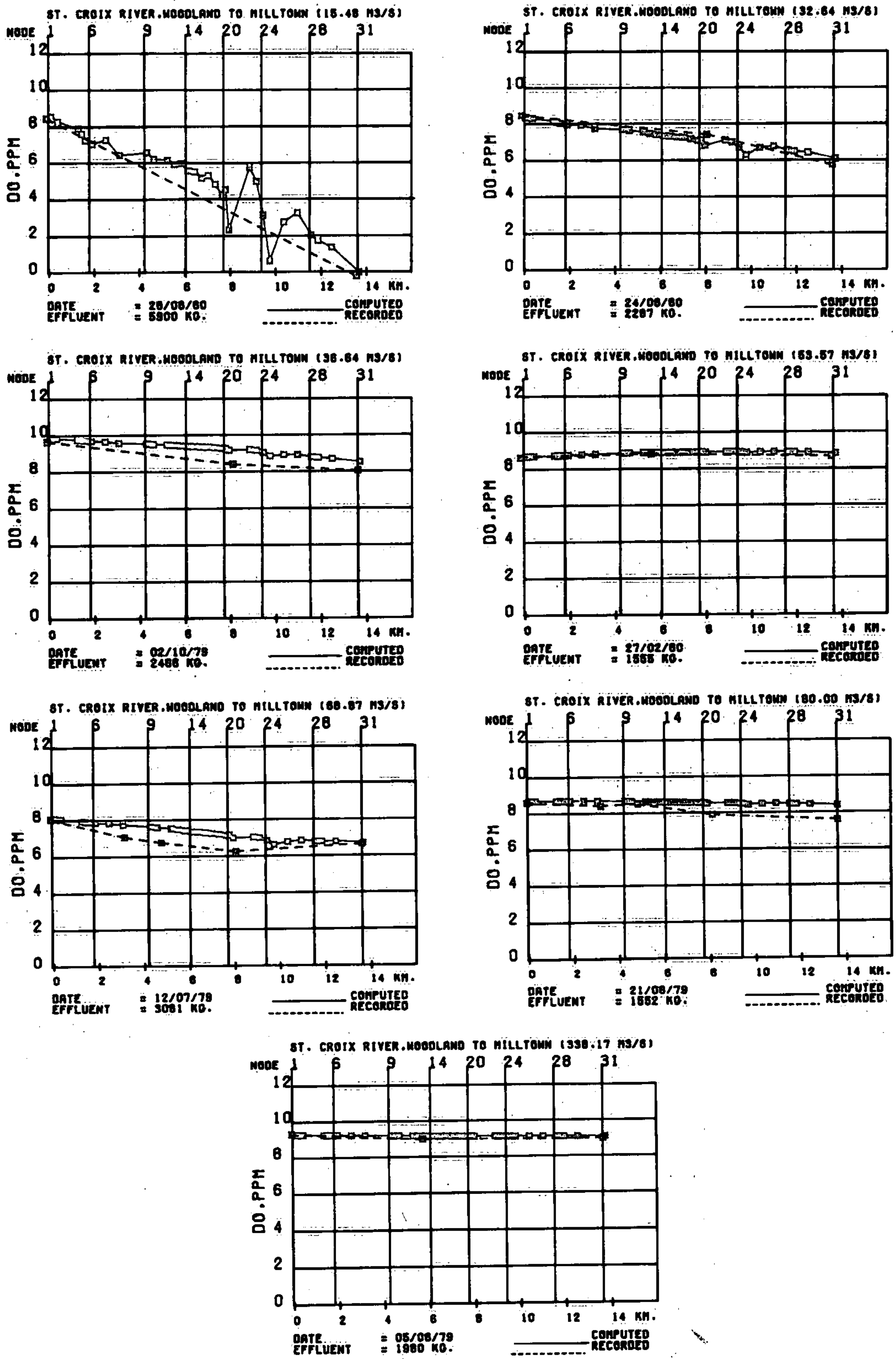

Figure 4-4. Comparison of computed dissolved oxygen levels with recorded field values.

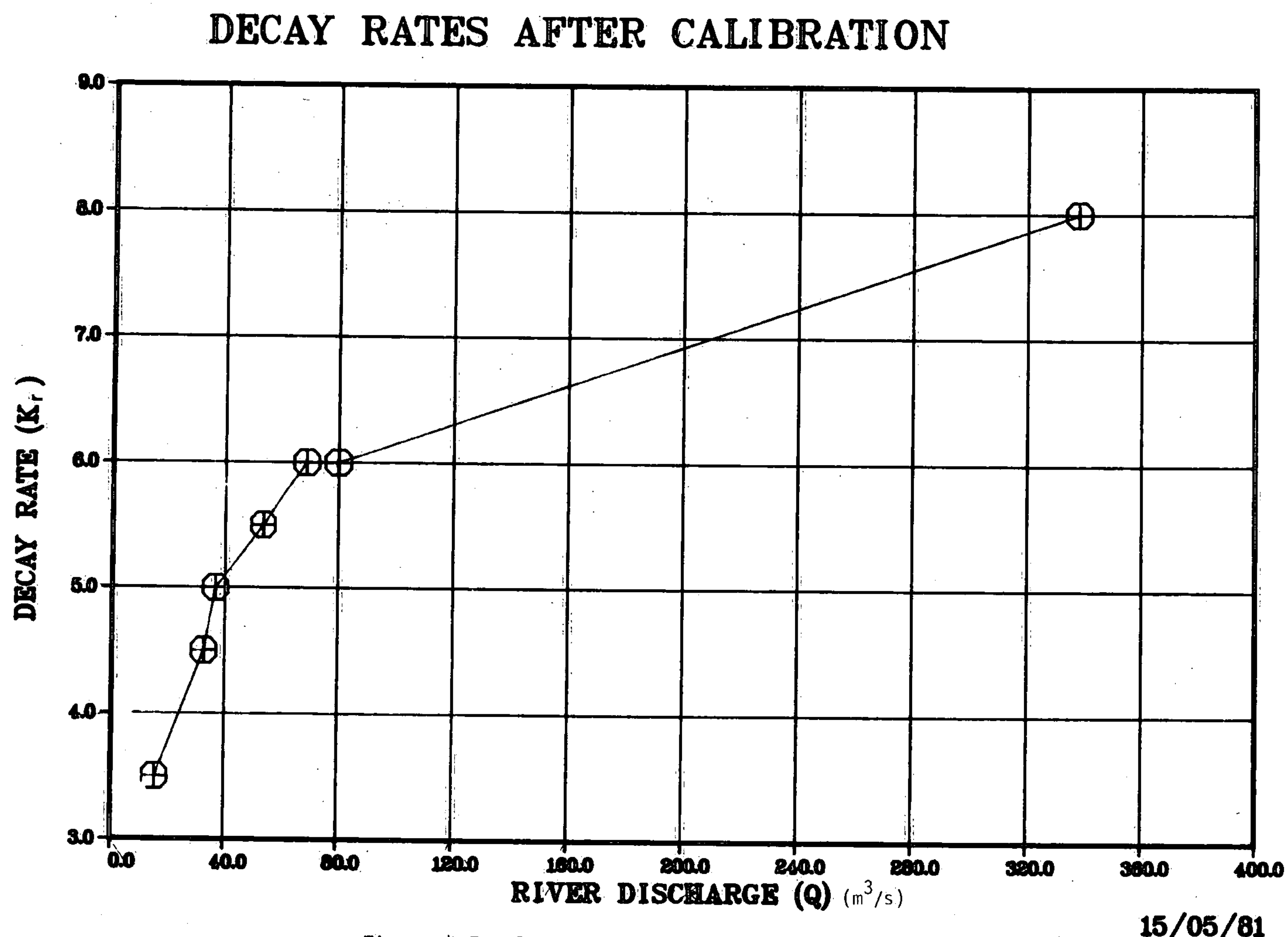

Figure 4-5. Decay rates after calibration.

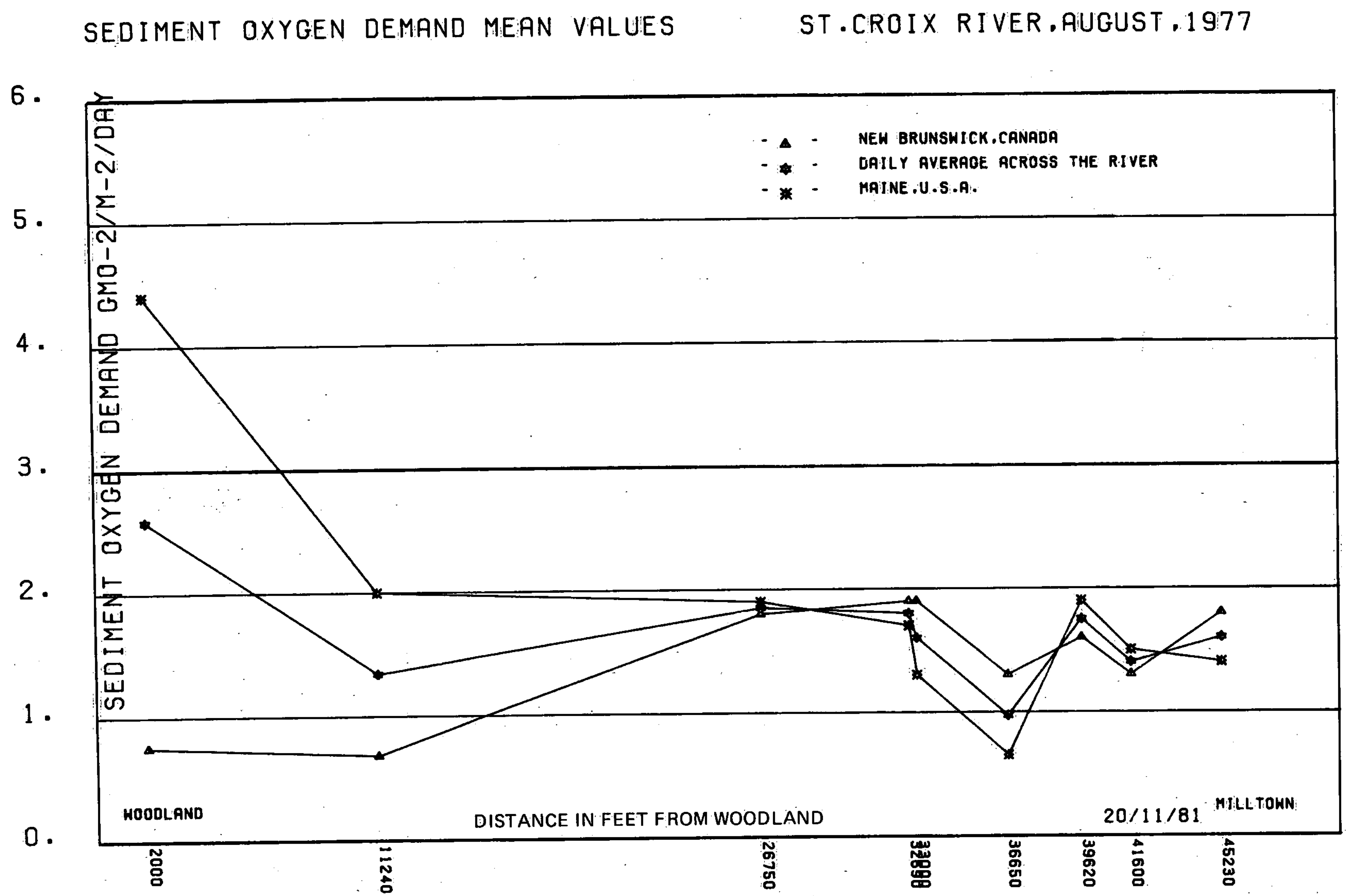

Figure 4-6. Sediment oxygen demand.

Table 4-3. Decay Rates of Organic Matter at Specific Effluent and River Discharges

Date	River discharge (m^3/sec)	Effluent discharge (kg)	Value of K_r
28/08/80	15.48	5900	3.5
24/06/80	32.64	2287	4.5
27/02/80	53.57	1555	5.5
02/10/79	36.64	2486	5.0
21/08/79	80.00	1552	6.0
12/07/79	68.87	3081	6.0
05/06/79	338.17	1980	8.0

the effluent discharge. Deoxygenation, which describes changes in oxygen demand, is affected by such things as sedimentation, turbulence, biological growth on the river bed, nutrient deficiency and unacclimatized bacteria.

5. RESULTS AND DISCUSSION

Once both models had been calibrated and validated, a series of runs were made to simulate a range of temperature, loading and flow conditions. Table 5-1 shows the input conditions for the simulations which were performed.

One should note that the data used to calibrate the WATQUAL model were collected during different years. The water quality and quantity data provided by Water Quality Branch of Moncton span 1979 and 1980, while the sediment oxygen demand data from the U.S. Environmental Protection Agency were collected in 1977. The cross sections surveyed by the U.S. Corps of Engineers were made in 1967.

Table 5-1. Parameters Modelled in the WATQUAL Simulations

Water Temperature:	(°C)	0	10	18	25
	(°F)	32	50	64	77
Effluent Loadings:					
kg BOD_5/day		455	2272	4545	6818
lbs BOD_5/day		1000	5000	10000	15000
River Discharge:					
(m^3/s)		21	71	142	
(cfs)		750	2500	5000	

5.1 HEC-2

The St. Croix River varies in shape along the 14-km study reach, which causes a wide range of velocities. At Woodland, the river is narrow and shallow with a mean velocity of 1.0 m/s at a discharge rate of 21 m^3/s and 1.65 m/s at a flow of 142 m^3/s. Above and below Upper Mills-Baring, however, the river forms deep lakes with velocities as low as 0.036 m/s at 21 m^3/s discharge and 0.12 m/s at 142 m^3/s. Downstream, towards Milltown, the river narrows again with increasing water velocity.

5.2 WATQUAL

Simulation results of the WATQUAL modelling are shown in Figures 5-1 to 5-3 and Tables 5-2 to 5-4. The figures and tables indicate the predicted mean dissolved oxygen value at any point in the study reach for the indicated temperature, loading and discharge values. The results predict little change in DO levels from Woodland to Milltown when the temperature is at 0°C, even at various river levels and effluent discharges, since minimal decomposition is occurring. With higher temperatures, however, increased effluent loads coupled with low river discharges indicate a decrease in oxygen levels. If a level of 6.0 ppm DO is used as an acceptable objective for fish passage, under minimum discharge conditions of 21 m^3/s effluent discharges greater than 4545kg BOD/day should not be permitted when the water temperature is greater than 18°C. When the river discharge is between 71 m^3/s and 142 m^3/s, DO levels approach unacceptable limits only when temperature rises to 25°C and the effluent inputs are greater than 4545 kg/day. The model indicates that river discharge is probably the most important variable in the control of DO in the St. Croix River, with DO becoming critical under extremely low flow conditions.

It should be emphasized that the values predicted at each node are mean cross-sectional values. As the effluent plume is known to keep to the U.S. side of the river until Upper Mills-Baring and only becomes well mixed below this point, model simulation above this area does not provide a realistic description of water quality. The model is not applicable to the upper 9 km of the river, where fish can be assumed to swim on the Canadian side where the dissolved oxygen is usually near the saturation level. Below Upper Mills-Baring, however, the effluent is mixed across the river and the mean DO levels do depict actual conditions. Simulated DO levels are consequently most accurate between stations (nodes) 21 and 31, with values from stations 1 to 20 setting up results for the following sites. This limitation of a one-dimensional modelling approach is unavoidable, since information was not available for a more complete two-dimensional study.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Modelling

Based on the operation of the HEC-2 and WATQUAL models, a number of improvements in basic data should be made:

a) measured cross sections should be closer together, especially where critical flow is reached in the Upper Mills-Baring area. The 1000-m reach between cross

Table 5-2. St. Croix River Discharges (21 m^3/s) with Simulated Dissolved Oxygen Concentrations

Station	Effluent Discharge 455 kg/day				Effluent Discharge 2272 kg/day				Effluent Discharge 4545 kg/day				Effluent Discharge 6818 kg/day			
	Calculated DO at Temp.				Calculated DO at Temp.				Calculated DO at Temp.				Calculated DO at Temp.			
	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C
1	14.20	10.90	9.20	8.10	14.20	10.90	9.20	8.10	14.20	10.90	9.20	8.10	14.20	10.90	9.20	8.10
2	.21	.91	.21	.08	.20	.90	.17	7.99	.19	.88	.12	7.88	.19	.88	.05	7.77
3	.23	.94	.22	.03	.22	.91	.12	.80	.20	.86	8.99	.50	.19	.81	8.87	.21
4	.23	.94	.21	.00	.22	.90	.08	.70	.20	.84	.92	.31	.19	.78	.76	6.93
5	.23	.94	.20	7.97	.21	.88	.04	.58	.19	.81	.84	.09	.18	.74	.64	.60
6	.24	.96	.21	.94	.22	.88	.00	.47	.19	.79	.75	6.89	.17	.69	.50	.30
7	.26	.99	.23	.96	.23	.90	.01	.51	.20	.79	.74	.95	.16	.68	.47	.39
8	.27	.99	.20	.85	.23	.86	8.88	.18	.19	.71	.49	.34	.17	.55	.09	5.50
9	.30	11.02	.21	.87	.25	.87	.86	.23	.19	.67	.43	.44	.14	.48	7.99	.65
10	.30	.02	.20	.82	.25	.85	.81	.10	.18	.63	.32	.20	.13	.41	.82	.30
11	.31	.03	.19	.80	.25	.83	.77	.06	.17	.59	.23	.13	.11	.34	.70	.20
12	.31	.03	.18	.75	.24	.81	.71	6.94	.16	.54	.12	5.92	.09	.26	.53	4.90
13	.32	.03	.17	.74	.24	.80	.68	.90	.15	.51	.07	.85	.07	.22	.45	.80
14	.32	.03	.15	.68	.24	.77	.61	.74	.14	.45	7.93	.58	.06	.14	.26	.41
15	.32	.03	.15	.67	.24	.77	.60	.74	.13	.44	.91	.57	.04	.11	.23	.40
16	.32	.03	.14	.63	.23	.75	.55	.63	.12	.40	.82	.38	.03	.05	.08	.13
17	.32	.03	.14	.64	.23	.74	.55	.68	.12	.38	.81	.48	.01	.02	.07	.28
18	.32	.02	.12	.58	.22	.71	.48	.54	.10	.32	.68	.23	.00	9.93	6.88	3.92
19	.32	.02	9.09	.50	.21	.67	.39	.34	.07	.24	.51	4.89	13.97	.80	.63	.44
20	.33	10.99	.10	.54	.22	.68	.41	.44	.08	.25	.56	5.08	.94	.82	.70	.71
21	.32	11.03	.01	.26	.18	.55	.13	5.77	.01	.01	.02	3.91	.83	.46	5.91	2.04
22	.34	.01	.10	.60	.20	.63	.42	.71	.03	.13	.56	5.58	.86	.64	6.71	4.46
23	.34	10.98	.06	.47	.19	.57	.29	.42	13.99	.02	.33	.10	.80	.46	.37	3.78
24	.33	.92	8.95	.13	.14	.42	7.98	.71	.90	9.72	6.75	3.94	.66	.01	5.53	2.17
25	.32	.94	.80	6.62	.07	.19	.55	.76	.75	.28	5.99	2.42	.44	8.37	4.43	0.09
26	.33	.94	.88	7.01	.07	.24	.82	5.70	.74	.36	6.50	4.06	.42	.48	5.18	2.41
27	.33	.94	.88	.02	.05	.21	.85	.83	.70	.30	.56	.33	.35	.39	.27	.84
28	.32	.90	.79	6.69	.00	.07	.64	.35	.60	.03	.20	3.67	.19	7.99	4.77	1.98
29	.32	.89	.75	.67	13.98	.02	.57	.20	.56	8.94	.09	.47	.13	.85	.62	.75
30	.31	.87	.71	.42	.94	9.94	.49	.05	.48	.79	5.98	.33	.02	.63	.46	.62
31	.29	.81	.55	5.81	.84	.72	.21	4.33	.28	.36	.53	2.48	12.73	.00	3.86	.64
Diff. of	+ 0.09	- 0.09	- .65	-2.29	-0.16	-1.18	-1.99	-3.77	-0.92	-2.54	-3.67	-5.62	-1.47	-3.90	-5.34	-7.46

Table 5-3. St. Croix River Discharges (71 m^3/s) with Simulated Dissolved Oxygen Concentrations

Station	Effluent Discharge 455 kg/day				Effluent Discharge 2272 kg/day				Effluent Discharge 4545 kg/day				Effluent Discharge 6818 kg/day			
	Calculated DO at Temp.				Calculated DO at Temp.				Calculated DO at Temp.				Calculated DO at Temp.			
	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C
1	14.16	10.92	9.18	8.17	14.16	10.92	9.18	8.16	14.16	10.92	9.17	8.14	14.16	10.92	9.16	8.13
2	.17	.93	.19	.16	.16	.92	.18	.13	.16	.92	.16	.10	.16	.91	.14	.06
3	.17	.94	.18	.10	.17	.92	.14	7.99	.16	.90	.08	7.85	.15	.88	.02	7.71
4	.17	.94	.18	.09	.17	.92	.13	.96	.16	.89	.06	.80	.15	.87	.00	.64
5	.17	.94	.18	.08	.17	.92	.12	.94	.16	.89	.05	.76	.15	.86	8.97	.58
6	.18	.94	.18	.05	.17	.91	.10	.86	.16	.88	.01	.63	.15	.84	.91	.40
7	.18	.95	.18	.02	.17	.90	.08	.80	.16	.87	8.97	.53	.15	.82	.85	.25
8	.18	.95	.17	7.96	.17	.90	.04	.68	.16	.84	.88	.32	.14	.78	.73	6.96
9	.20	.96	.17	.91	.18	.89	.00	.57	.16	.82	.80	.16	.13	.74	.60	.74
10	.20	.96	.16	.88	.18	.89	8.98	.52	.15	.80	.76	.07	.13	.71	.54	.62
11	.20	.96	.15	.84	.18	.88	.95	.44	.15	.78	.70	6.95	.12	.68	.45	.46
12	.20	.96	.14	.80	.17	.87	.92	.37	.14	.76	.65	.84	.11	.65	.37	.31
13	.20	.96	.13	.77	.17	.86	.90	.33	.14	.74	.61	.77	.11	.62	.31	.22
14	.20	.96	.13	.74	.17	.85	.88	.28	.14	.73	.57	.70	.10	.60	.26	.12
15	.20	.96	.12	.73	.17	.85	.87	.27	.13	.72	.56	.68	.10	.59	.24	.10
16	.20	.96	.12	.71	.17	.85	.86	.24	.13	.71	.53	.64	.09	.57	.20	.04
17	.20	.96	.11	.69	.17	.84	.84	.19	.13	.69	.49	.58	.09	.55	.15	5.97
18	.20	.95	.11	.66	.17	.83	.82	.15	.12	.68	.46	.52	.08	.52	.10	.89
19	.20	.95	.10	.63	.17	.82	.79	.11	.12	.66	.42	.46	.07	.49	.04	.81
20	.20	.95	.10	.63	.17	.82	.79	.11	.12	.65	.41	.47	.07	.49	.04	.83
21	.20	.95	.07	.55	.16	.80	.74	6.99	.11	.61	.32	.30	.05	.43	7.90	.60
22	.21	.95	.07	.54	.16	.79	.73	7.01	.10	.59	.31	.35	.04	.39	.88	.69
23	.21	.95	.07	.51	.16	.78	.72	6.98	.10	.57	.28	.31	.04	.37	.84	.65
24	.21	.94	.04	.42	.15	.76	.66	.86	.08	.52	.18	.16	.01	.29	.70	.47
25	.21	.93	.00	.27	.14	.72	.58	.68	.06	.45	.05	5.94	13.98	.18	.52	.20
26	.21	.94	.01	.31	.14	.72	.60	.78	.06	.44	.08	6.12	.97	.16	.56	.45
27	.22	.94	.01	.31	.14	.71	.60	.82	.05	.43	.09	.21	.96	.14	.58	.60
28	.22	.94	8.99	.22	.14	.69	.56	.72	.04	.38	.02	.10	.94	.07	.49	.48
29	.22	.93	.98	.18	.13	.68	.54	.69	.03	.37	.00	.07	.93	.05	.46	.45
30	.22	.93	.97	.13	.13	.67	.52	.65	.02	.34	7.97	.04	.91	.01	.42	.44
31	.22	.92	.92	6.95	.12	.63	.45	.46	13.99	.26	.87	5.85	.86	9.89	.28	.24
Diff. of	+0.06	0.00	-0.26	-1.22	-0.04	-0.29	-0.73	-1.70	-0.17	-0.66	-1.30	-2.29	-0.30	-1.03	-1.88	-2.89

Table 5-4. St. Croix River Discharges (142 m^3/s) with Simulated Dissolved Oxygen Concentrations.

Station	Effluent Discharge 455 kg/day				Effluent Discharge 2272 kg/day				Effluent Discharge 4545 kg/day				Effluent Discharge 6818 kg/day			
	Calculated DO at Temp.				Calculated DO at Temp.				Calculated DO at Temp.				Calculated DO at Temp.			
	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C	0°C	10°C	18°C	25°C
1	14.20	10.90	9.20	8.10	14.20	10.90	9.20	8.09	14.20	10.90	9.20	8.08	14.20	10.90	9.20	8.07
2	.20	.90	.20	.09	.20	.90	.19	.08	.20	.90	.19	.06	.20	.89	.18	.04
3	.20	.91	.20	.05	.20	.90	.17	7.99	.20	.89	.19	7.92	.20	.89	.11	7.85
4	.20	.91	.19	.04	.20	.90	.17	.98	.20	.89	.14	.90	.19	.88	.10	.82
5	.21	.91	.19	.04	.20	.90	.16	.97	.20	.88	.14	.88	.19	.87	.09	.79
6	.21	.91	.19	.02	.20	.89	.15	.93	.20	.88	.13	.81	.19	.86	.06	.70
7	.21	11.27	.19	7.99	.20	11.27	.14	.88	.20	11.27	.11	.74	.19	11.27	.02	.60
8	.21	.26	.18	.95	.20	.21	.12	.81	.20	.14	.08	.62	.19	.08	8.96	.44
9	.21	.25	.17	.89	.21	.19	.08	.71	.19	.12	.04	.47	.18	.05	.87	.24
10	.21	.25	.17	.87	.20	.19	.07	.67	.19	.11	8.98	.42	.18	.04	.84	.17
11	.22	.25	.16	.83	.20	.18	.05	.61	.19	.10	.95	.33	.18	.02	.78	.05
12	.22	.25	.15	.80	.20	.18	.03	.56	.19	.09	.92	.27	.17	.01	.74	6.97
13	.22	.25	.14	.78	.20	.17	.02	.53	.19	.08	.89	.22	.17	10.99	.71	.91
14	.22	.24	.14	.76	.20	.17	.01	.50	.18	.08	.86	.18	.17	.98	.68	.86
15	.22	.24	.14	.75	.20	.17	.00	.49	.18	.07	.85	.17	.16	.98	.67	.84
16	.22	.24	.13	.74	.20	.17	.00	.47	.18	.07	.84	.14	.16	.97	.65	.81
17	.22	.24	.13	.71	.20	.16	8.98	.44	.18	.06	.83	.10	.16	.96	.62	.76
18	.22	.24	.12	.69	.20	.16	.97	.42	.18	.06	.80	.07	.16	.95	.60	.72
19	.22	.24	.12	.67	.20	.15	.96	.38	.18	.05	.79	.02	.15	.94	.57	.67
20	.22	.24	.12	.67	.20	.15	.96	.38	.18	.05	.76	.02	.15	.94	.57	.66
21	.22	.24	.11	.62	.20	.15	.94	.32	.17	.03	.73	6.95	.15	.92	.51	.57
22	.22	.23	.10	.60	.20	.14	.93	.30	.17	.02	.71	.93	.14	.90	.49	.56
23	.22	.23	.10	.58	.20	.13	.92	.28	.17	.01	.69	.90	.14	.89	.46	.53
24	.22	.23	.08	.51	.20	.12	.88	.20	.16	10.99	.64	.81	.13	.86	.40	.42
25	.22	.22	.06	.43	.19	.11	.85	.10	.15	.97	.58	.69	.12	.83	.32	.29
26	.22	.22	.05	.39	.19	.10	.83	.07	.15	.95	.56	.67	.11	.81	.29	.28
27	.22	.21	.04	.36	.19	.09	.82	.05	.15	.94	.54	.66	.10	.79	.26	.27
28	.22	.21	.03	.30	.19	.08	.80	6.99	.14	.92	.51	.60	.10	.77	.22	.21
29	.22	.21	.03	.28	.19	.08	.79	.97	.14	.92	.50	.58	.09	.76	.21	.19
30	.23	.21	.02	.25	.19	.07	.78	.94	.14	.91	.48	.56	.09	.74	.19	.18
31	.23	.20	8.99	.14	.18	.06	.74	.84	.13	.88	.43	.45	.07	.70	.12	.07
Diff. of	+0.03	+0.30	-0.21	-0.96	-0.02	+0.16	-0.46	-1.25	-0.07	-0.02	-0.77	-1.63	-0.13	-0.20	-1.08	-2.00

St. Croix River, Woodland to Milltown (21 m^3/s)

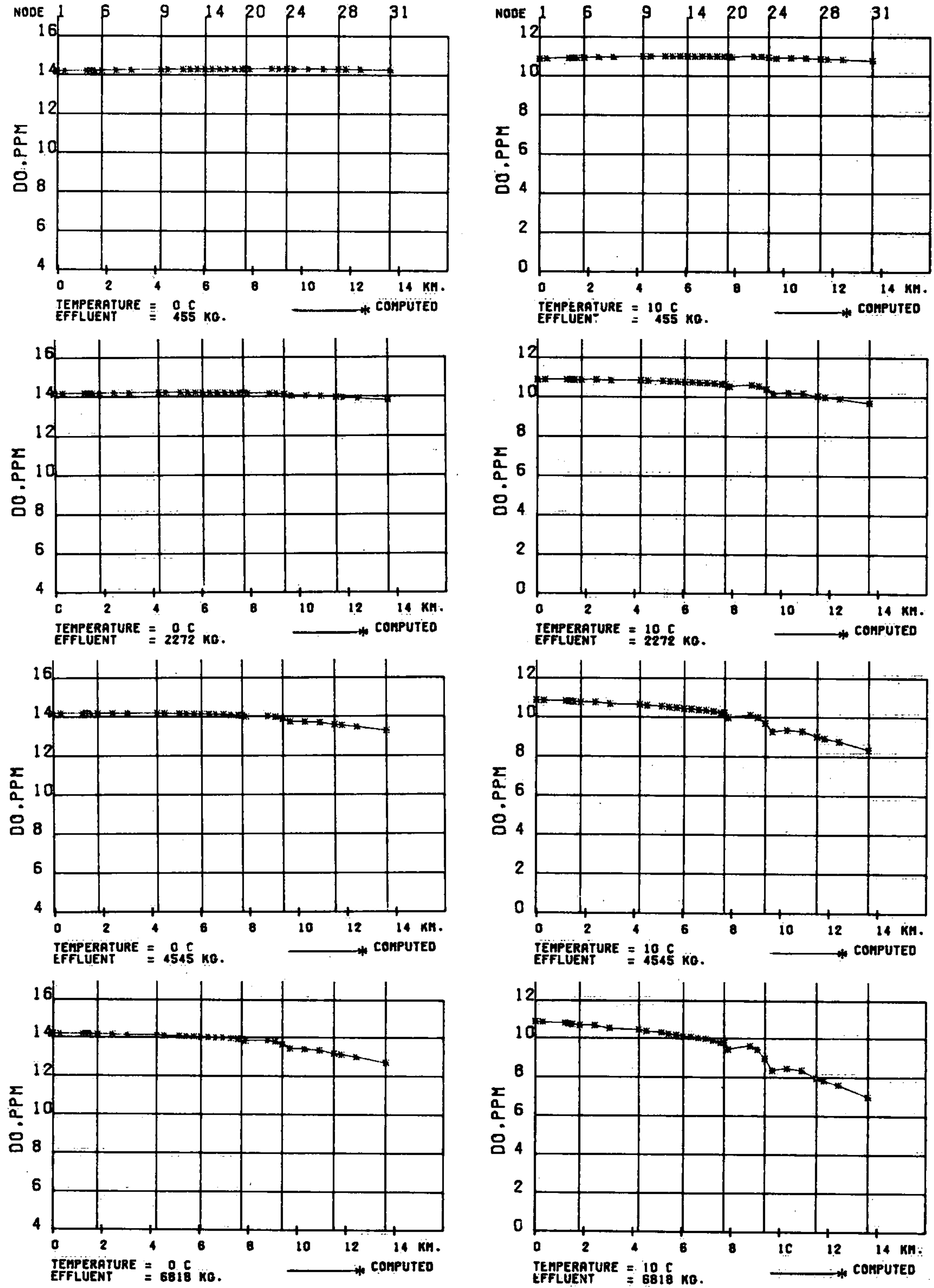

Figure 5-1. Dissolved oxygen simulation, 21 m^3/s flow.

St. Croix River, Woodland to Milltown (21 m^3/s)

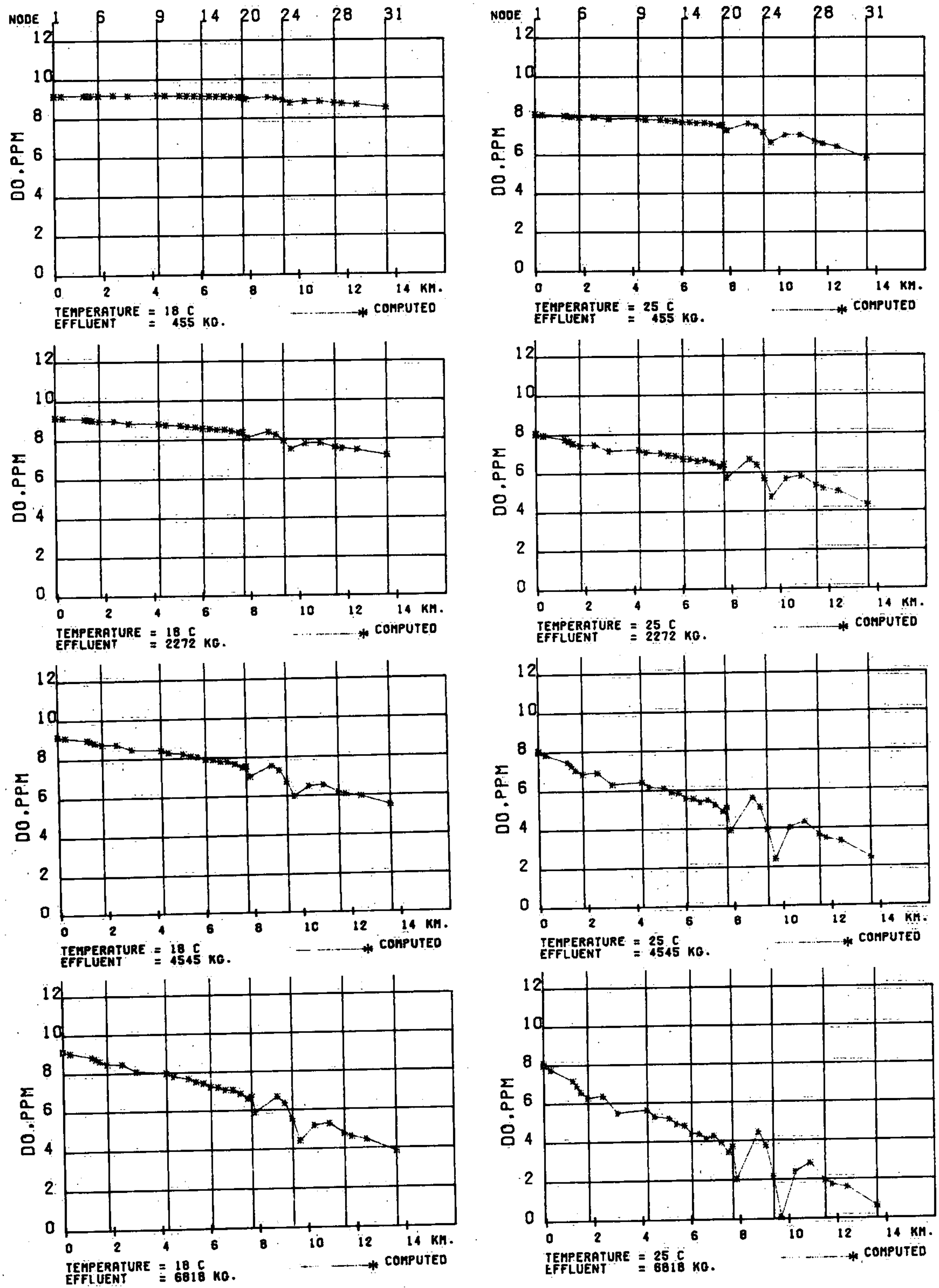

Figure 5-1. (cont'd)

St. Croix River, Woodland to Milltown (71 m^3/s)

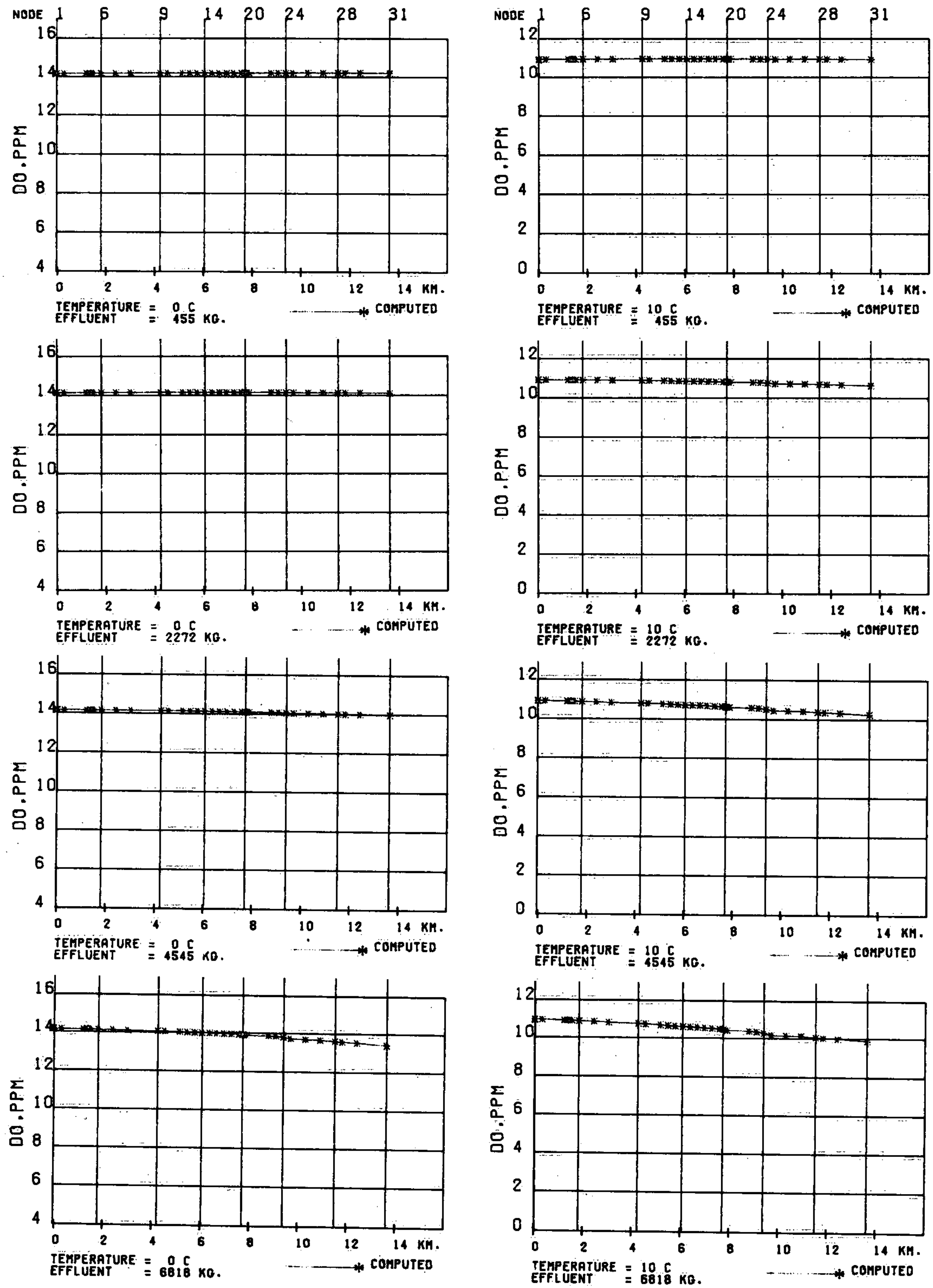

Figure 5-2. Dissolved oxygen simulation, 71 m^3/s flow.

St. Croix River, Woodland to Milltown (71 m^3/s)

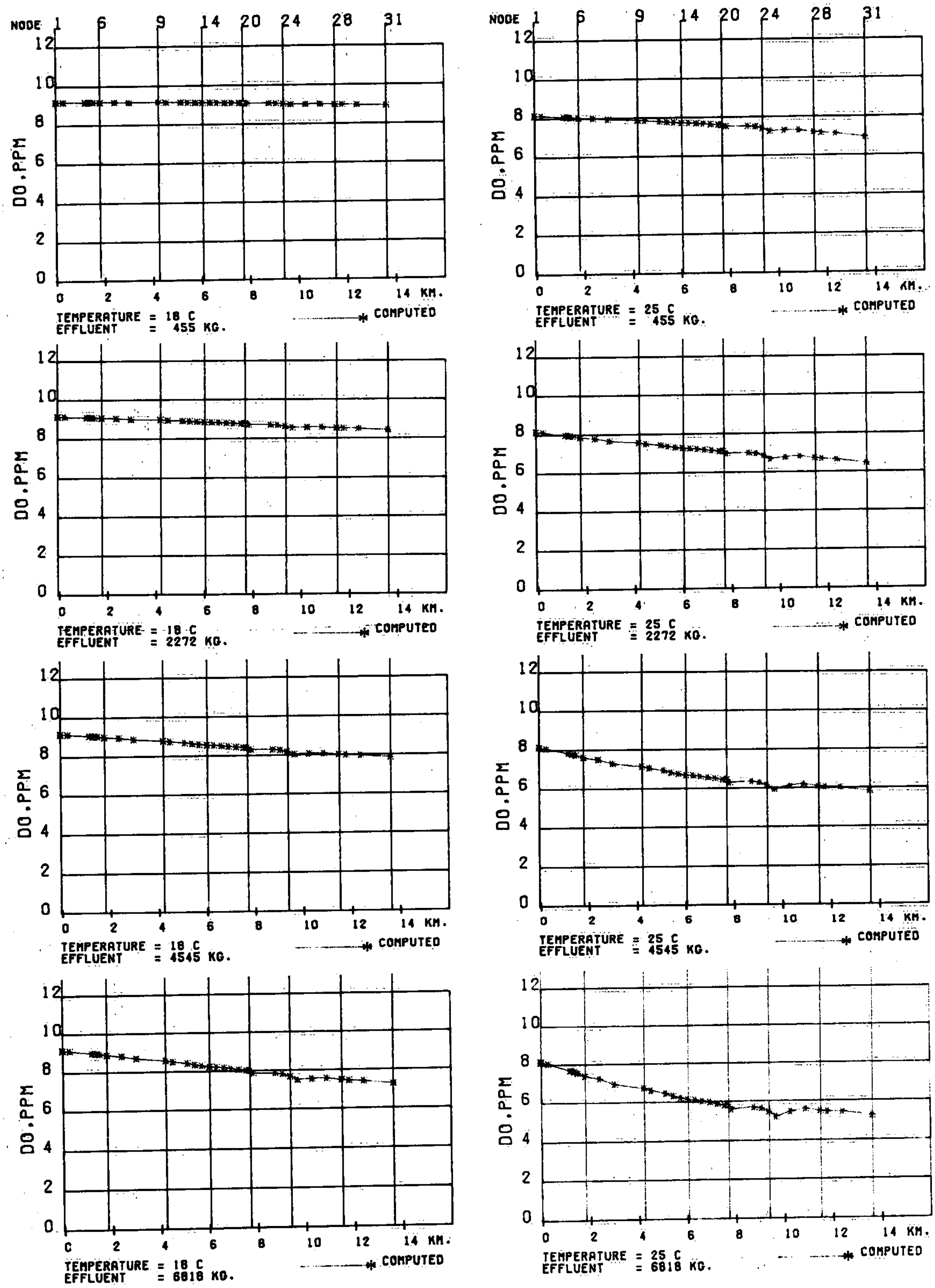

Figure 5-2. (cont'd)

St. Croix River, Woodland to Milltown (142 m^3/s)

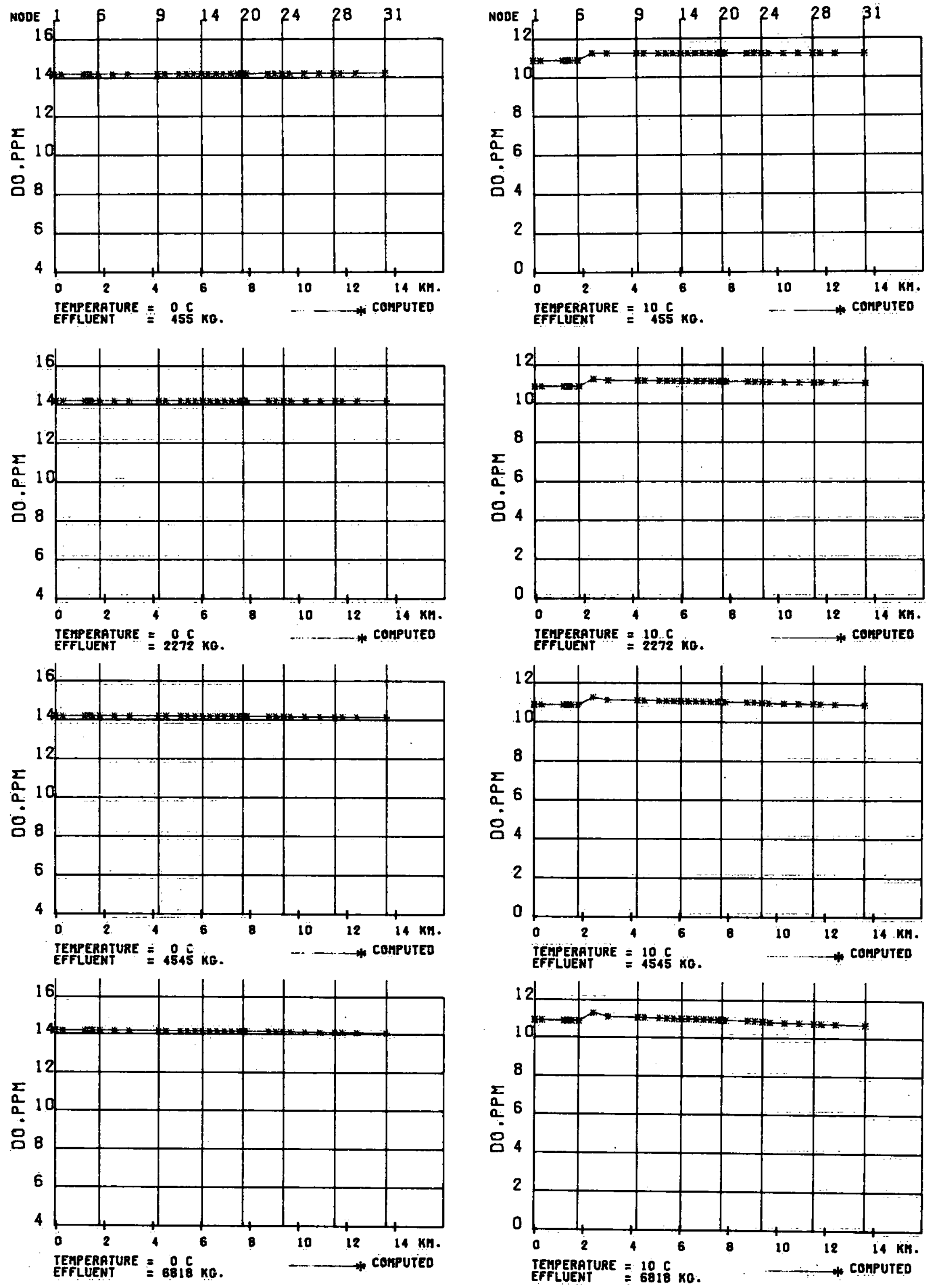

Figure 5-3. Dissolved oxygen simulation, 142 m3/s flow.

St. Croix River, Woodland to Milltown (142 m^3/s)

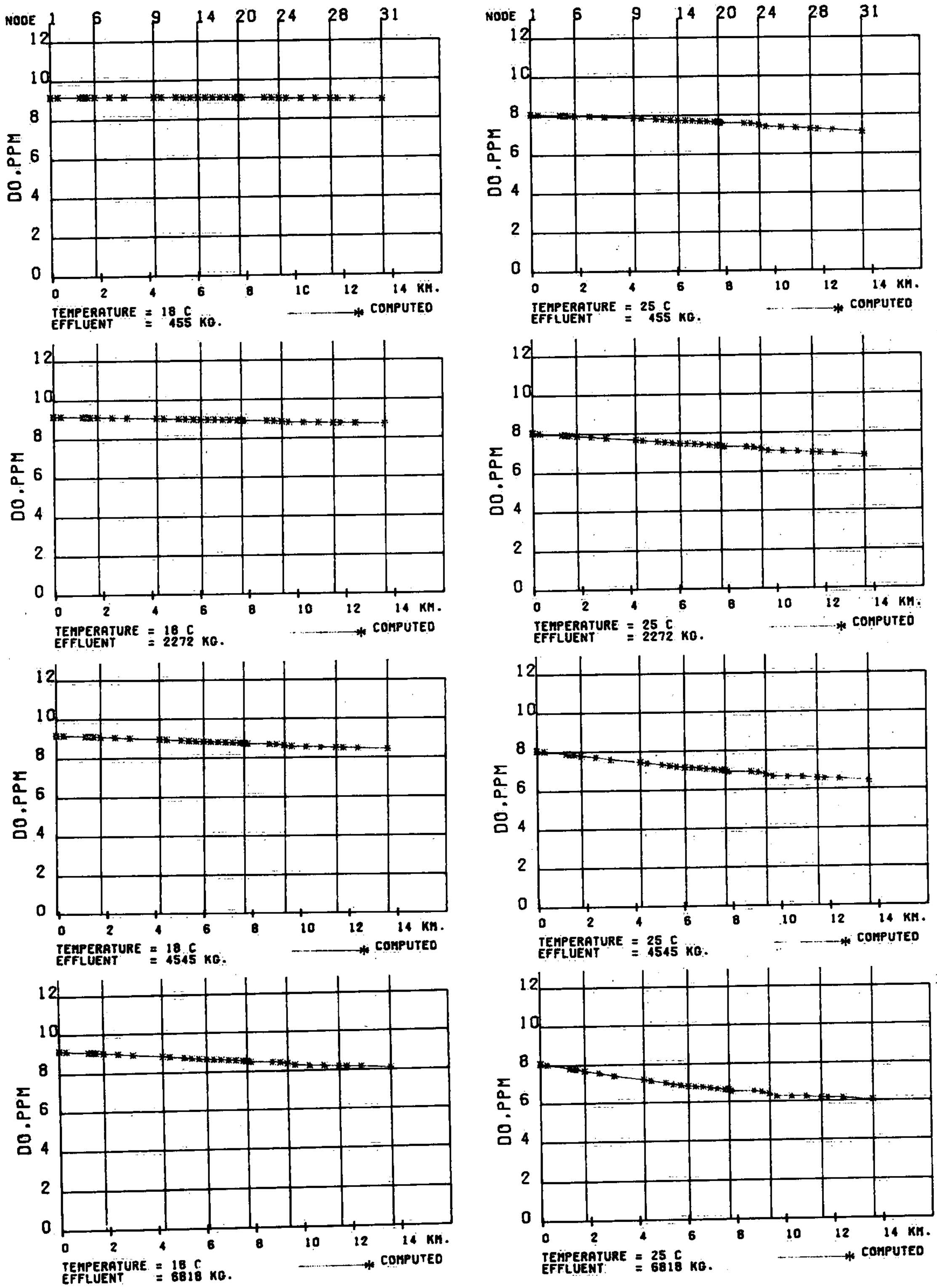

Figure 5-3. (cont'd)

sections 27000 and 30000 was too long and the bottom slope was too steep to be properly handled by the model.

b) Short-term continuous sampling of effluent and river discharge values would add precision to the model that was not possible using daily mean discharge and BOD inputs.

c) Based on the calibration and validation results, the model predictions are good indicators of expected river conditions.

6.2 Water Quality Management

a) Model predictions show that at temperatures higher or equal to 18°C, with the present minimum allowable discharge of 21 m^3/s, DO levels will be lower than 6.0 ppm if the BOD load is greater than 4545 kg/day.

b) Although the DO concentration is the best indicator of river conditions for the fish survival, it does not fully explain the river as a fish habitat. Synergistic effects between oxygen levels and the other physical and chemical parameters in the river may have profound effects on the aquatic environment and fish viability.

c) Though dissolved oxygen levels are the main water quality concern in the St. Croix River, other parameters such as ammonia, total nitrogen and total suspended solids can also be a danger to migrating fish. These should be potential candidates for future uses of WATQUAL or any other water quality model.

7. ACKNOWLEDGMENTS

The authors would like to thank D.H. Cullen, P.E. Belliveau, Water Quality Branch, Moncton, and D.W. Farley, Water Planning and Management Branch, Ottawa, for their support and encouragement in initiating the study and preparing the report, and S.H. Whitlow, Water Quality Branch, Ottawa, for his editorial assistance.

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