INSTITUTE of HYDROLOGY

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ROADFORD ENVIRONMENTAL INVESTIGATION

TAMAR RIVER QUALITY MODEL:

PHASE 2 REPORT TO WRC/SWWA

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Summary

The Tamar River Water Quality model has been validated using observed 1986 water quality data for six sites and at six different periods throughout the year.

The option within the model to simulate any conservative pollutant has been altered to model temperature along the river profile. In addition short term oxygen production/respiration relationships have been investigated using continuous water quality data.

Simulated reservoir releases have also been reproduced for the six periods used in the validation exercise in order to assess the impact of releases of waters high in BOD, nitrate and ammonia upon the downstream river system.

1. Introduction

This report describes progress made in the Second Phase of a water quality modelling study of the River Tamar. This stage follows the application of the IHQM (Institute of Hydrology Quality Model) to the River Tamar, described in the report on Phase 1 of this study.

Development of the model during this phase of the study has been as follows:

1.1 Validation of the model using historical data, to provide an accurate simulation of existing river conditions.

1.2 To replace the IHQM facility for modelling any conservative pollutant with the facility to model temperature along the profile.

1.3 To assess the impact of simulated releases of water from Roadford reservoir upon the river quality profile under a range of existing flow regimes and seasonal conditions.

1.4 To investigate existing dissolved oxygen/algal growth relationships within the profile in order to enable simulation of daily oxygen balance of the river, as well as to assess the influence of other factors upon the diurnal oxygen variation, such as solar radiation and flow rates.

Results of model development made so far are presented and requirements for further research into the algal growth/DO relationship and the influence of other factors upon that relationship are investigated.

2. Model Validation

The model has been validated using 1986 water quality data for six sites along the river. Because of the marked seasonal variation in flow rates and water quality, the model has been adapted to include tributary input data on a monthly basis. In order to test the variability validation has been carried out for six time periods throughout the year for which water quality data is available for all six sites along the river.

The six sites used for validation and the six time periods for which the model has been run are as follows:

<u>Sites</u>

Gunnislake	Horsebridge	Greystones
Lifton	Tinhay	River Wolf

<u>Simulation dates</u>

20.01.1986	03.03.86	26.04.86
17.06.86	02.09.86	15.12.86

Tables 1 to 6 show comparisons of the observed and simulated water quality parameters (BOD, DO, nitrate and ammonia) at the six sites along the river and for the six time periods considered. Table 7 shows the Mean Errors between observed and simulated water quality for each of the six time periods. Figures 1a and 1b show observed and simulated water quality for one validation period.

The validation exercise shows that the model reproduces the existing water quality conditions for 1986 fairly accurately although there is a need for good quality data for the tributaries flowing into the river to enable the model to reproduce variations along the length of the profile. This is particularly important in the case of the main Tamar tributary, which the model shows has the dominant influence on water quality throughout the lower reaches of the profile. This is due to the flow rate of the Tamar which tends to dominate river hydrology and because of the Launceston Sewage Works which exerts a major influence on the water quality of the Tamar.

3. Continuously Monitored Data

Figure 2 shows the sites along the river profile at which water quality is continuously monitored (every 20 minutes). These sites are Gunnislake, Lifton, Rexon and St. Leonards on the Tamar. Figure 2a shows the reach structure of the river. Determinands monitored at all sites are conductivity, pH, dissolved oxygen and temperature. Figures 3a and 3b show two example plots of a month's continuous data for the sites at Gunnislake and St. Leonards. All the continuously monitored data available for 1987 are shown in Appendix I. The principal use of the continuously monitored data for this study has been to investigate the dissolved oxygen-algal growth relationships along the river (see Section 4) although continuous data on pH show some interesting patterns and indicates that pH is correlated with DO.

4. Oxygen Production Relationships in the Tamar

Figure 4 shows a plot of the chlorophyll A data available for 1987 at Gunnislake and Figures 5a b and c show example plots of dissolved oxygen, flow rates and solar radiation for Gunnislake.

The diurnal cycle in oxygen production in the river is dependent primarily upon the amount of algae present and the solar radiation although this relationship may be complicated by flow dependence in relatively fast flowing rivers such as the Tamar.

Investigations into the correlation between the daily range in dissolved oxygen levels and both chlorophyll A and solar radiation data for 1987 have not yielded an improved equation for predicting daily net oxygen production to that already existing in the model (see Phase 1 Report). However, if the model were to be converted to a short term (eg. hourly) model improved primary oxygen production and respiration terms will be required. Further detailed research in this area is required in order to develop these relationships.

5. Impact of Roadford Reservoir releases upon Water Quality in the River Tamar

The facility within the model for altering upstream input impulses to the Tamar has been used to simulate releases of water from the proposed Roadford Reservoir into the top of the river profile for periods of up to thirty days. The flow rate from the reservoir may be varied as may the concentrations of BOD, nitrate and ammonia in turn, as well as temperature. This facility has been used to investigate the impact of discharging water of poor quality into the river at a rate identified as the likely maximum required to maintain a sufficient flow at Gunnilake to enable continued abstraction. Simulations have also been carried out of releases of water of similar quality to that in an existing reservoir (Wimbleball reservoir) in the region, for which data are available. Reservoir releases have been sustained for periods of between twenty to thirty days to allow the river to reach a steady state and a comparison has been made between high and low level releases (eg. 1 cumec and 0.1 cumecs). The results of these simulations are shown in Appendix 2 and Tables 8-13. Figures 6a, b and c and 7a, b, and c show example plots of the model steady state conditions and simulations edited to reproduce reservoir releases. All simulations were run over the six time periods used in the validation exercise.

The results of these simulations show that the reservoir releases have a much more significant impact upon the reaches of the river upstream of the Tamar confluence, where the flow rate is much lower, than on reaches below it. There is a marked seasonal variation in the impact of a flow change due to flows being lower during the summer months and the effect of the releases is exacerbated at these times because of the need for higher compensation flows.

Under the scenario of large releases of water of poor quality there is a significant impact upon the upper reaches of the river as can be seen from Figures 6b and c which show that in June when flows are relatively low, a reservoir release of 1 cumec with a BOD of 6 mg/L, nitrate of 10 mg/L and ammonia of 0.2 mg/L will cause increases of 4 mg/L in BOD, 0.13 mg/L in ammonia and 6 mg/L in nitrate at the top of the first reach with high levels of these determinands persisting in the river above the Tamar confluence. However simulations using Wimbleball reservoir data show that reservoir releases will not produce severe shocks to the river system. This can be seen from the plots in Appendix 2 which show the effects of releases of water low in BOD, nitrate and ammonia upon the river system. The temperature simulations show that releases of large volumes of low temperature water will have a significant impact under low flow conditions. This is shown in Figure 6a where a release of 1 cumec of water at 5°C causes a drop in temperature at the top of the first reach from approximately 13°C to approximately 6.5°C. Figures 7a, b and c show that under conditions of high flow reservoir releases of 1 cumec with poor water quality will, at most, double concentrations of BOD, ammonia and nitrate in the top reach of the river and that these effects will not persist below the Tamar confluence.

6. Conclusions and recommendations

The Second Phase of the Roadford environmental investigation confirms that the river model adequately reproduces steady state water quality including temperature and can be used to simulate releases from the reservoir.

Our overall conclusion is that the releases of reservoir water will not have a major effect on river quality downstream of the main Tamar river confluence. However there is likely to be some effect on the upper reaches although this will be minimal if the reservoir quality is similar to the Wimbleball reservoir quality. A potential problem is the release of low temperature water from the reservoir if stratification occurs. Also high BOD loads from dead algae may occur if the reservoir becomes highly eutrophic at some stage in the future. There may also be some seeding of algae from the reservoir into the river under low flow summer conditions.

Finally, the model could be transferred to SWWA for use on a PDP micro or VAX system if required under Phase 3 of the IH-WRC contract.

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TABLE 1

COMPARISON OF OBSERVED AND SIMULATED VALUES OF PRINCIPAL WATER QUALITY PARAMETERS

Site	BOD			D.O.			Nitrate			Ammonia		
	Observed	Simulated	Error	Observed	Simulated	Error	Observed	Simulated	Error	Observed	Simulated	Error
Gunnislake	2.3	2.2	-0.1	11.0	10.8	-0.2	3.2	2.8	-0.4	0.20	0.22	0.02
Horsebridge	2.7	2.3	-0.4	10.1	10.8	0.7	3.2	2.9	-0.3	0.20	0.22	0.02
Greystones	2.9	2.4	-0.5	10.5	10.7	0.2	3.1	2.8	-0.3	0.29	0.27	-0.02
Lifton	2.8	2.9	0.1	11.0	11.0	0.0	2.3	2.3	0.0	0.29	0.29	0.00
Tinhay	3.6	3.4	-0.2	10.5	10.1	-0.4	1.9	1.8	-0.1	0.42	0.38	-0.04
R. Wolf	3.1	2.4	-0.7	10.8	10.7	-0.1	1.7	1.4	-.03	0.33	0.22	-0.11
MEAN ERROR			-0.36			0.04			-0.28			-0.026

Date: 20.01.86

TABLE 2

COMPARISON OF OBSERVED AND SIMULATED VALUES OF PRINCIPAL WATER QUALITY PARAMETERS

Site	BOD			D.O.			Nitrate			Ammonia		
	Observed	Simulated	Error	Observed	Simulated	Error	Observed	Simulated	Error	Observed	Simulated	Error
Gunnislake	1.0	0.9	-0.1	13.3	11.6	-1.7	3.3	2.2	-1.1	0.07	0.10	0.03
Horsebridge	1.8	1.1	-0.7	13.1	12.1	-1.0	3.3	2.5	-0.8	0.08	0.12	0.04
Greystones	1.6	1.3	-0.3	13.1	12.7	-0.4	3.4	2.8	-0.6	0.24	0.17	-0.07
Lifton	1.7	1.7	0.0	13.5	13.5	0.0	2.2	2.3	0.1	0.08	0.07	-0.01
Tinhay	1.5	1.5	0.0	13.3	13.2	-0.1	2.0	2.0	0.0	0.11	0.13	0.02
R. Wolf	1.3	1.2	-0.1	13.5	12.9	-0.6	1.8	1.7	-0.1	0.06	0.05	-0.01
MEAN ERROR			-0.24			-0.76			-0.5			0.00

Date: 03.03.86

TABLE 3

COMPARISON OF OBSERVED AND SIMULATED VALUES OF PRINCIPAL WATER QUALITY PARAMETERS

Site	BOD Observed	BOD Simulated	BOD Error	D.O. Observed	D.O. Simulated	D.O. Error	Nitrate Observed	Nitrate Simulated	Nitrate Error	Ammonia Observed	Ammonia Simulated	Ammonia Error
Gunnislake	3.6	2.9	-0.7	11.0	11.0	0.0	2.7	2.9	0.2	0.32	0.20	-0.12
Horsebridge	2.9	3.0	0.1	10.5	11.1	0.6	2.9	2.9	0.0	0.28	0.20	-0.08
Greystones	3.1	3.2	0.1	10.8	10.7	-0.1	2.9	2.8	-0.1	0.27	0.25	-0.02
Lifton	2.4	2.4	0.0	10.6	10.8	0.2	2.9	2.8	-0.1	0.08	0.09	0.01
Tinhay	2.4	2.3	-0.1	10.0	10.3	0.3	2.8	2.6	-0.2	0.16	0.14	-0.02
R. Wolf	2.4	2.2	-0.2	10.5	11.4	0.9	2.5	2.3	-0.2	0.07	0.05	-0.02
MEAN ERROR			-0.16			0.38			-0.08			-0.05

Date: 26.04.86

TABLE 4

COMPARISON OF OBSERVED AND SIMULATED VALUES OF PRINCIPAL WATER QUALITY PARAMETERS

Site	BOD Observed	BOD Simulated	BOD Error	D.O. Observed	D.O. Simulated	D.O. Error	Nitrate Observed	Nitrate Simulated	Nitrate Error	Ammonia Observed	Ammonia Simulated	Ammonia Error
Gunnislake	0.6	0.8	0.2	8.9	9.8	0.9	2.6	1.7	-0.9	0.08	0.08	0.00
Horsebridge	0.8	0.9	0.1	9.0	9.6	-0.6	2.5	2.0	-0.5	0.07	0.09	0.02
Greystones	1.2	0.8	-0.4	8.4	9.2	0.8	2.6	2.1	-0.5	0.15	0.13	-0.02
Lifton	0.3	0.6	0.3	11.0	10.3	-0.7	2.0	1.7	-0.3	0.03	0.05	0.02
Tinhay	0.6	0.5	-0.1	10.4	10.3	-0.1	1.8	1.6	-0.2	0.06	0.06	0.00
R. Wolf	0.6	0.5	-0.1	11.2	10.3	-0.9	1.7	1.3	-0.4	0.03	0.03	0.00
MEAN ERROR			0.0			-0.12			-0.56			0.004

Date: 17.06.86

TABLE 5

COMPARISON OF OBSERVED AND SIMULATED VALUES OF PRINCIPAL WATER QUALITY PARAMETERS

Site	BOD Observed	BOD Simulated	BOD Error	D.O. Observed	D.O. Simulated	D.O. Error	Nitrate Observed	Nitrate Simulated	Nitrate Error	Ammonia Observed	Ammonia Simulated	Ammonia Error
Gunnislake	1.8	1.2	-0.6	10.2	10.1	-0.1	3.5	2.6	-0.4	0.03	0.05	0.02
Horsebridge	1.7	1.3	-0.4	10.4	10.2	-0.2	3.6	2.7	-0.9	0.03	0.05	0.02
Greystones	1.6	1.3	-0.3	9.9	10.1	0.2	3.4	2.9	-0.5	0.09	0.05	-0.04
Lifton	1.2	1.1	-0.1	10.6	10.4	-0.2	2.6	2.2	-0.4	0.04	0.04	-.00
Tinhay	1.1	1.0	-0.1	10.4	10.3	-0.1	2.5	2.3	-0.2	0.04	0.04	0.00
R. Wolf	0.9	0.9	0.0	10.2	10.2	0.0	2.3	1.9	-0.4	0.04	0.03	-0.01
MEAN ERROR			-0.3			-0.08			-0.62			-0.002

Date: 02.09.86

TABLE 6

COMPARISON OF OBSERVED AND SIMULATED VALUES OF PRINCIPAL WATER QUALITY PARAMETERS

Site	BOD Observed	BOD Simulated	BOD Error	D.O. Observed	D.O. Simulated	D.O. Error	Nitrate Observed	Nitrate Simulated	Nitrate Error	Ammonia Observed	Ammonia Simulated	Ammonia Error
Gunnislake	2.2	2.6	0.4	10.4	10.4	0.0	3.1	2.5	-0.6	0.15	0.20	0.05
Horsebridge	2.2	2.6	0.4	10.5	10.3	-0.2	3.1	2.5	-0.6	0.14	0.20	0.06
Greystones	2.7	2.7	0.0	9.8	9.9	0.1	2.6	2.3	-0.3	0.24	0.23	-0.01
Lifton	3.0	2.8	-0.2	10.6	10.6	0.0	1.5	1.7	0.2	0.20	0.18	-0.02
Tinhay	2.8	2.4	-0.4	10.0	10.1	0.1	1.4	1.4	0.0	0.20	0.17	-0.03
R. Wolf	3.8	1.8	-2.0	10.5	10.2	-0.3	1.2	1.3	0.1	0.20	0.09	-0.11
MEAN ERROR			-0.36			-0.06			-0.24			-0.012

Date: 15.12.86

TABLE 7

MEAN ERROR BETWEEN OBSERVED AND SIMULATED VALUES OF PRINCIPAL WATER QUALITY PARAMETERS

Date	BOD	D.O.	Nitrate	Ammonia
20.01.86	-0.36	0.04	-0.28	-0.026
03.03.86	-0,24	-0.76	-0.5	0.00
26.04.86	-0.16	0.38	-0.08	-0.05
17.06.86	0.0	-0.12	-0.56	0.004
02.09.86	-0.3	-0.08	-0.62	-0.002
15.12.86	-0.36	-0.100	-0.380	-0.012
MEAN	-0.237	-0.100	-0.380	-0.014

TABLE 8

EFFECT OF ROADFORD RESERVOIR RELEASES ON RIVER WATER QUALITY

Site	BOD	DO	NO_3	NH_3	Temperature
Combepark Farm	0.5(3.0)	10.4(10.3)	1.8(5.6)	0.03(0.11)	6.5(4.4)
Tinhay	0.5(1.6)	10.3(10.3)	1.8(3.4)	0.06(0.09)	6.8(6.5)
Lifton	0.5(1.0)	10.8(10.8)	1.8(2.8)	0.04(0.06)	7.2(6.7)
Tamar Confluence	0.8(1.0)	9.3 (9.3)	2.4(2.8)	0.14(0.14)	6.6(6.4)
Lowley Bridge	0.9(1.1)	9.5 (9.5)	2.4(2.8)	0.14(0.14)	6.7(6.5)
R. Inny	1.2(1.3)	9.8 (9.8)	2.4(2.8)	0.12(0.12)	7.2(7.0)
Gunnislake	1.2(1.3)	10.1(10.1)	2.4(2.7)	0.12(0.12)	7.2(7.0)

Date : 20 January 1986

Rate of reservoir release : 1 m^3/sec

Water quality of reservoir release

BOD	:	6 mg/L
NH_3	:	0.2 mg/L
NO_3	:	10 mg/L
Temp.	:	2 °C

Water quality values following reservoir releases are shown in brackets.

TABLE 9

EFFECT OF ROADFORD RESERVOIR RELEASES ON RIVER WATER QUALITY

Date : 03 March 1986

Site	BOD	DO	NO_3	NH_3	Temperature
Combepark Farm	0.4(5.2)	10.6(10.5)	1.6(8.8)	0.03(0.18)	0.1(1.8)
Tinhay	0.4(3.6)	10.9(10.9)	1.6(7.0)	0.05(0.15)	0.2(1.5)
Lifton	0.4(3.0)	11.4(11.2)	1.7(6.0)	0.04(0.12)	0.1(1.2)
Tamar Confluence	0.8(1.8)	9.8(10.2)	2.4(4.0)	0.14(0.15)	0.5(0.9)
Lowley Bridge	0.8(1.6)	10.2(10.4)	2.3(3.9)	0.13(0.14)	0.7(1.1)
R. Inny	1.0(1.4)	10.4(10.5)	2.0(3.0)	0.10(0.12)	2.3(2.3)
Gunnislake	0.6(1.0)	11.0(11.0)	1.8(2.9)	0.08(0.10)	2.1(2.1)

Rate of reservoir release : 1 m^3/sec

Water quality of reservoir release
BOD : 6 mg/L
NH_3 : 0.2 mg/L
NO_3 : 10 mg/L
Temp. : 2°C

Water quality values following reservoir releases are shown in brackets.

TABLE 10

EFFECT OF ROADFORD RESERVOIR RELEASES ON RIVER WATER QUALITY

Site	BOD	DO	NO_3	NH_3	Temperature
Combepark Farm	0.5(3.4)	10.5(10.4)	1.8(6.0)	0.03(0.12)	6.2(4.5)
Tinhay	0.6(1.7)	10.6(10.6)	1.8(3.8)	0.06(0.09)	6.4(5.8)
Lifton	0.5(1.3)	11.0(10.9)	1.9(3.1)	0.04(0.06)	7.2(6.6)
Tamar Confluence	0.8(1.1)	9.4 (9.4)	2.6(3.0)	0.14(0.14)	7.8(7.6)
Lowley Bridge	0.8(1.1)	9.6 (9.6)	2.6(3.0)	0.14(0.14)	7.9(7.7)
R. Inny	1.0(1.2)	10.0(10.0)	2.6(3.0)	0.12(0.12)	8.2(8.0)
Gunnislake	1.0(1.2)	10.5(10.5)	2.5(2.9)	0.12(0.12)	8.2(8.0)

Date : 26 April 1986

Rate of reservoir release : $1 m^3/sec$

Water quality of reservoir release
- BOD : 6 mg/L
- NH_3 : 0.2 mg/L
- NO_3 : 10 mg/L
- Temp. : 3°C

Water quality values following reservoir releases are shown in brackets.

TABLE 11

EFFECT OF ROADFORD RESERVOIR RELEASES ON RIVER WATER QUALITY

Date : 17 June 1986

Site	BOD	DO	NO_3	NH_3	Temperature
Combepark Farm	0.5(4.6)	10.2(10.0)	1.6(8.2)	0.02(0.16)	13.2 (6.6)
Tinhay	0.6(2.8)	10.0 (9.7)	1.6(5.4)	0.04(0.12)	13.2 (8.8)
Lifton	0.5(2.0)	10.5(10.1)	1.7(4.3)	0.03(0.09)	13.2(10.2)
Tamar Confluence	0.9(1.5)	9.2 (9.2)	2.2(3.2)	0.13(0.14)	15.8(13.8)
Lowley Bridge	0.9(1.4)	9.3 (9.3)	2.1(3.1)	0.12(0.13)	15.7(13.8)
R. Inny	1.0(1.2)	9.6 (9.5)	2.2(2.9)	0.10(0.11)	14.9(13.5)
Gunnislake	0.8(1.0)	9.6 (9.5)	1.6(2.0)	0.07(0.08)	14.9(13.5)

Rate of reservoir release : 1 m^3/sec

Water quality of reservoir release

BOD : 6 mg/L
NH_3 : 0.2 mg/L
NO_3 : 10 mg/L
Temp. : 5°C

Water quality values following reservoir releases are shown in brackets.

TABLE 12

EFFECT OF ROADFORD RESERVOIR RELEASES ON RIVER WATER QUALITY

Site	BOD	DO	NO_3	NH_3	Temperature
Combepark Farm	1.2(4.2)	10.5(10.3)	2.0(7.0)	0.02(0.13)	11.5 (8.6)
Tinhay	1.1(2.4)	10.5(10.4)	2.1(4.4)	0.05(0.10)	11.4 (9.9)
Lifton	1.0(1.8)	10.6(10.5)	2.1(3.6)	0.03(0.06)	11.2(10.4)
Tamar Confluence	1.3(1.5)	10.2(10.2)	3.0(3.5)	0.04(0.05)	11.0(10.8)
Lowley Bridge	1.3(1.5)	10.3(10.3)	2.8(3.1)	0.04(0.05)	11.0(10.8)
R. Inny	1.4(1.6)	10.5(10.5)	2.9(3.1)	0.04(0.05)	10.8(10.7)
Gunnislake	1.4(1.5)	10.8(10.7)	2.6(2.8)	0.04(0.05)	10.9(10.7)

Date : 02 September 1986

Rate of reservoir
Release : 1 m^3/sec

Water quality of reservoir release
BOD : 6 mg/L
NH_3 : 0.2 mg/L
NO_3 : 10 mg/L
Temp. : 7°C

Water quality values following reservoir releases are shown in brackets.

TABLE 13

EFFECT OF ROADFORD RESERVOIR RELEASES ON RIVER WATER QUALITY

Date : 15 December 1986

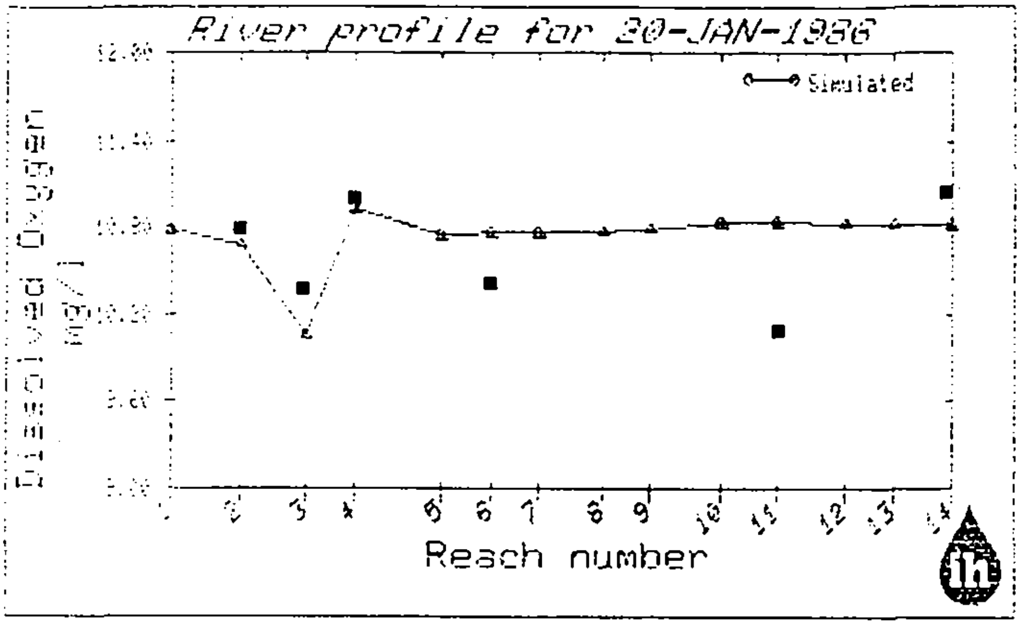
Site	BOD	DO	NO_3	NH_3	Temperature
Combepark Farm	0.5(1.4)	10.4(10.4)	1.8(3.2)	0.03(0.06)	8.4(7.9)
Tinhay	0.5(0.8)	10.2(10.2)	1.8(2.4)	0.05(0.06)	8.5(8.2)
Lifton	0.4(0.6)	10.8(10.8)	1.9(2.1)	0.04(0.04)	9.7(9.5)
Tamar Confluence	0.8(0.8)	9.2 (9.2)	2.6(2.7)	0.14(0.14)	9.2(9.2)
Lowley Bridge	0.8(0.8)	9.4 (9.4)	2.7(2.7)	0.14(0.14)	9.3(9.2)
R. Inny	1.2(1.2)	9.6 (9.6)	2.8(2.8)	0.12(0.12)	9.4(9.3)
Gunnislake	1.2(1.2)	10.0(10.0)	2.7(2.7)	0.12(0.12)	9.4(9.3)

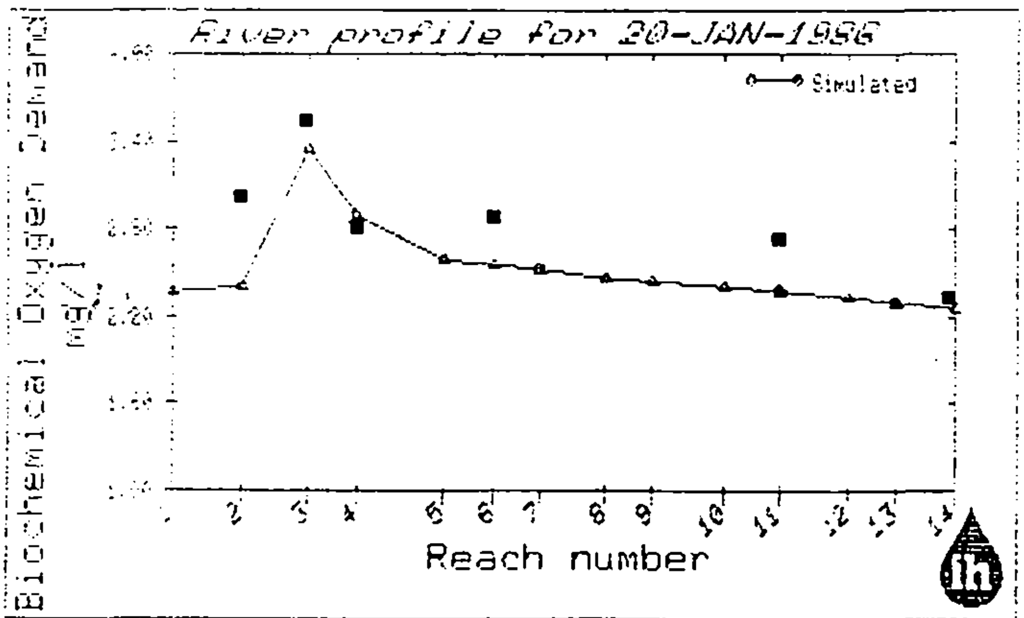
Rate of reservoir release : 1 m^3/sec

Water quality of reservoir release

- BOD : 6 mg/L
- NH_3 : 0.2 mg/L
- NO_3 : 10 mg/L
- Temp. : 3°C

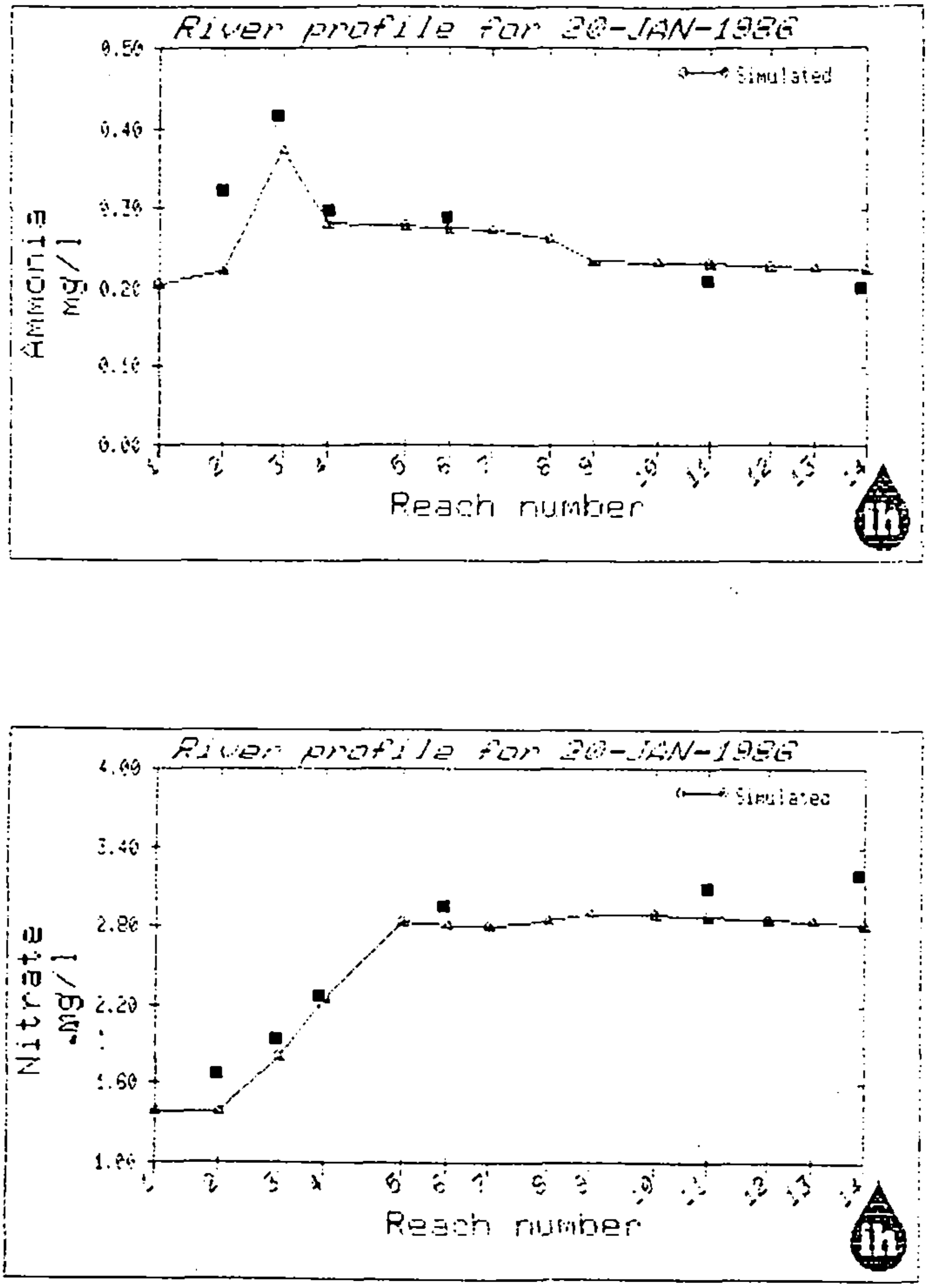
Water quality values following reservoir releases are shown in brackets.





■ = observed

Figure 1a. Observed and simulated BOD and DO for 20 January 1986



■ = observed

Figure 1b. Observed and simulated ammonia and nitrate for 20 June 1986

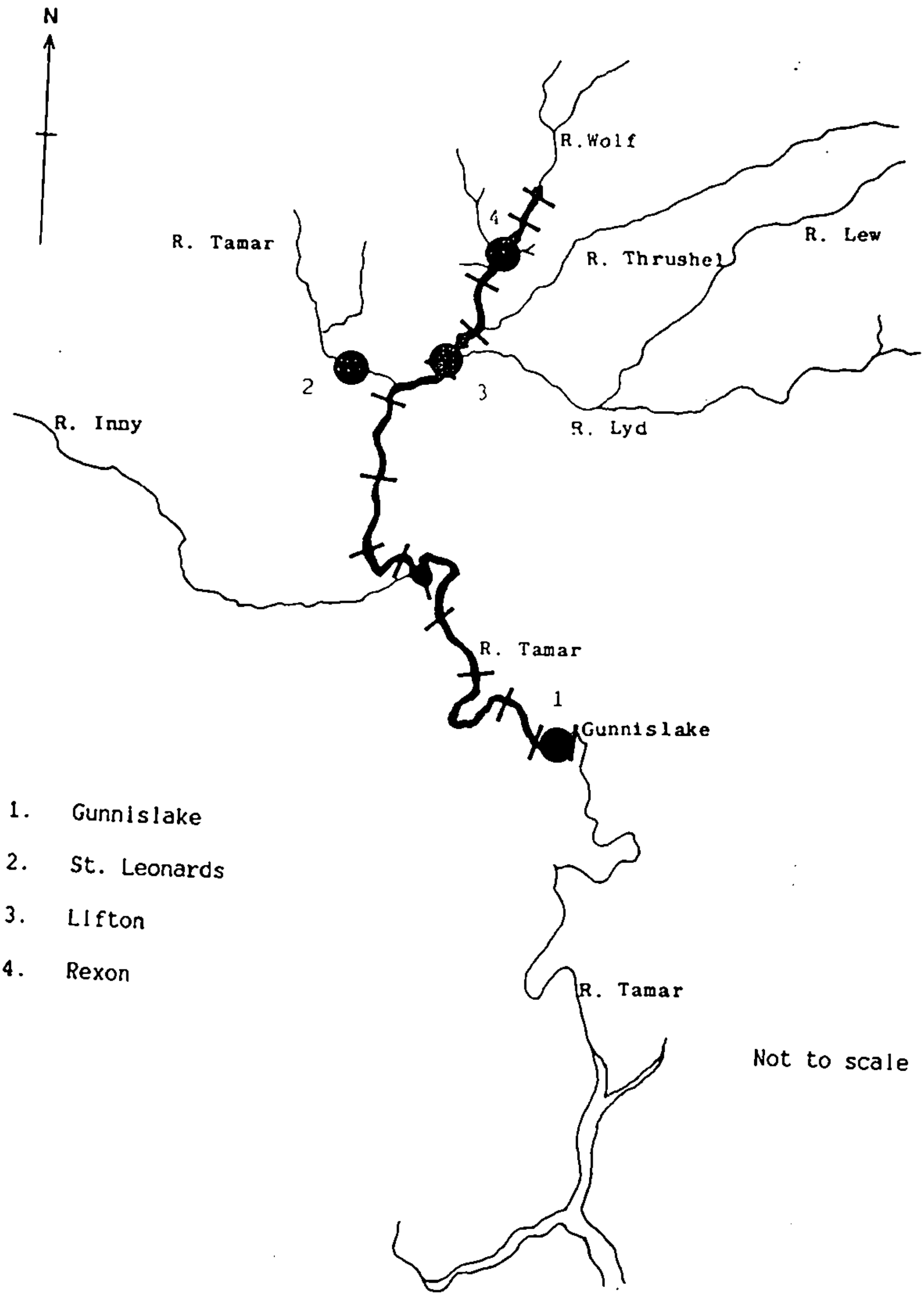


Figure 2. Map to show continuously monitored sites

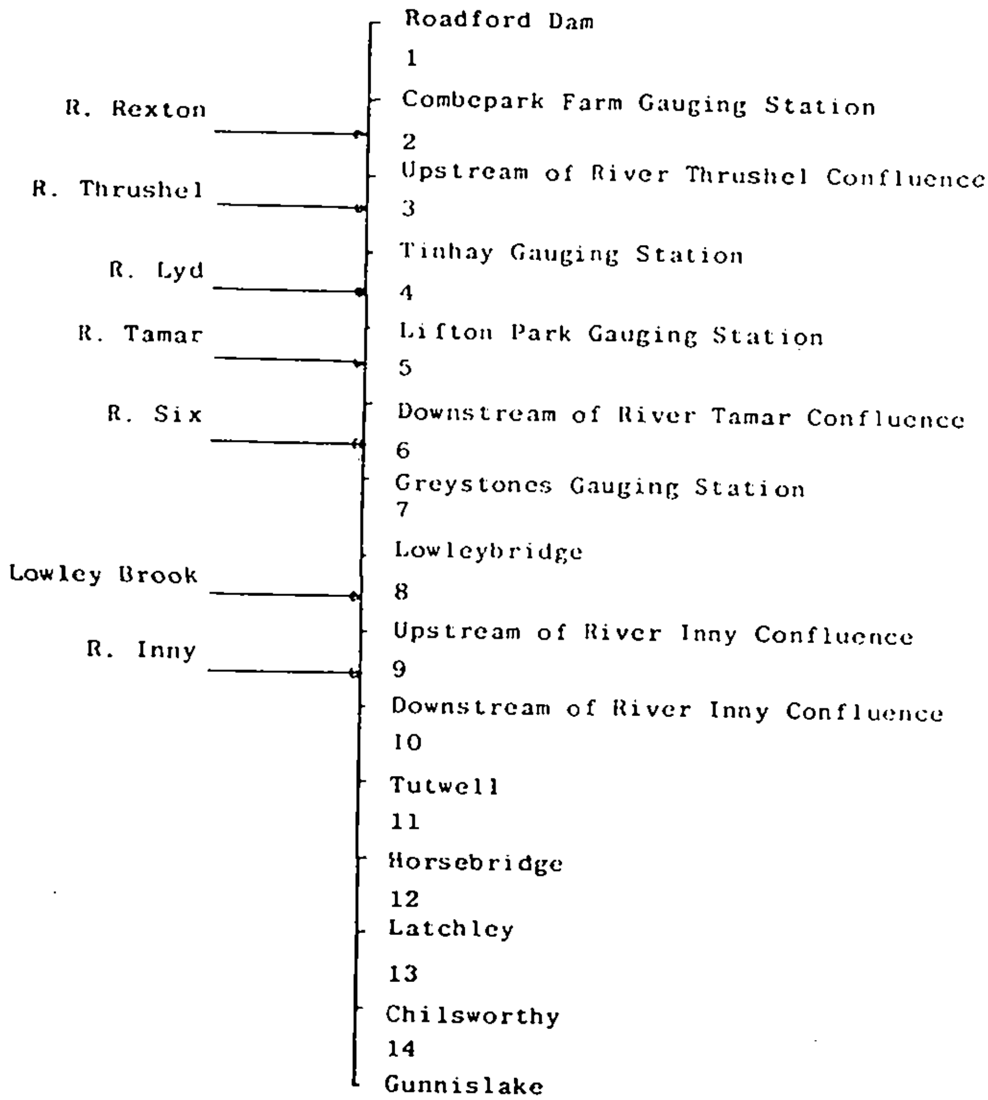


Figure 2a Diagram to show Reach Structure of River Tamar

FIGURE 3a

MAY 1987 CONTINUOUS DATA GUNNISLAKE

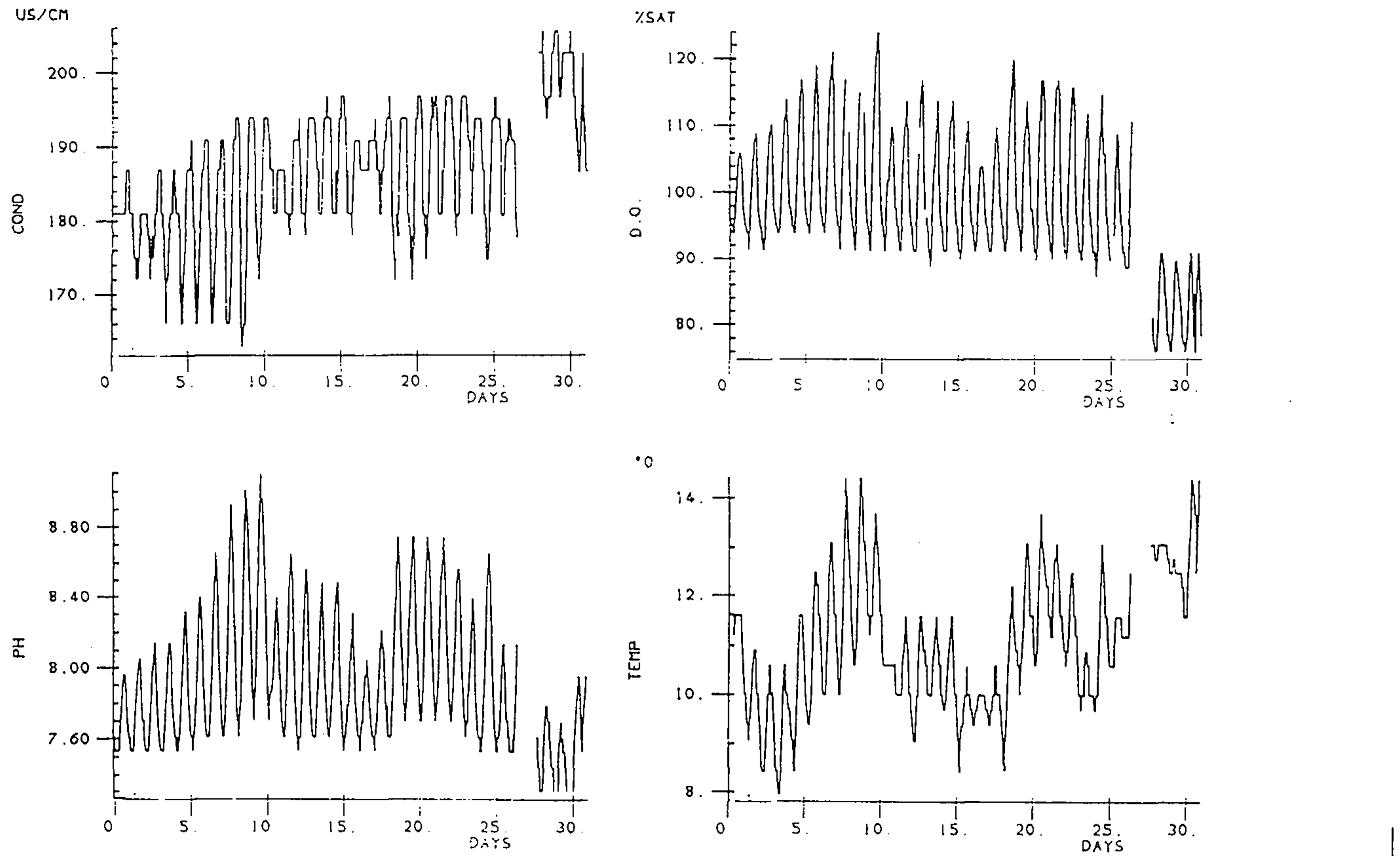
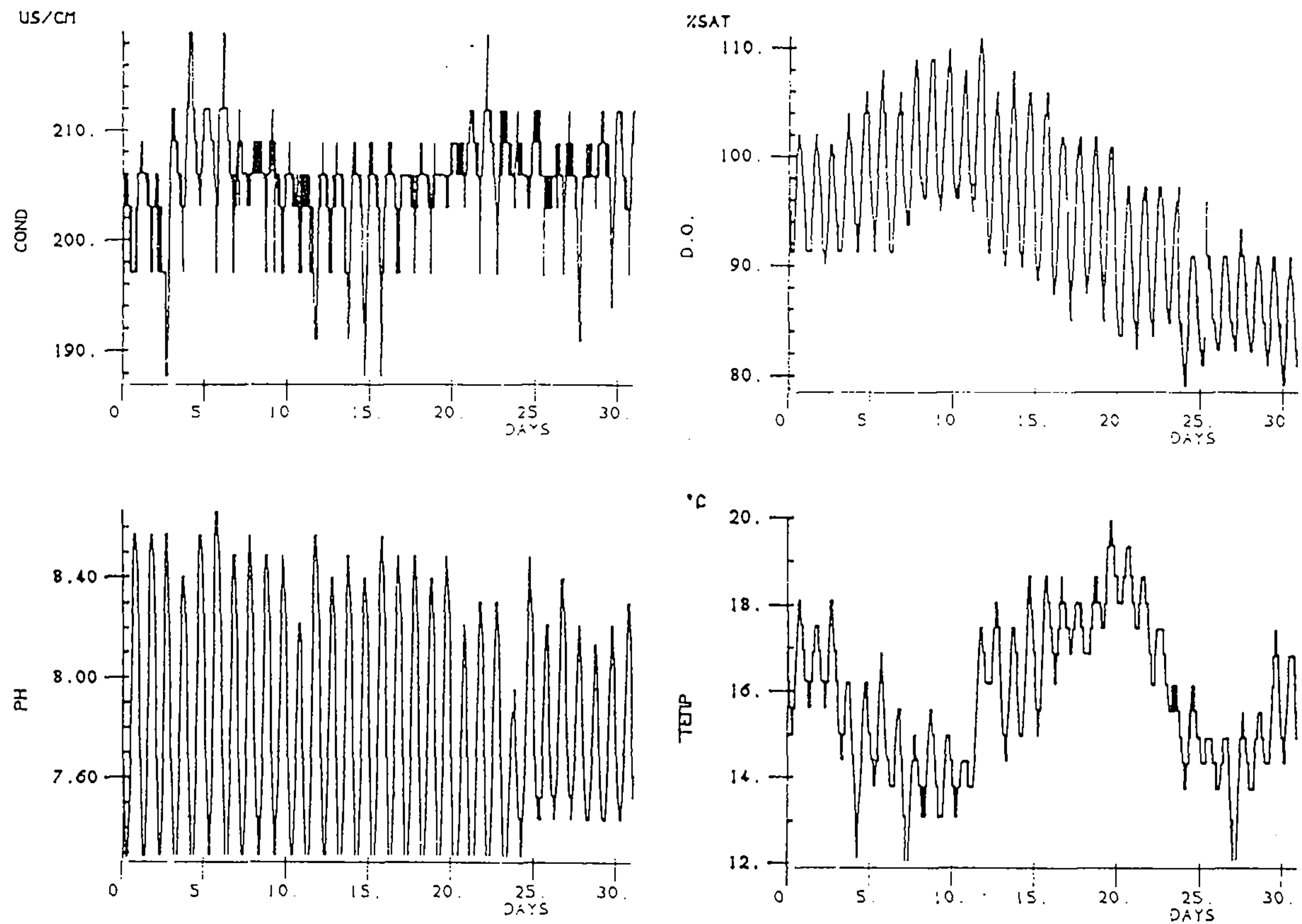


FIGURE 3b

AUGUST CONTINUOUS DATA ST.LEONARDS 1987



GUNNISLAKE CHLOROPHYLL A DATA 1987

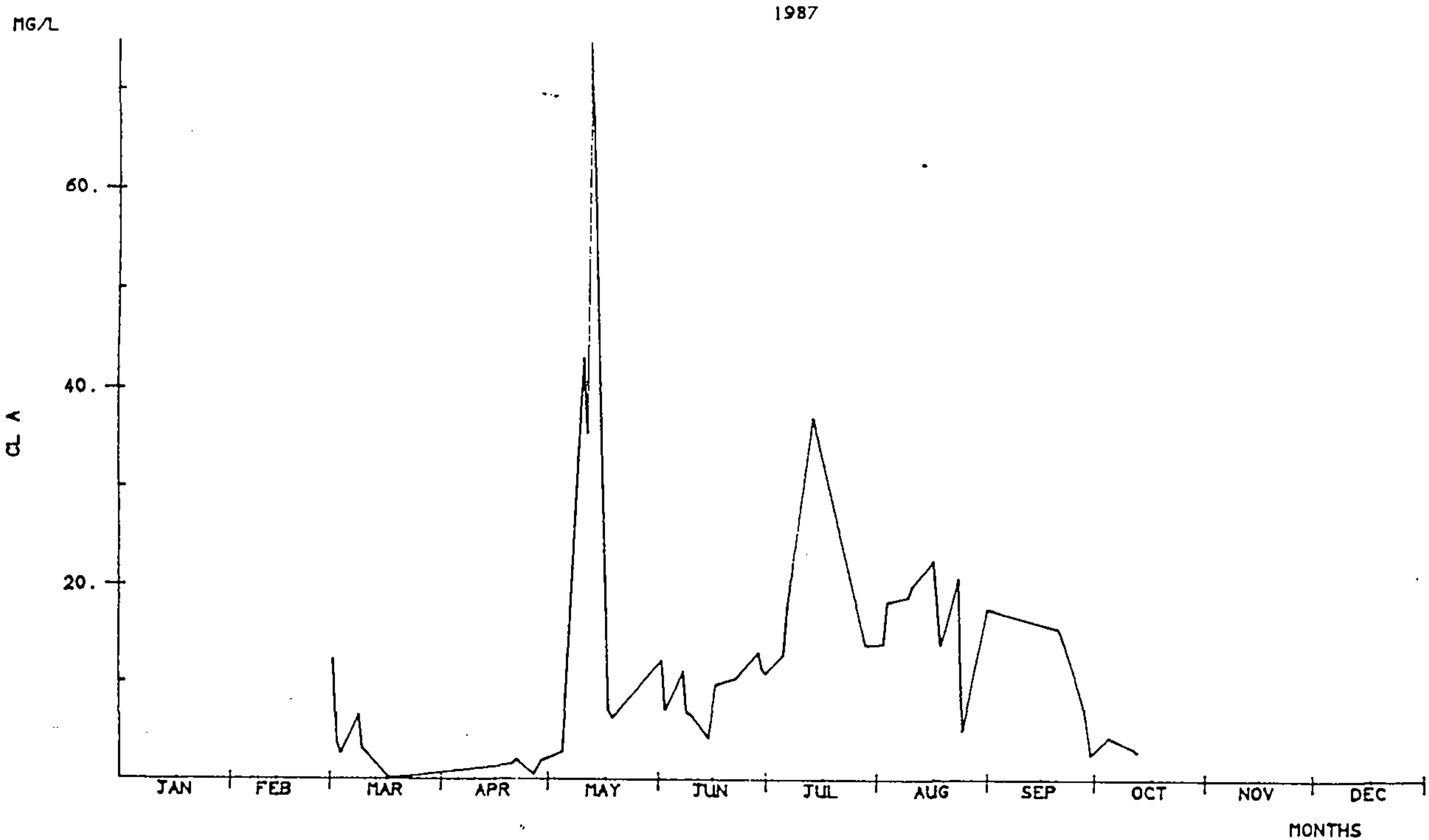


FIGURE 4

GUNNISLAKE DISSOLVED OXYGEN MAY 1987.

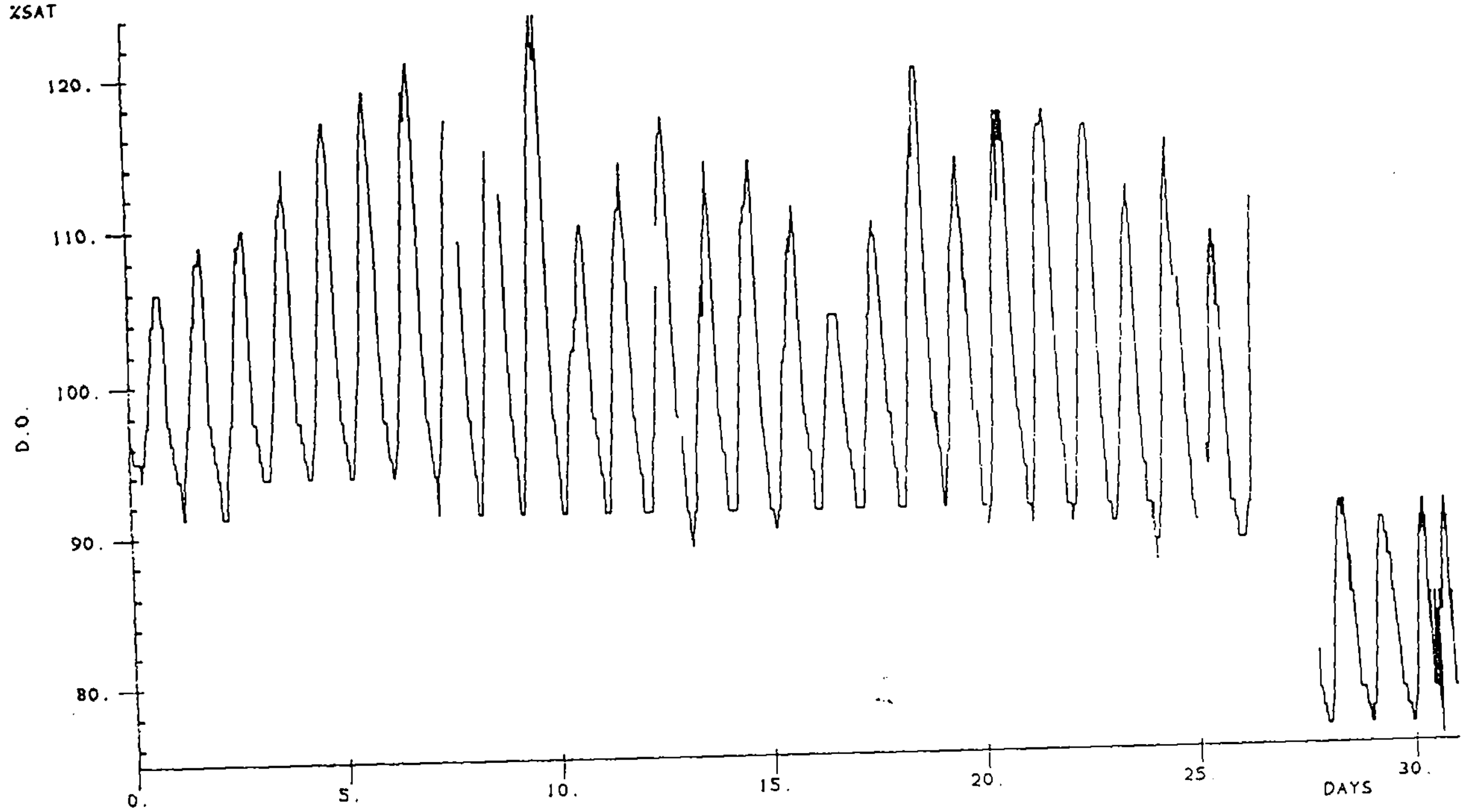


FIGURE 5a

GUNNISLAKE FLOWS MAY 1987

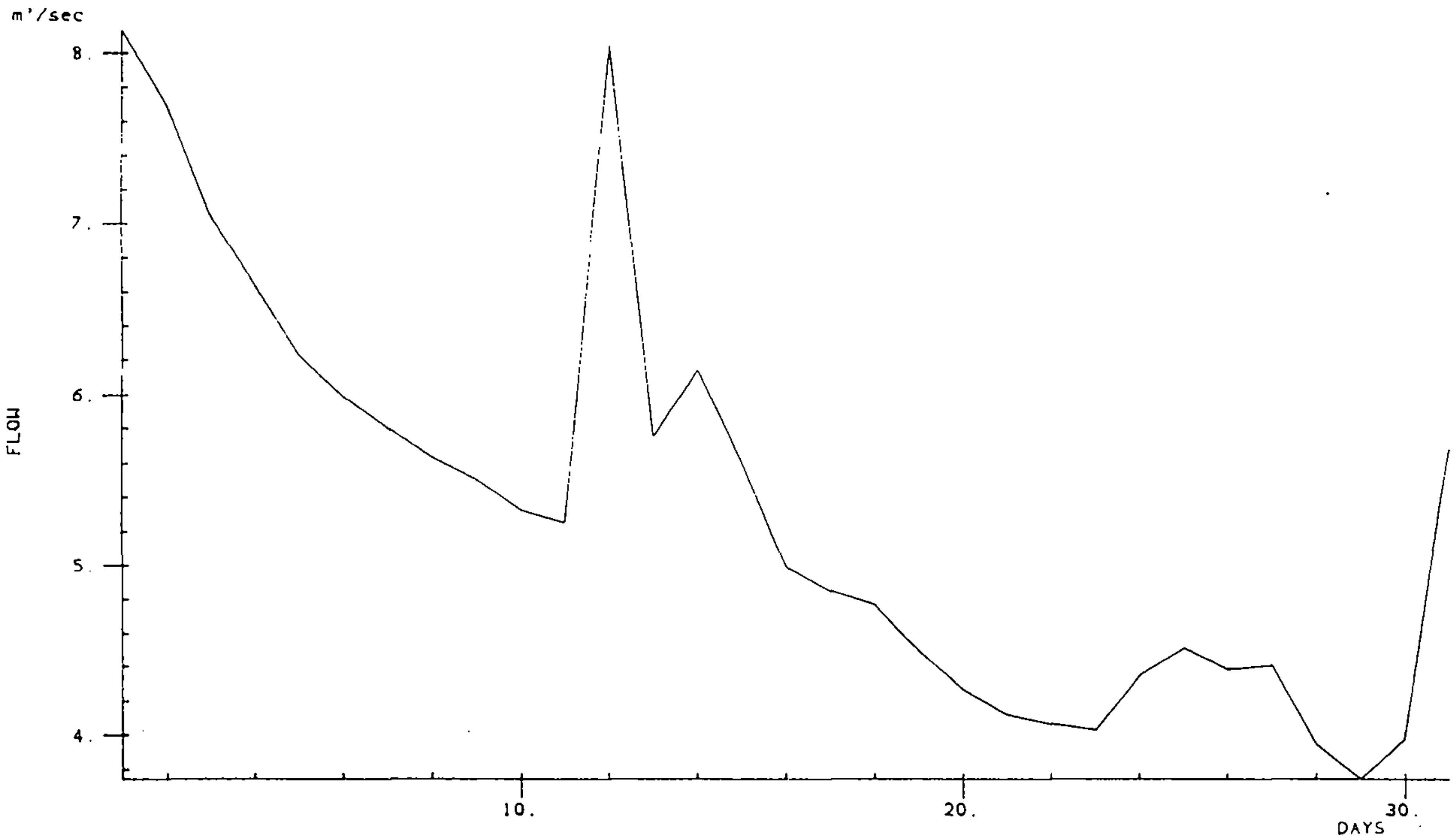


Figure 5b

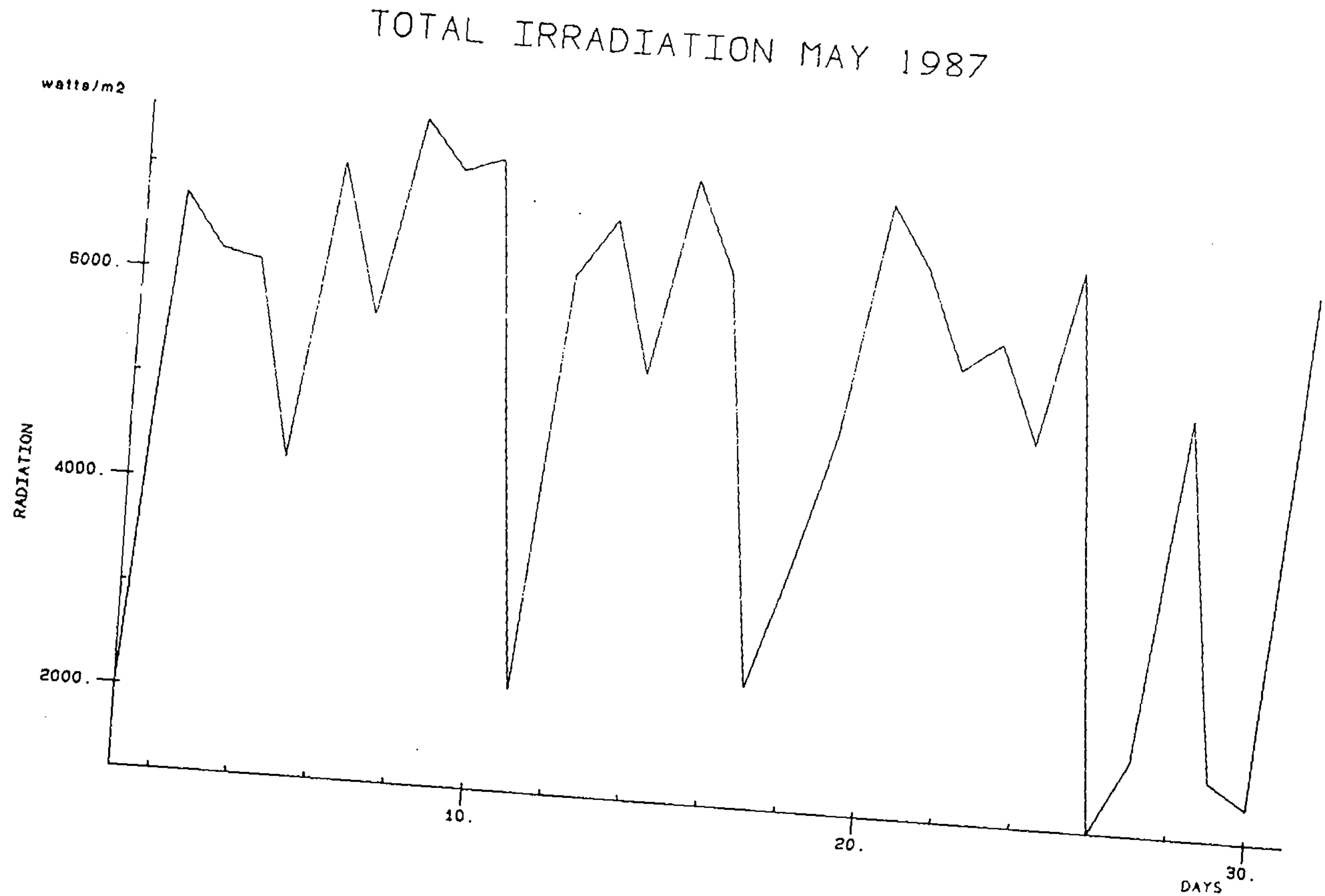
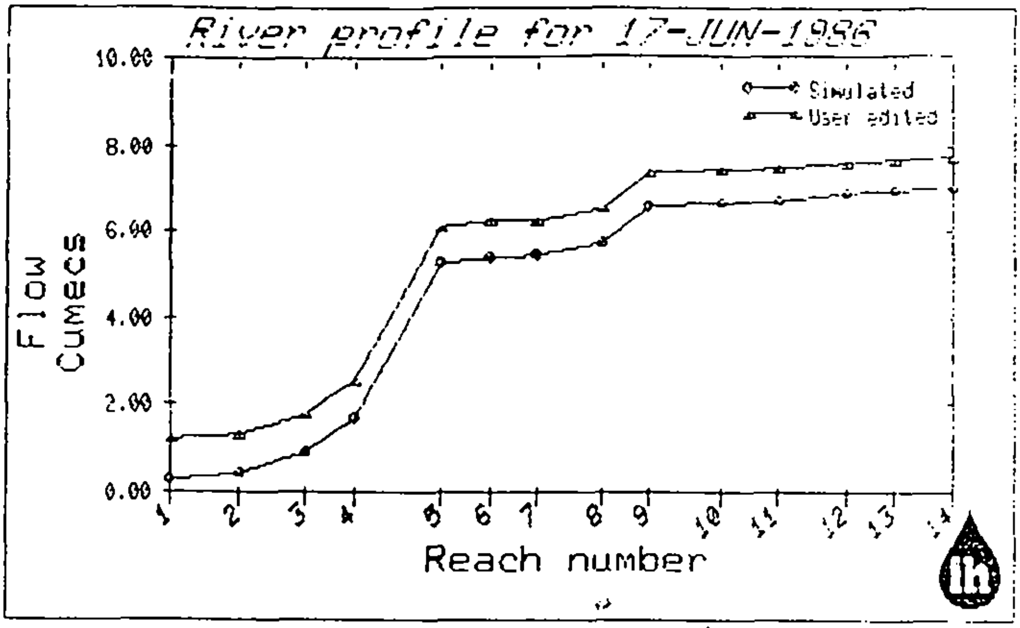

TOTAL IRRADIATION MAY 1987
watts/m2
RADIATION
6000.
4000.
2000.
10.
20.
30.
DAYS

Figure 5c



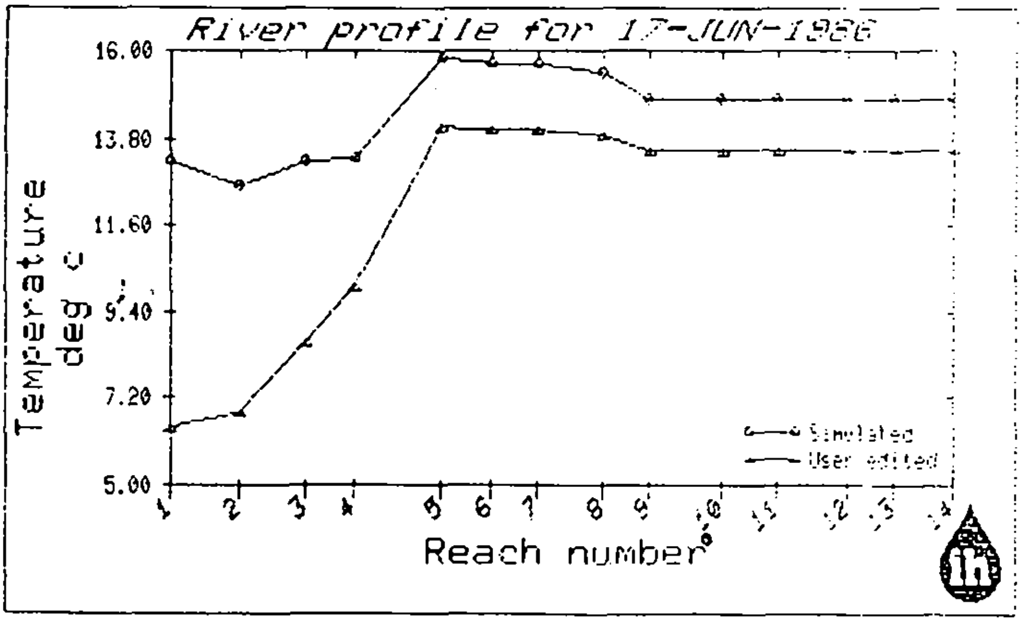
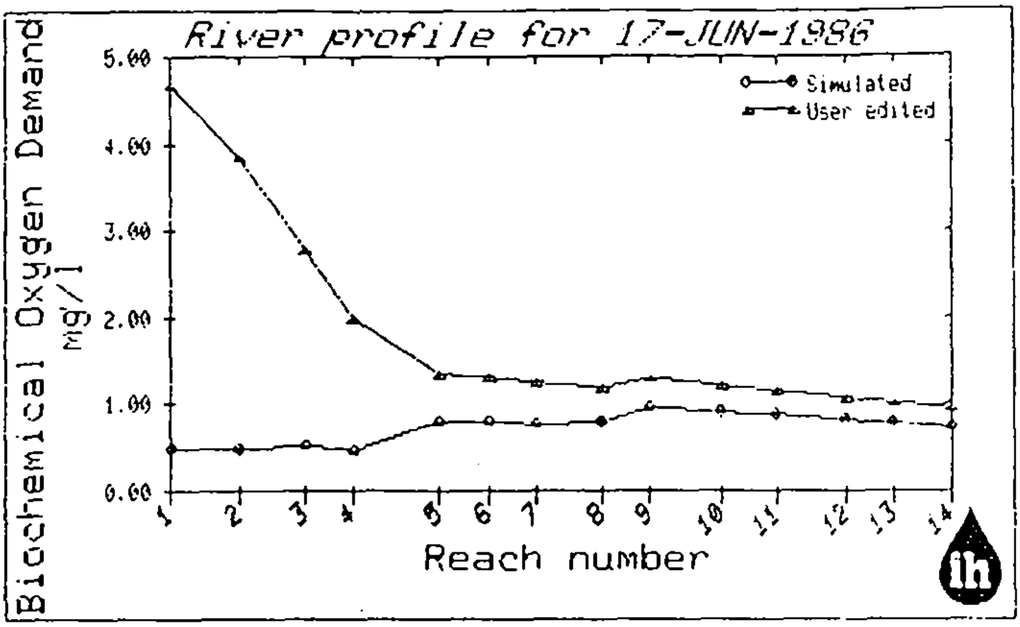


Figure 6a Simulated flow and temperature with user edited plot showing the effect of a reservoir release of 1 cumec and temperature of 5°C.



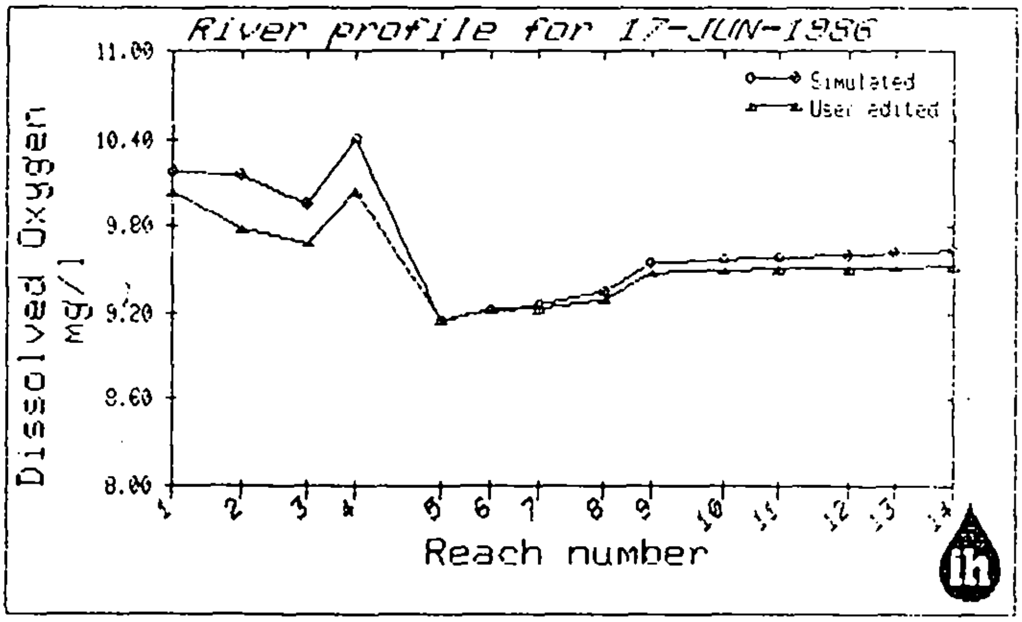
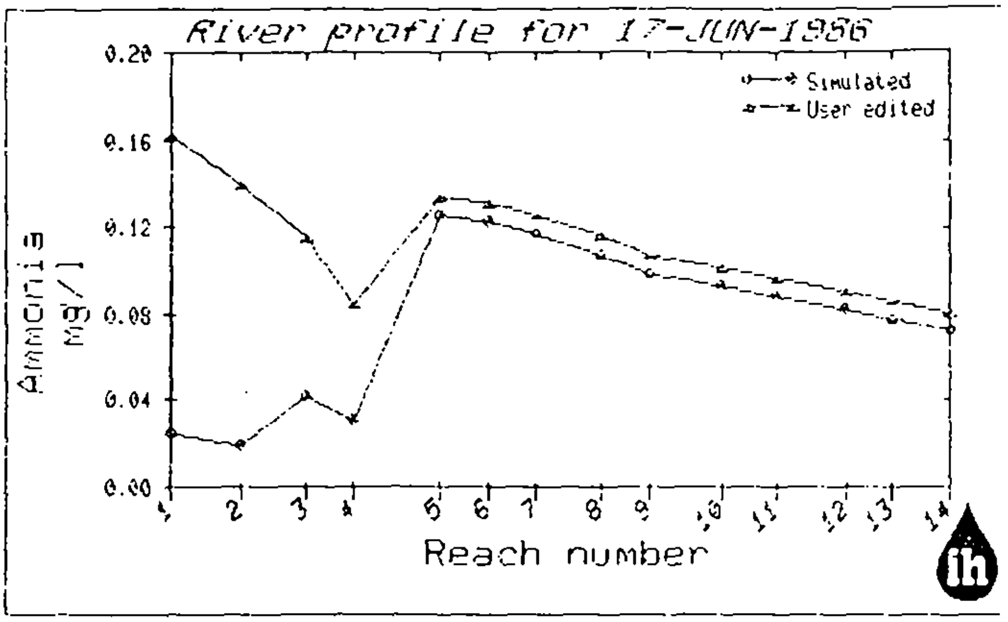


Figure 6b Simulated BOD and DO with user edited plot showing the effect of a reservoir release of 1 cumec with a BOD of 6 mg/L.



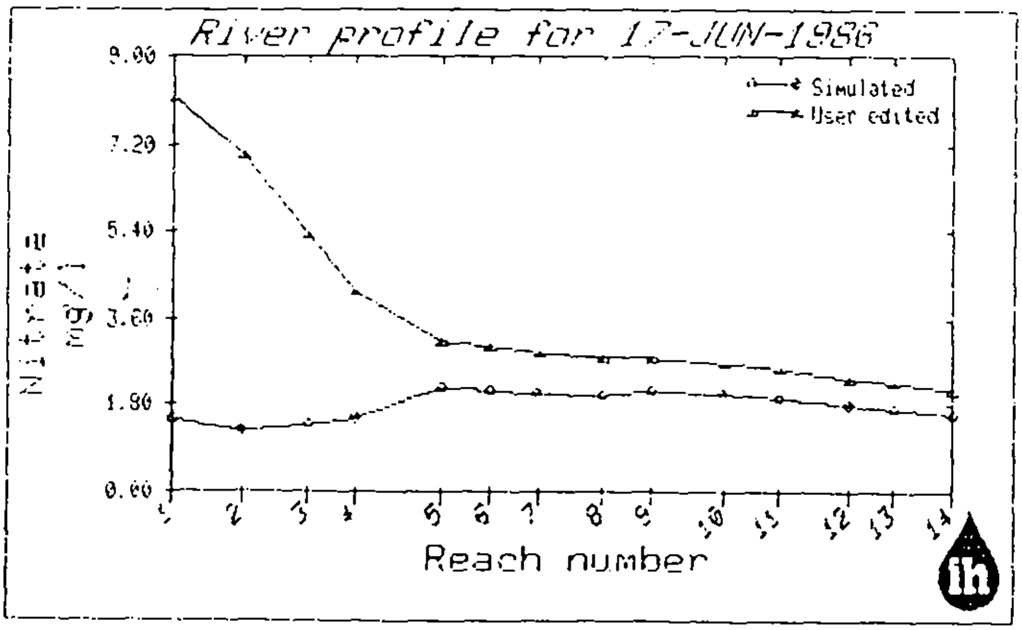
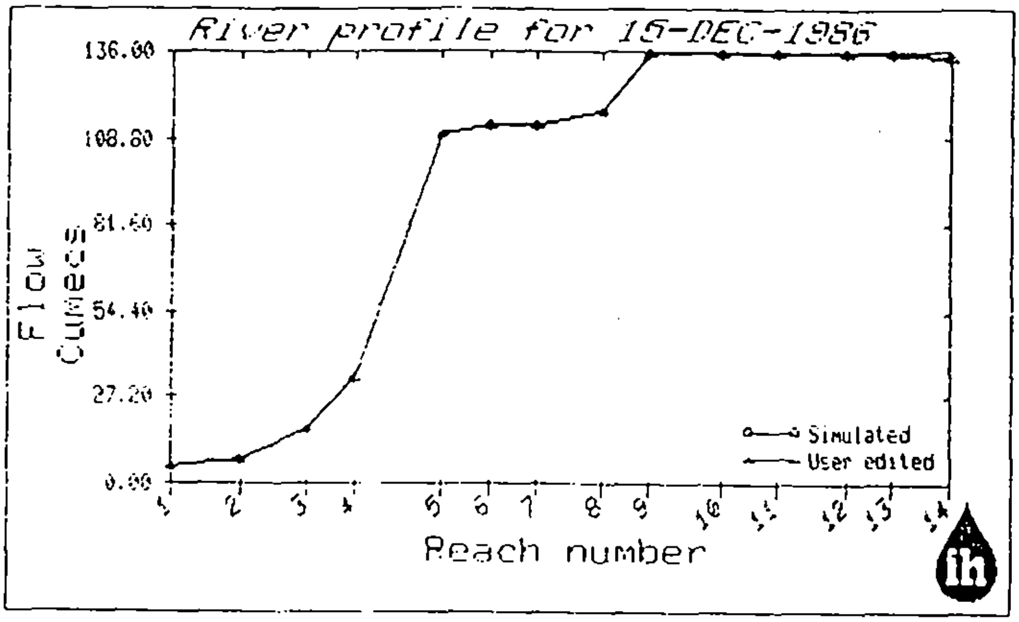


Figure 6c Simulated ammonia and nitrate with user edited plot showing the effect of a reservoir release of 1 cumec with nitrate of 10 mg/L and ammonia of 0.2 mg/L.



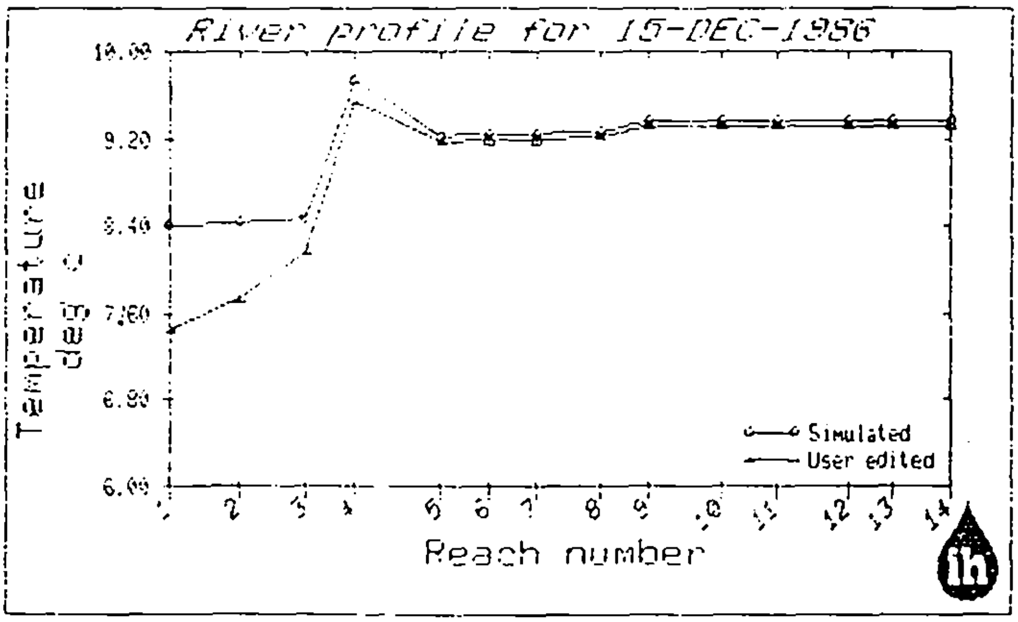
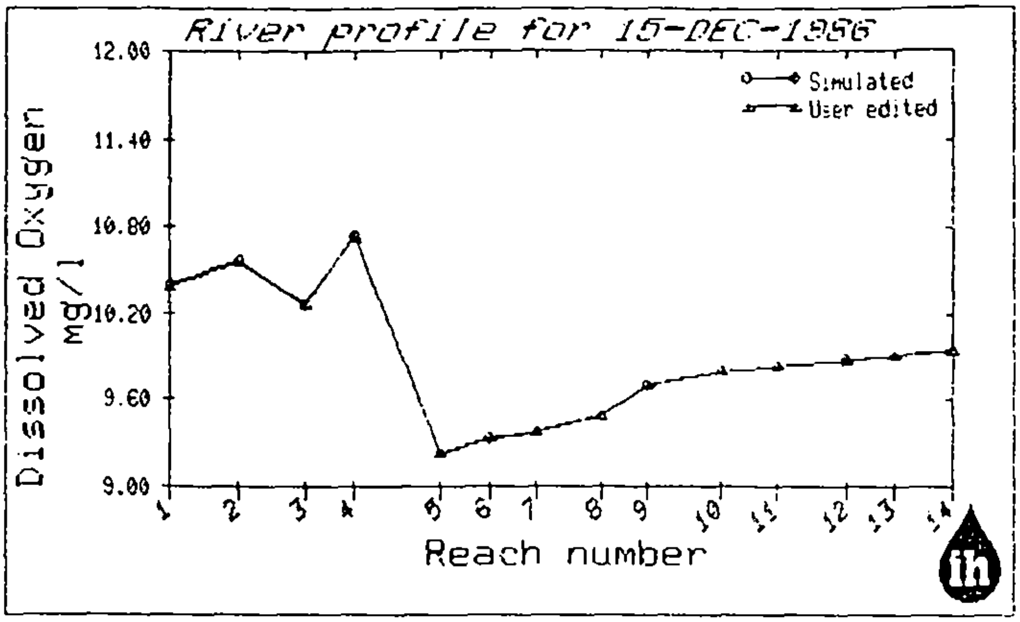


Figure 7a Simulated flow and temperature with user edited plot showing the effect of a reservoir release of 1 cumec and temperature of 3°C



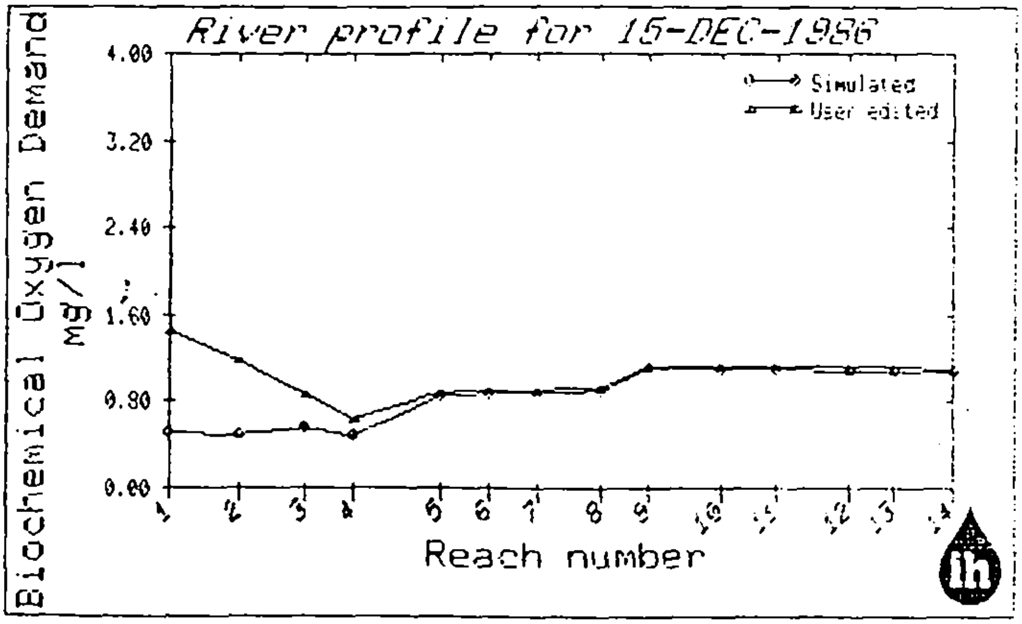
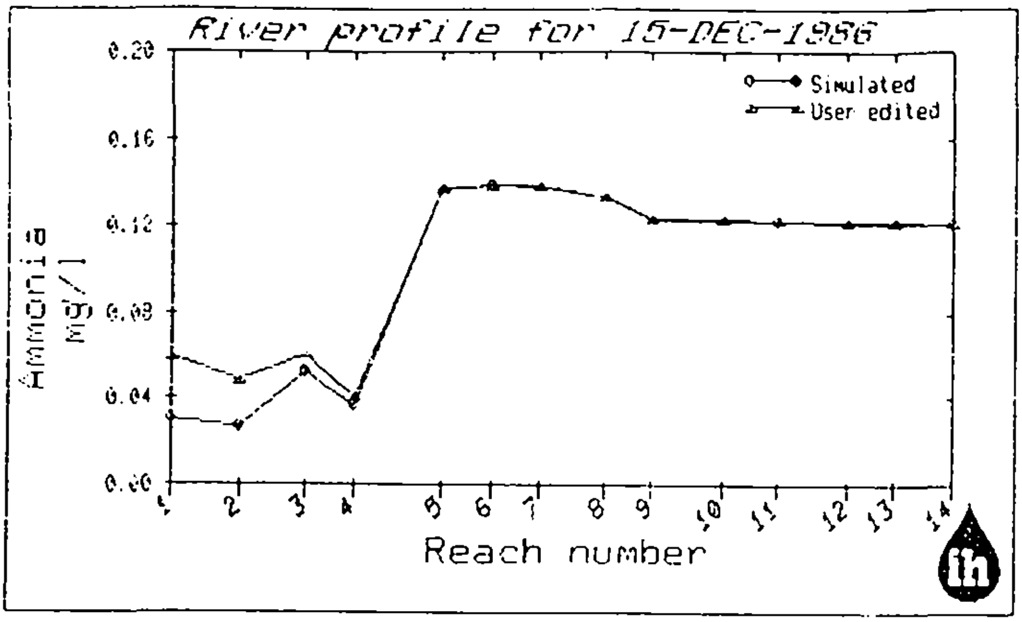


Figure 7b Simulated BOD and DO with user edited plot to show the effect of a reservoir release of 1 cumec with a BOD of 6 mg/L.



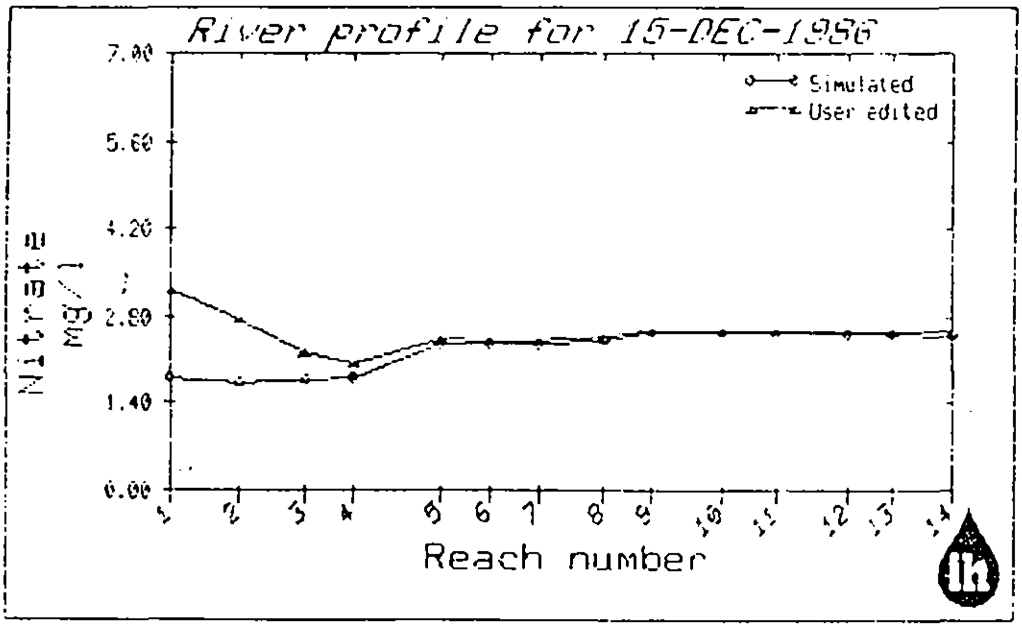


Figure 7c Simulated nitrate and ammonia with user edited plot showing the effect of a reservoir release of 1 cumec with nitrate of 10 mg/L and ammonia of 0.2 mg/L.

Appendix 1

Monthly plots of continuously monitored data from:-

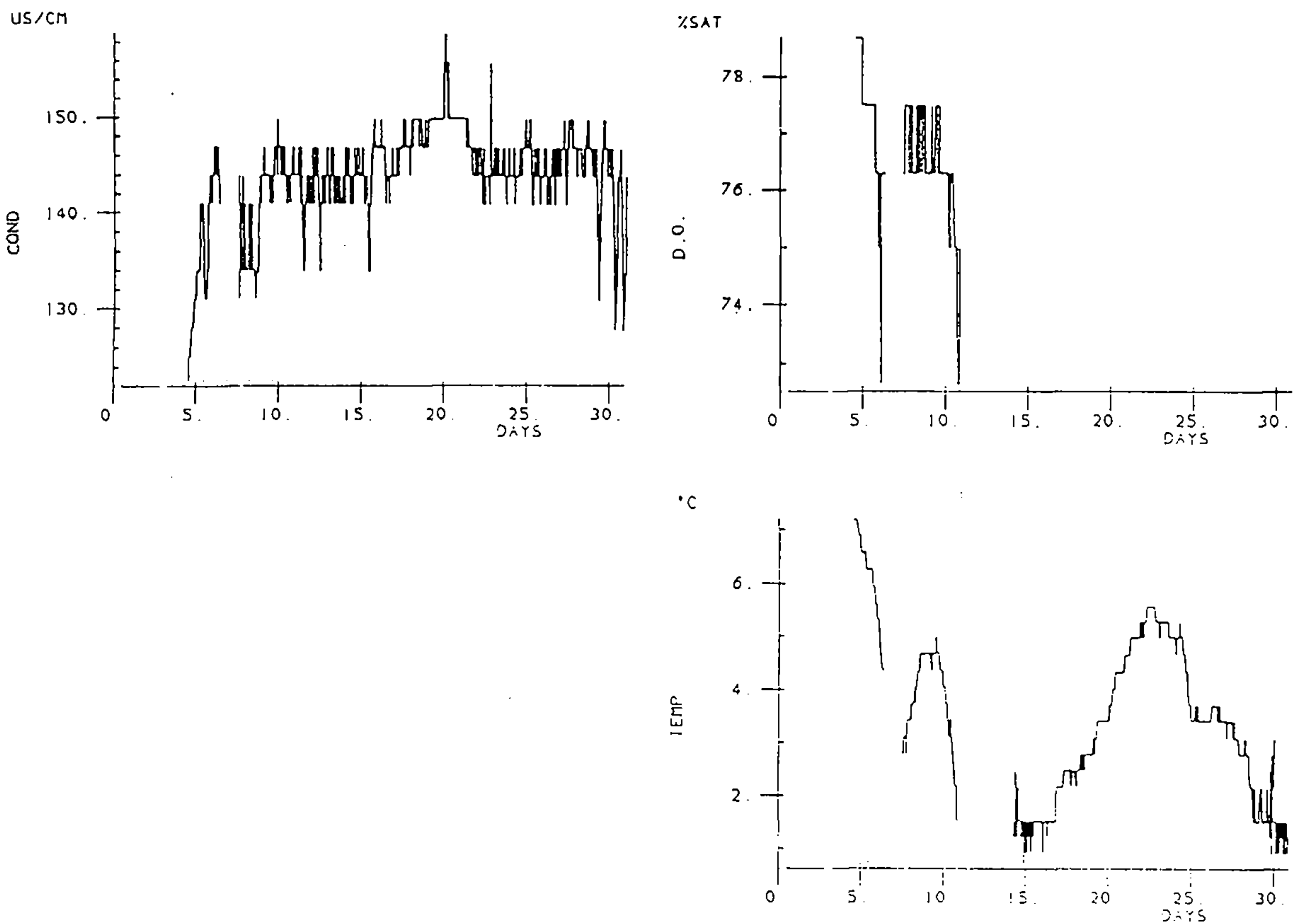
Gunnislake

St Leonards

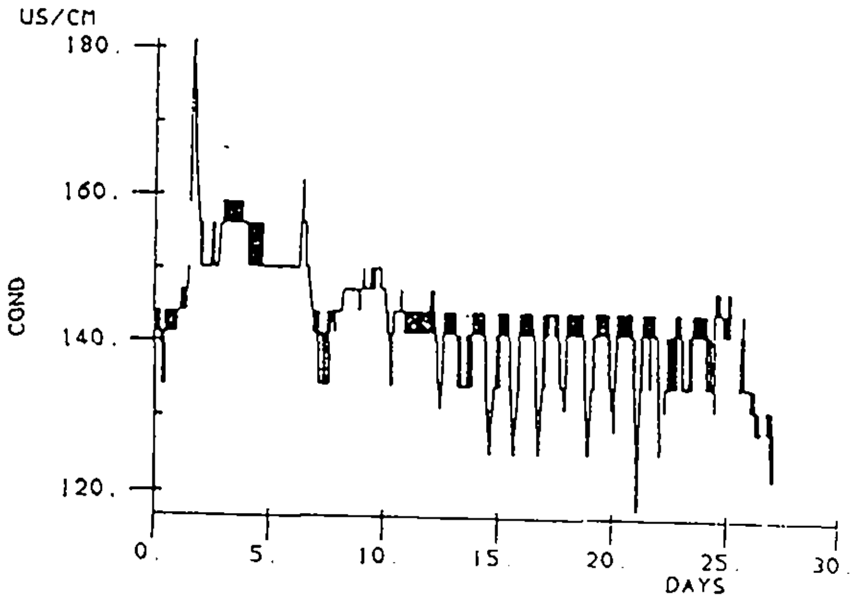
Lifton

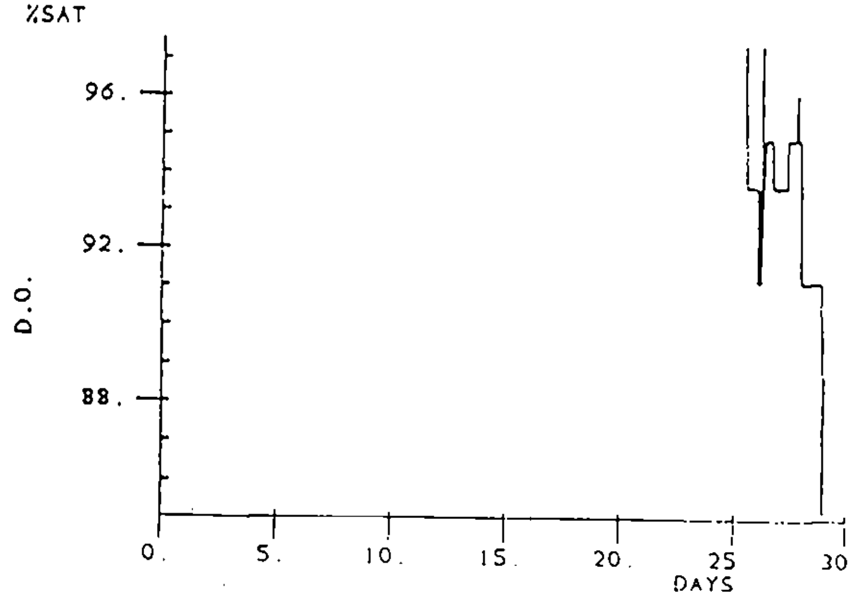
Rexon

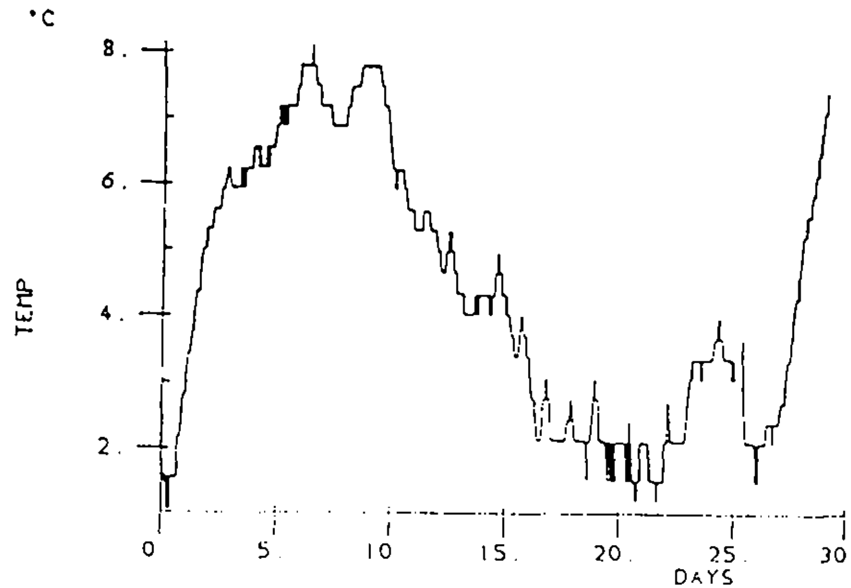
JANUARY CONTINUOUS DATA GUNNISLAKE 1987



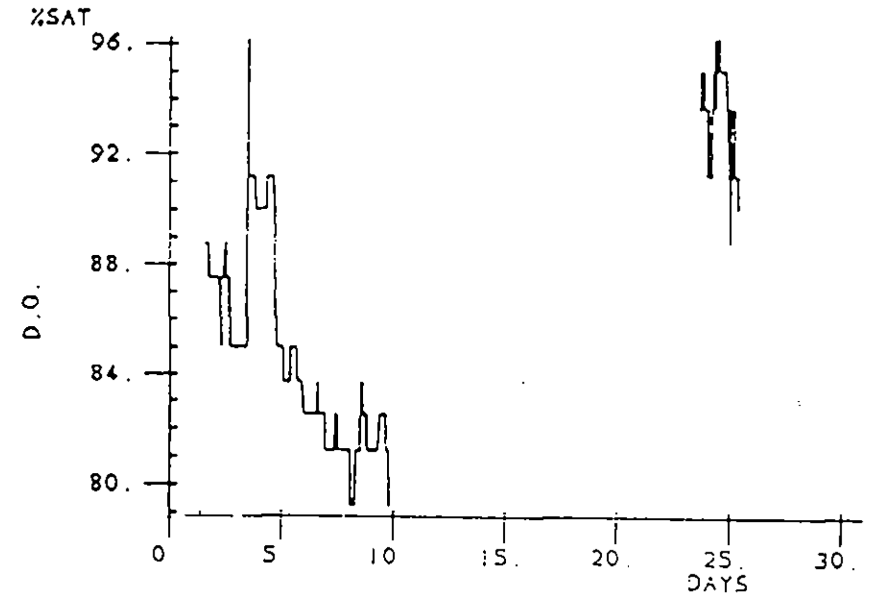
FEBRUARY 1987 GUNNISLAKE CONTINUOUS DATA

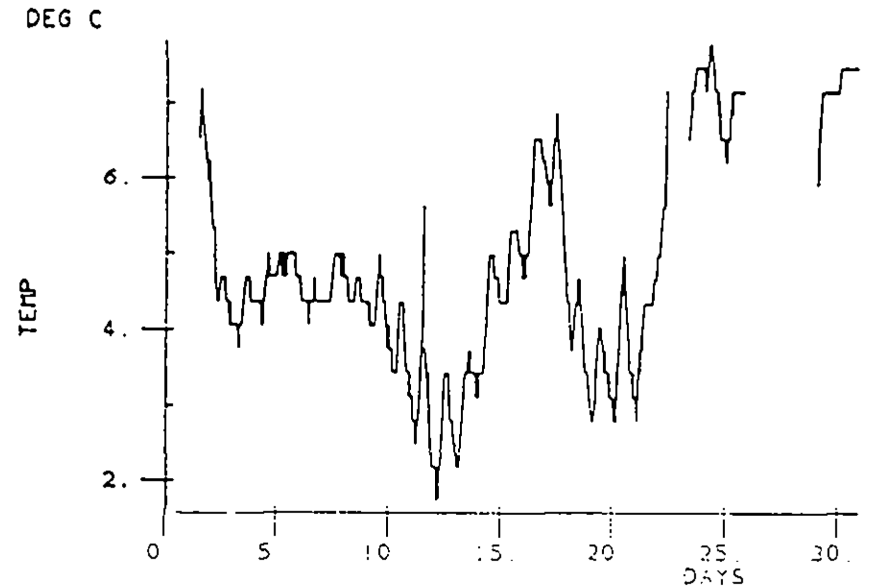




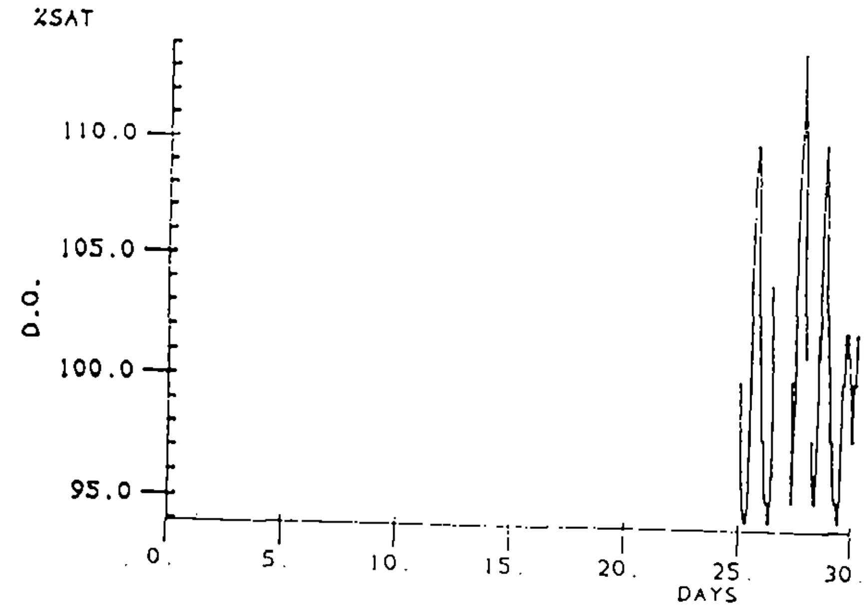


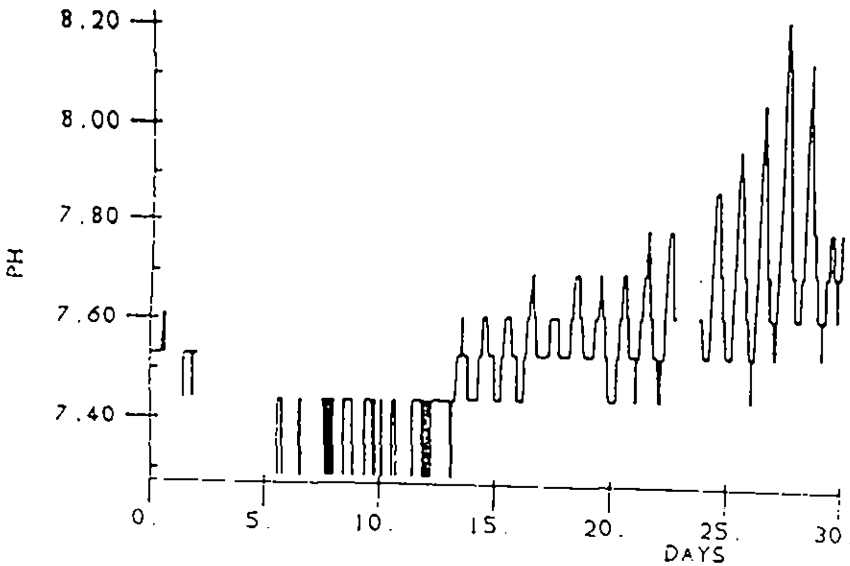
MARCH 1987 GUNNISLAKE CONTINUOUS DATA

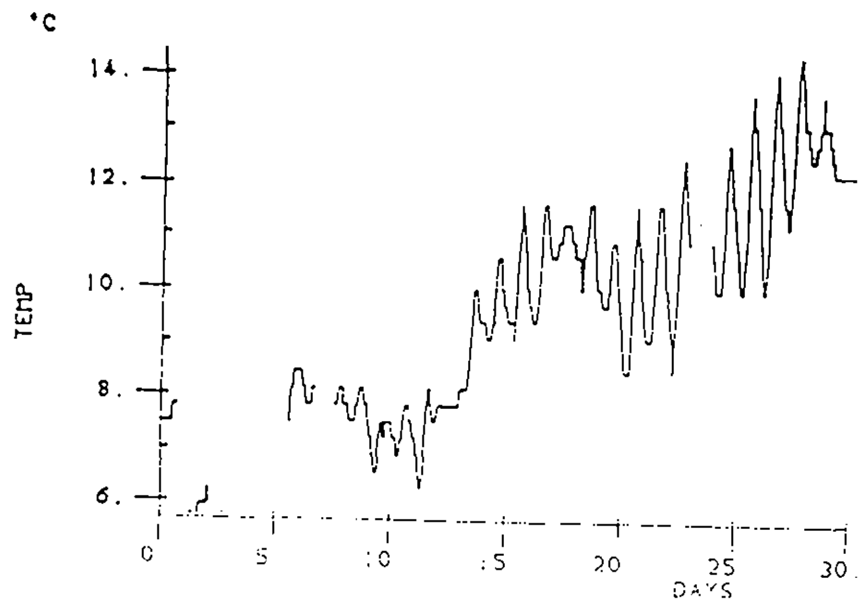




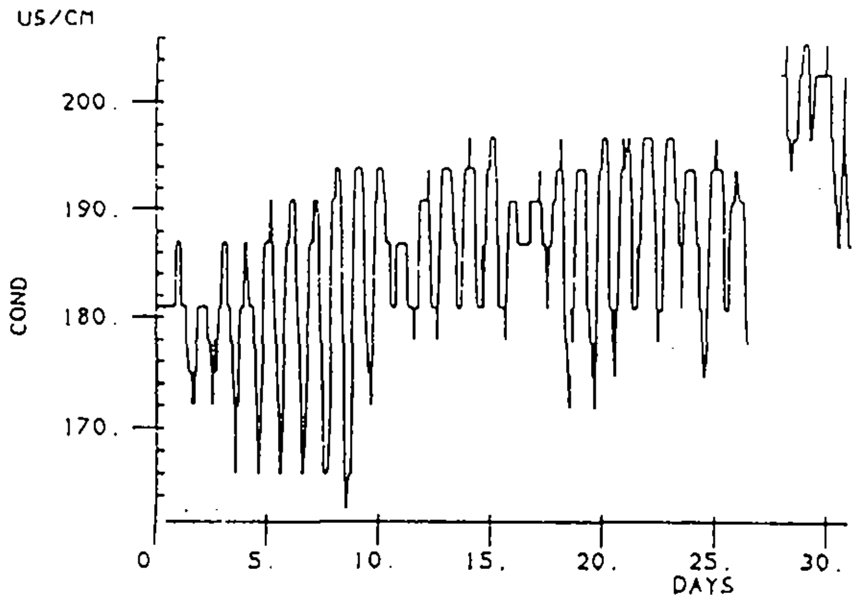
APRIL 1987 GUNNISLAKE CONTINUOUS DATA

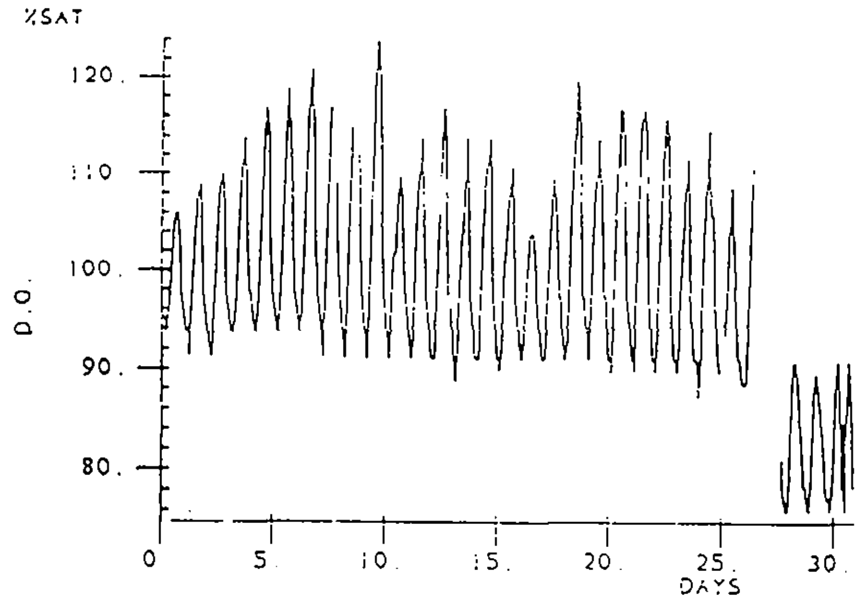


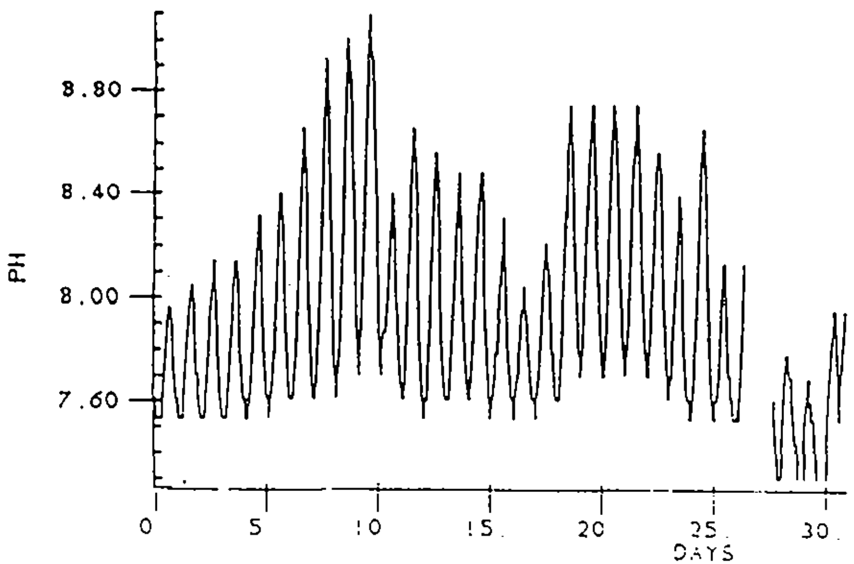


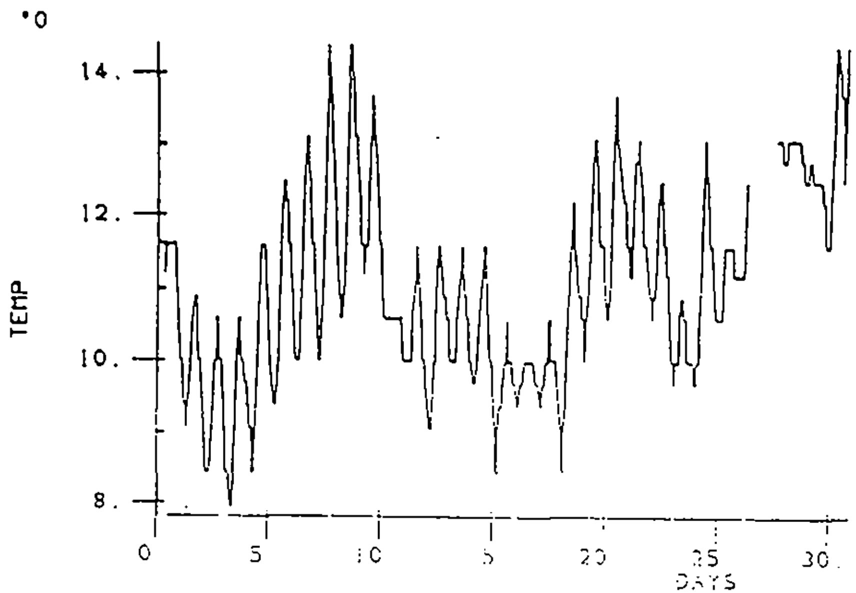


MAY 1987 CONTINUOUS DATA GUNNISLAKE

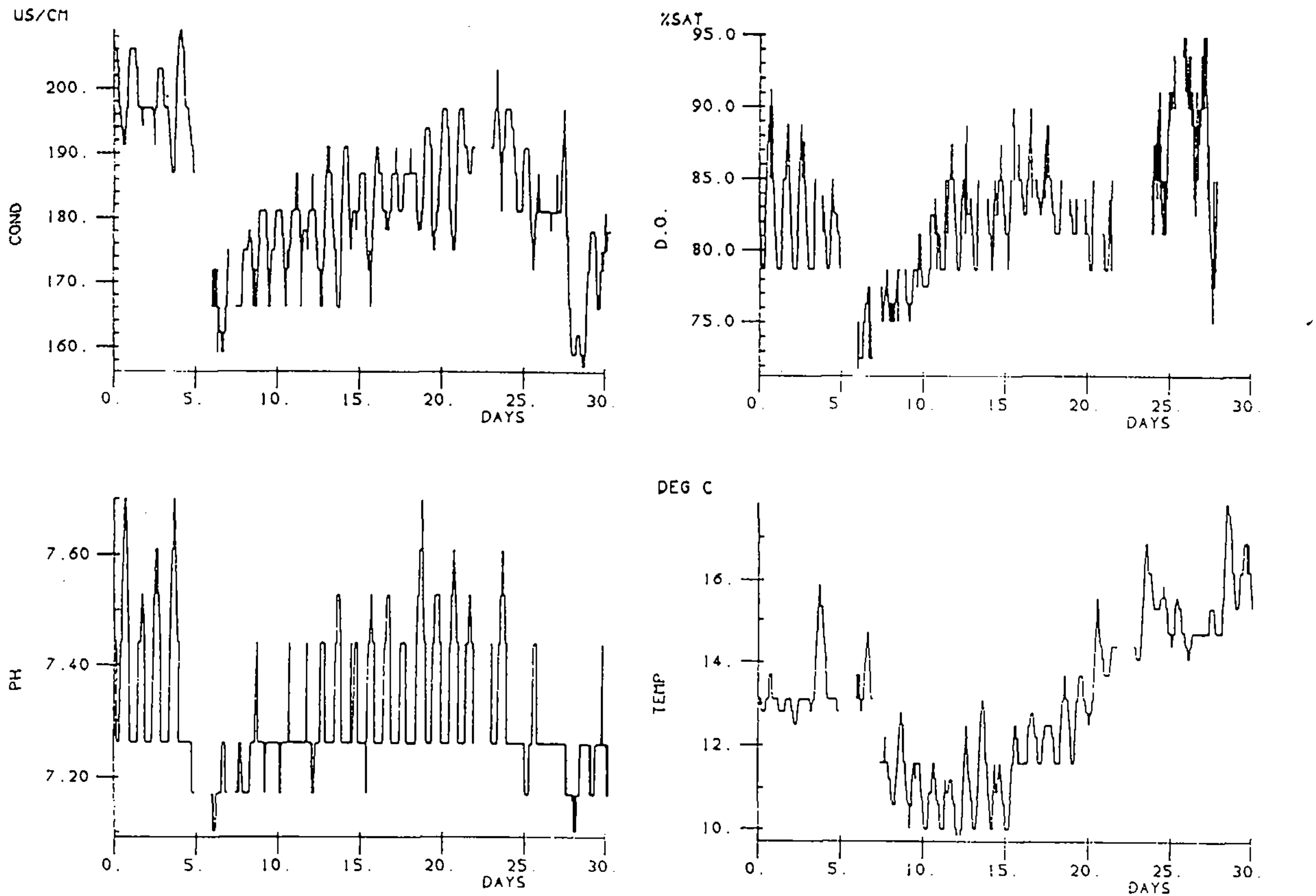




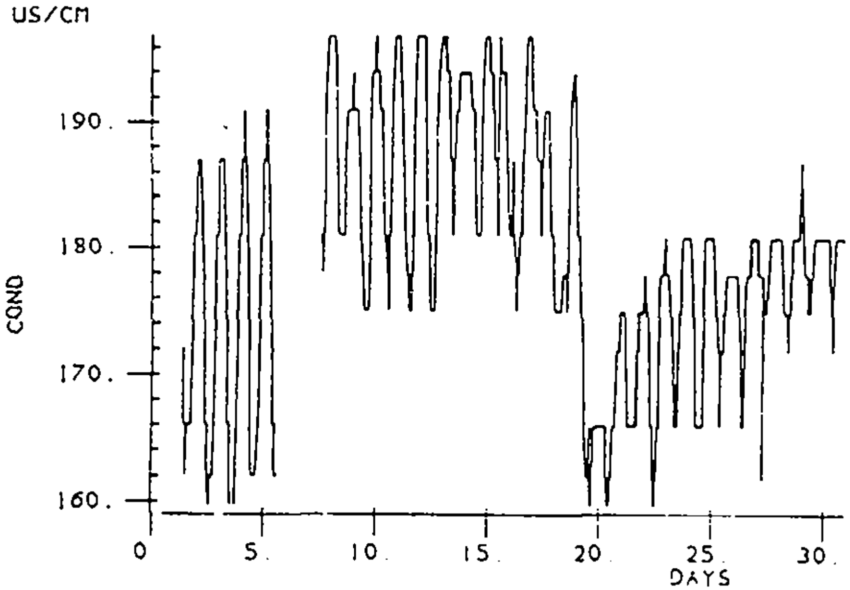


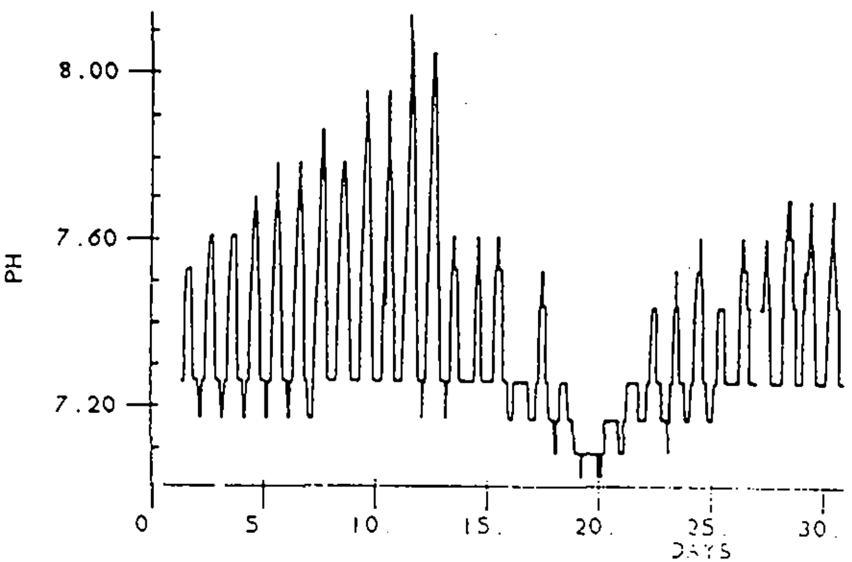


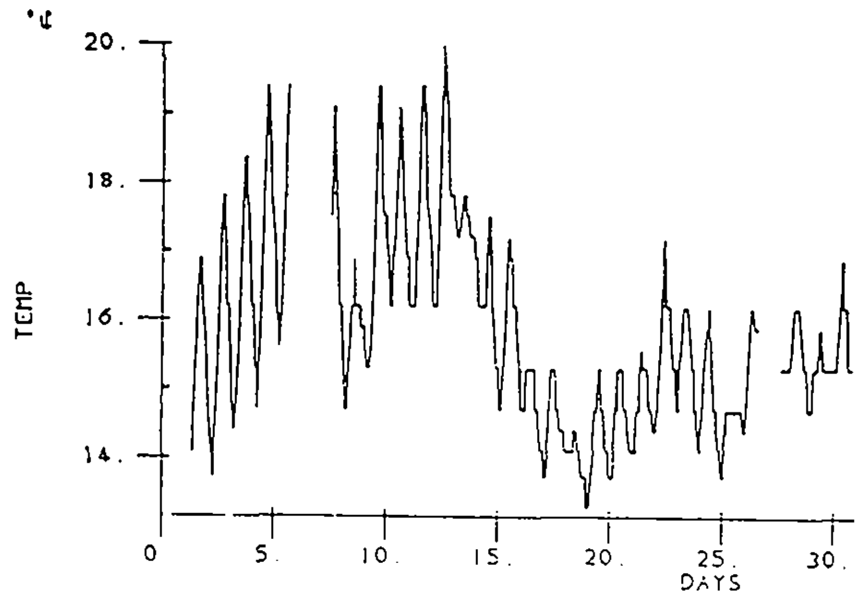
JUNE 1987 GUNNISLAKE CONTINUOUS DATA



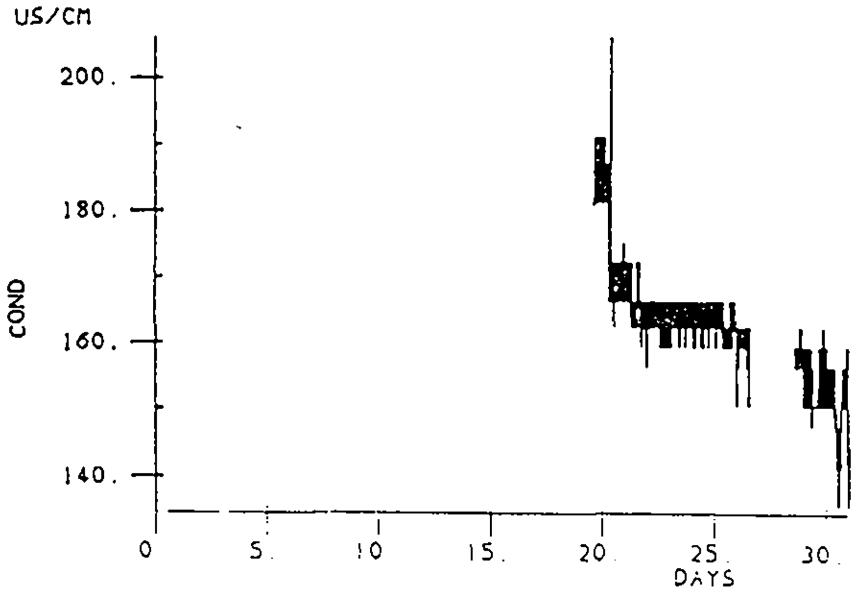
JULY 1987 CONTINUOUS DATA GUNNISLAKE

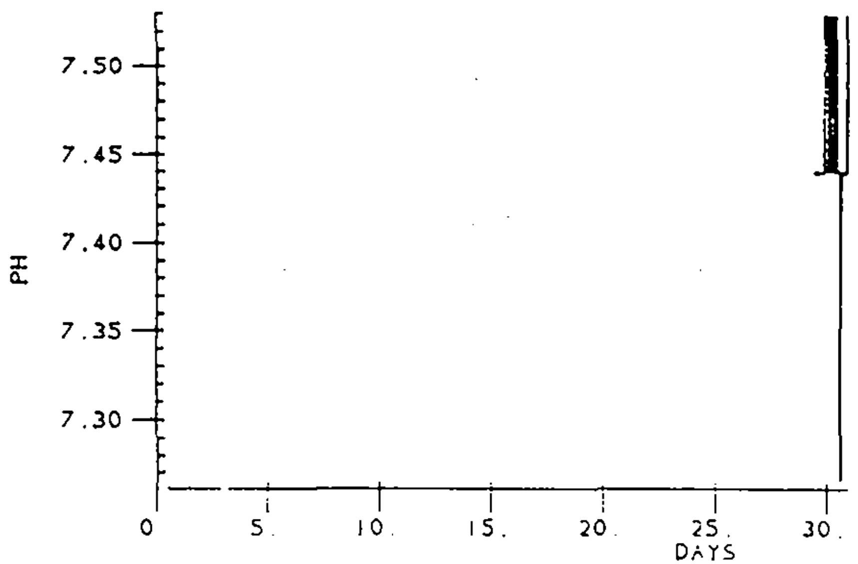


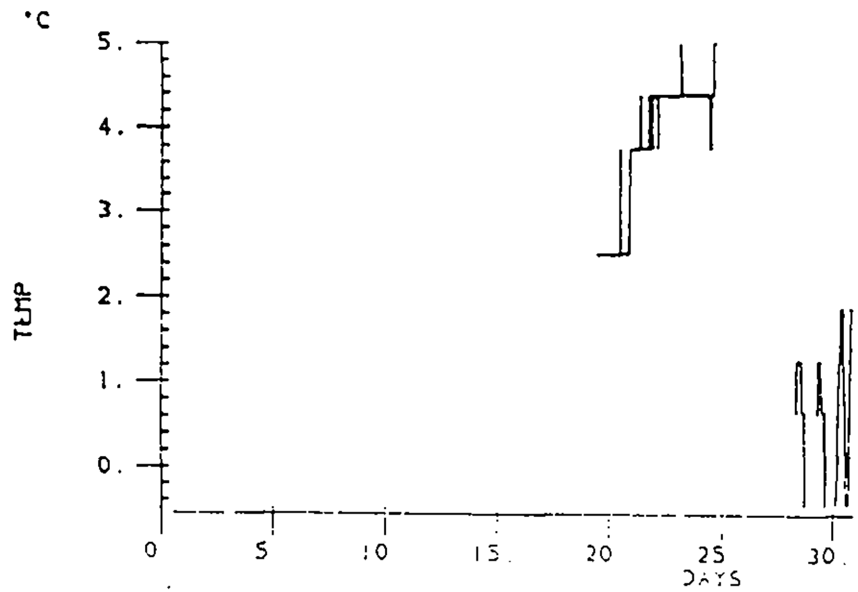




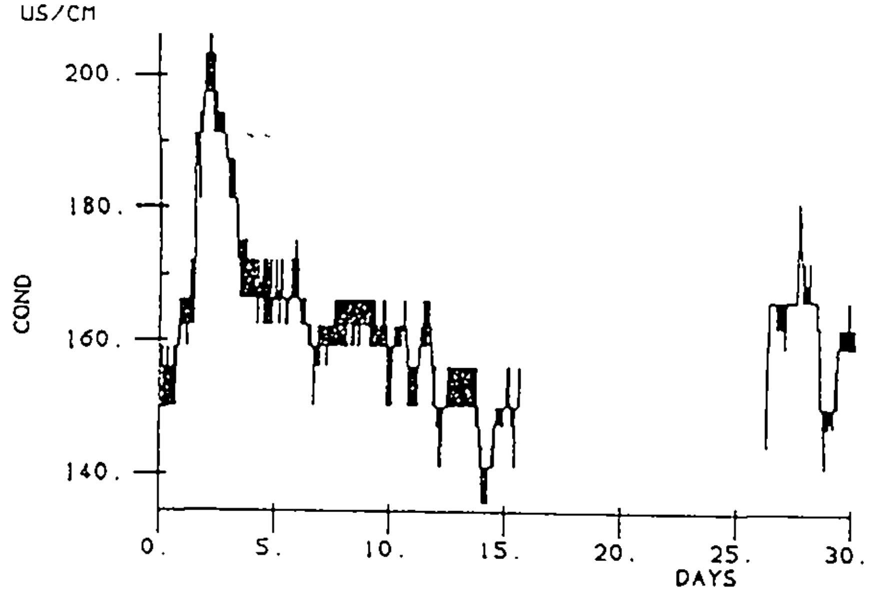
JANUARY 1987 CONTINUOUS DATA ST.LEONARDS

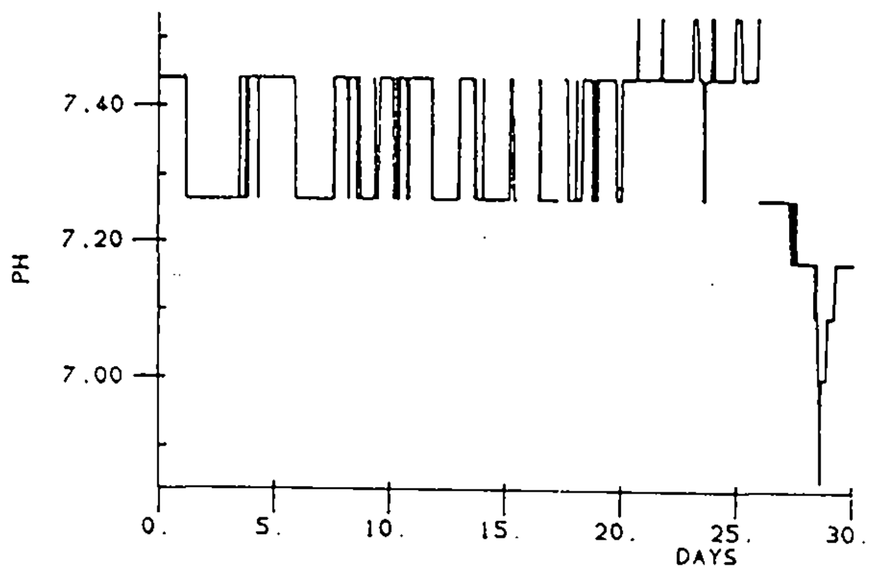


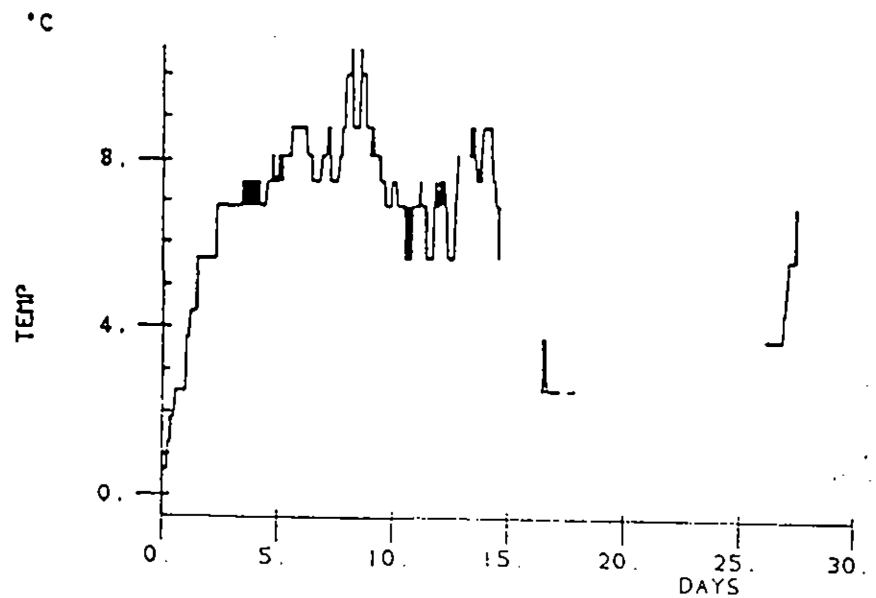




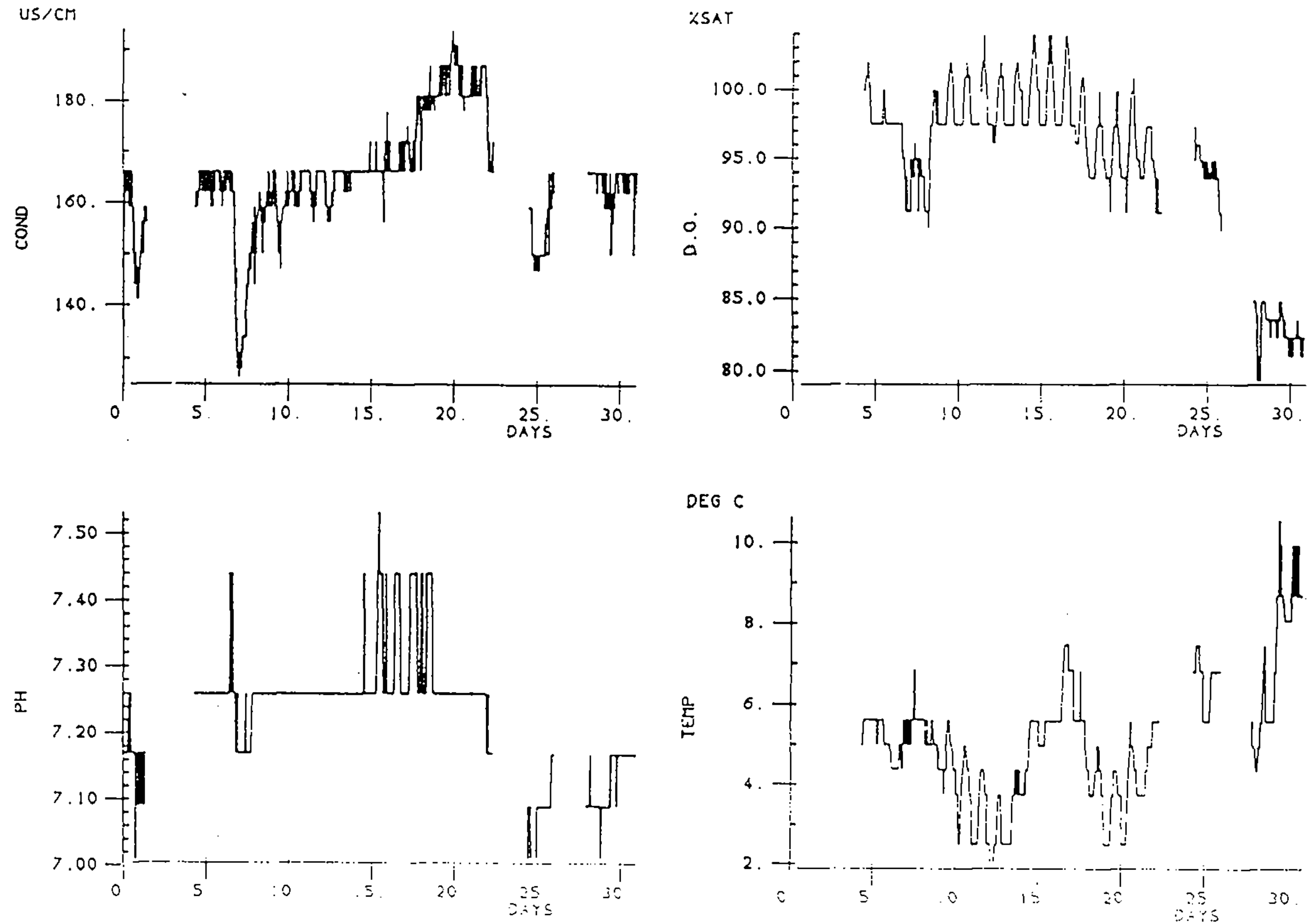
FEBRUARY 1987 ST.LEONARDS CONTINUOUS DATA



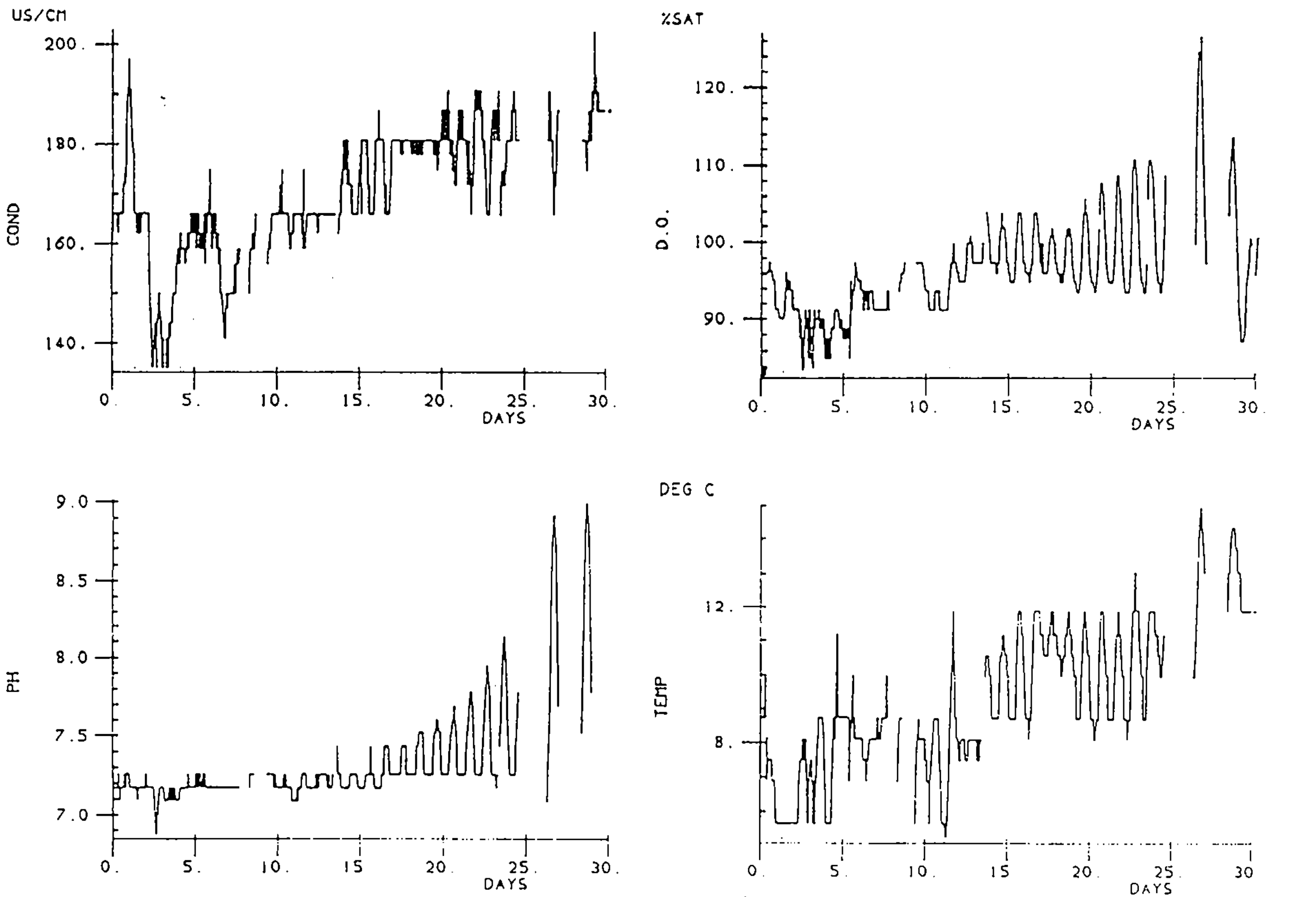




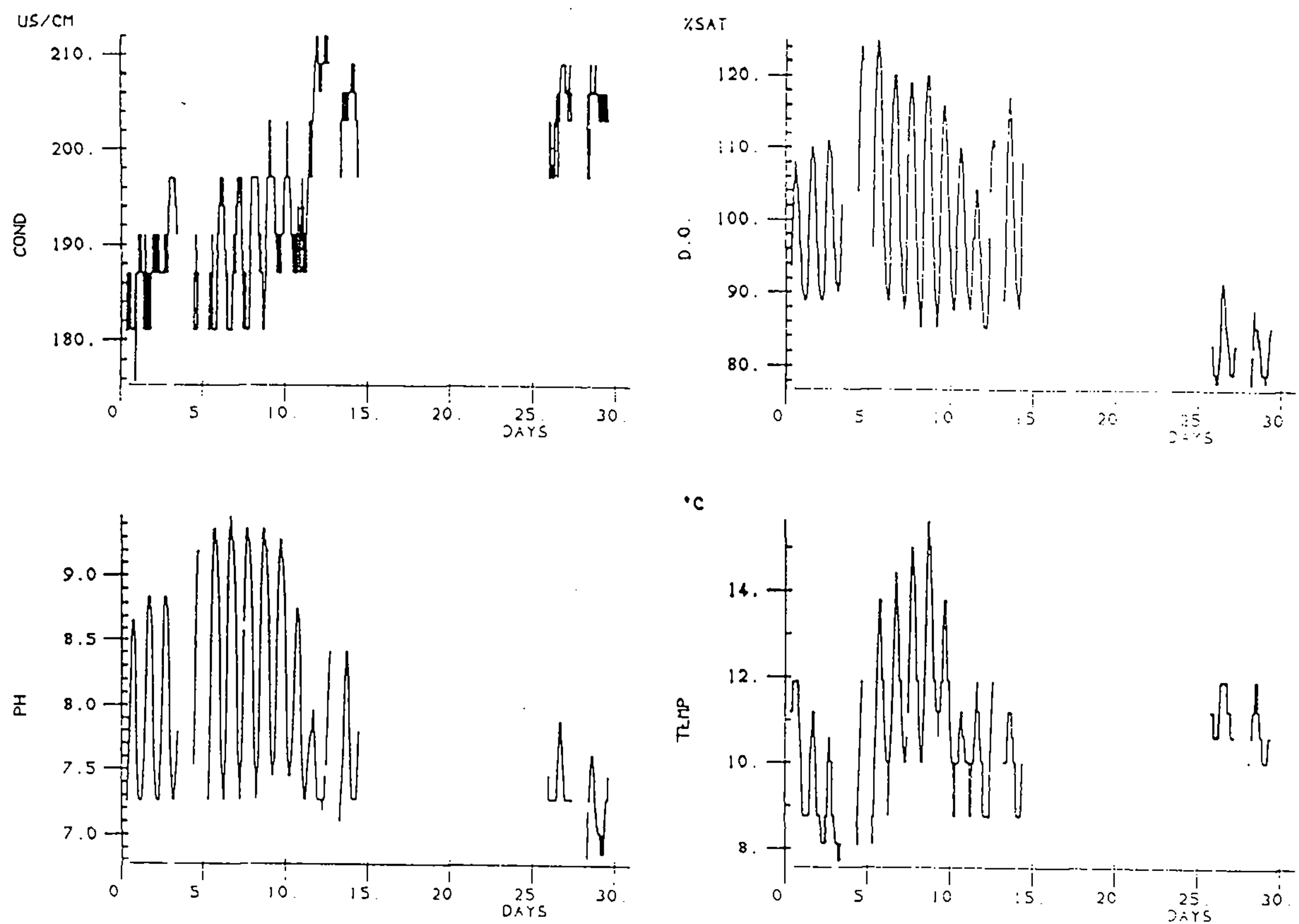
MARCH 1987 ST. LEONARDS CONTINUOUS DATA



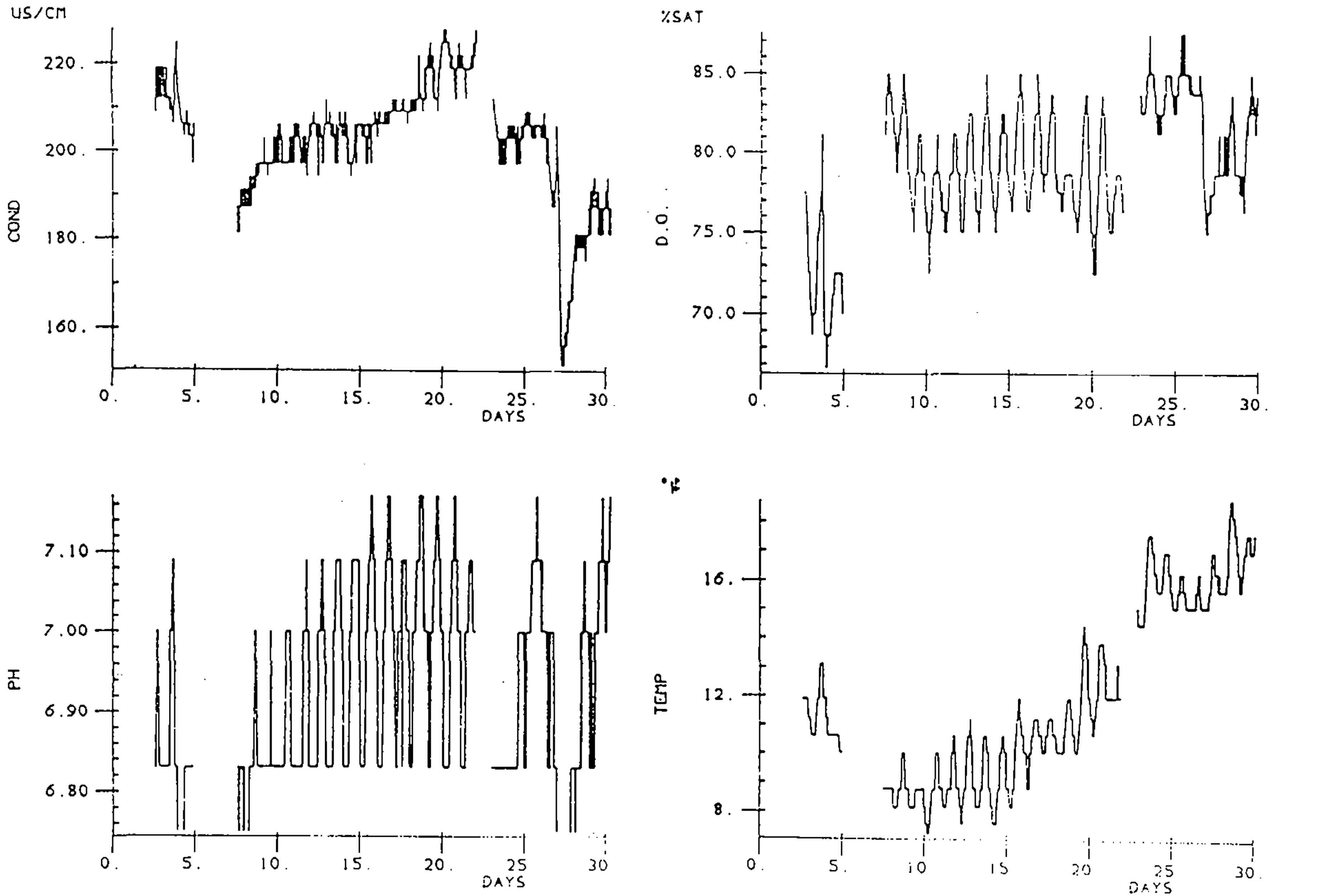
APRIL 1987 ST.LEONARDS CONTINUOUS DATA



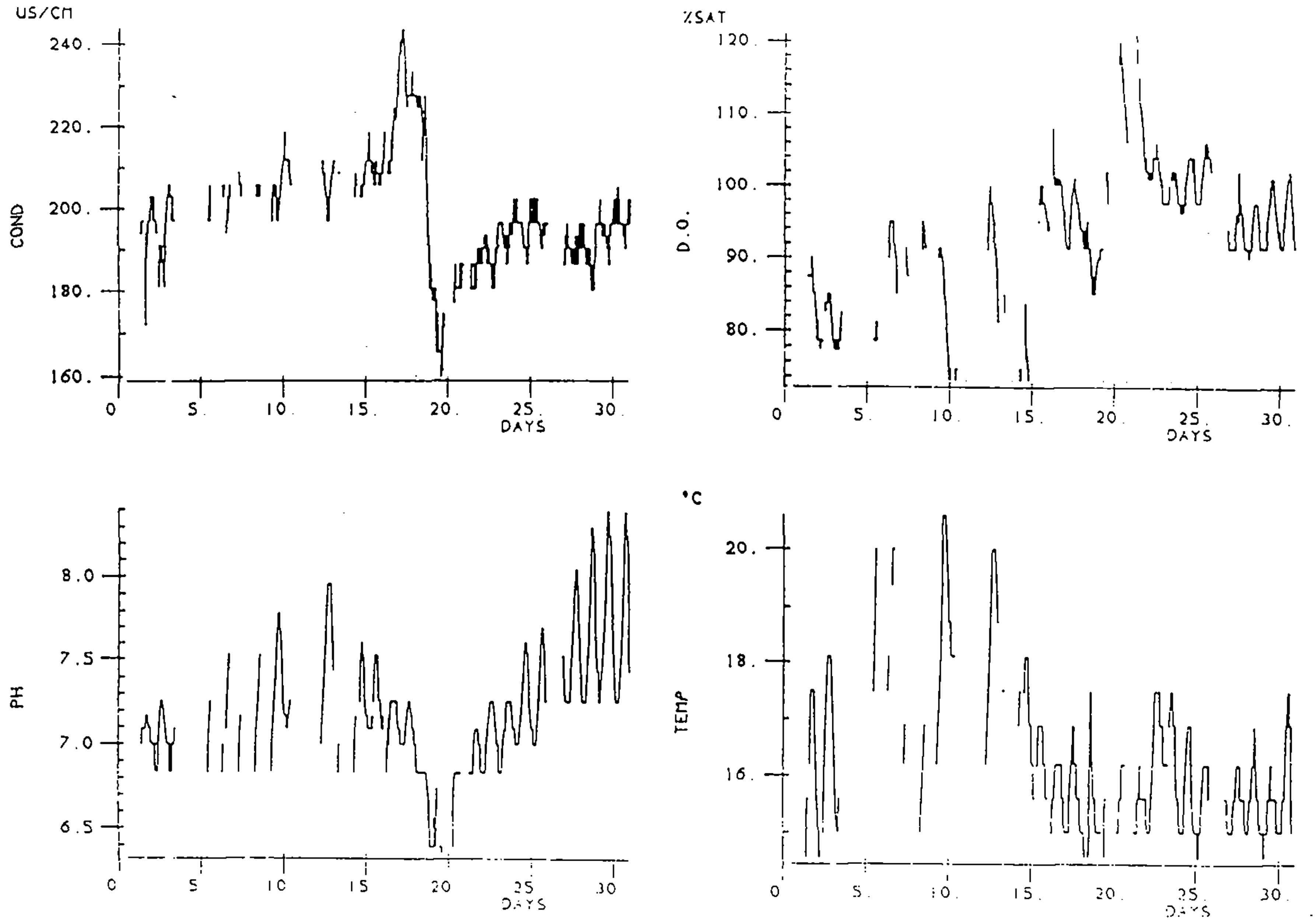
MAY 1987 ST.LEONARDS CONTINUOUS DATA



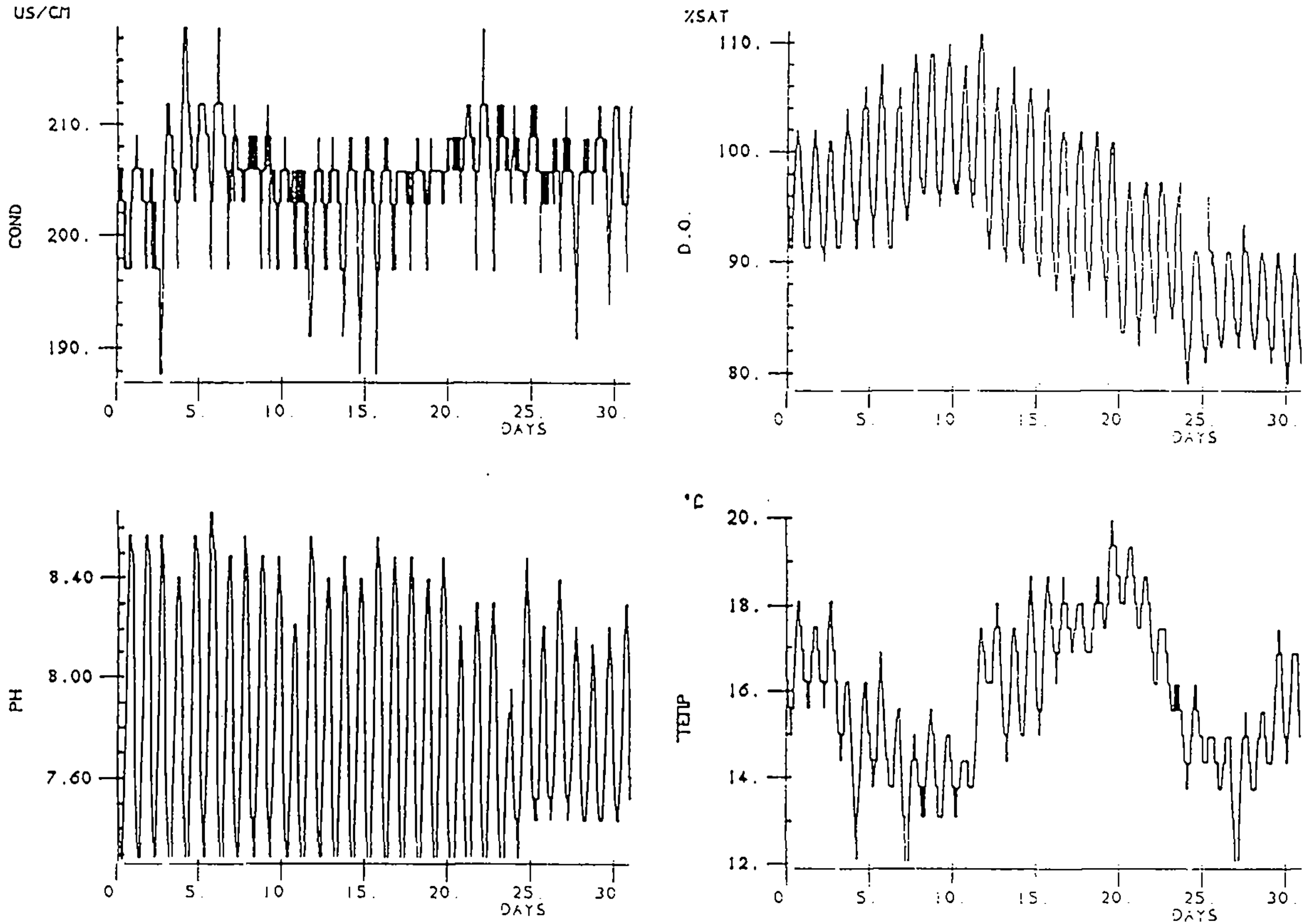
JUNE 1987 CONTINUOUS DATA ST.LEONARDS



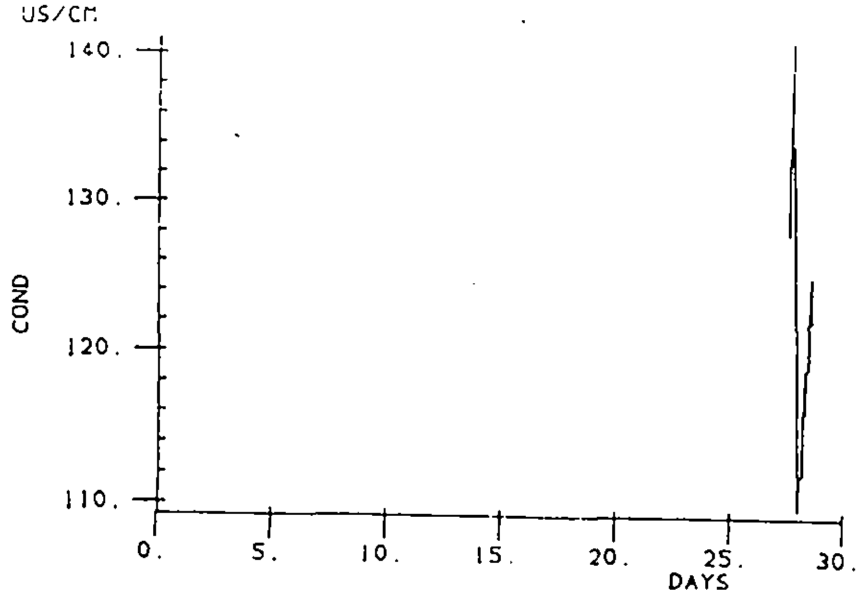
JULY 1987 CONTINUOUS DATA ST.LEONARDS

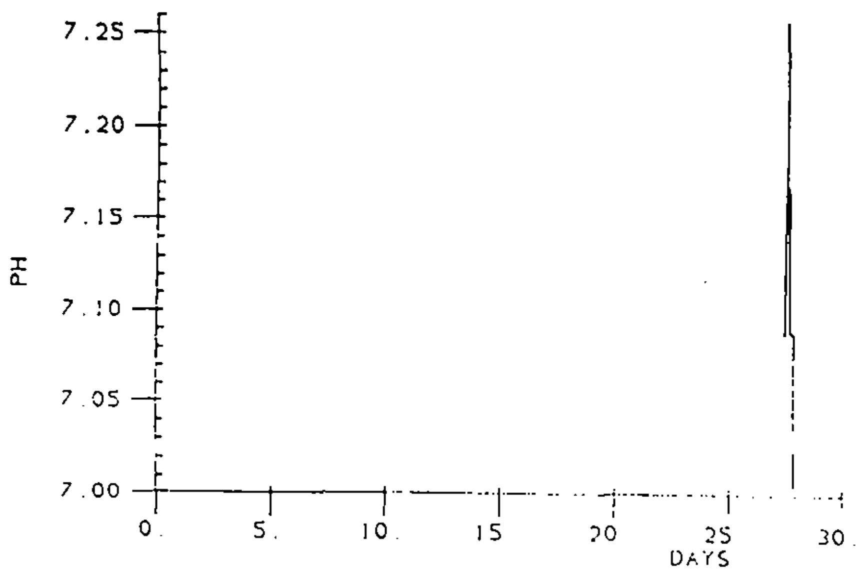


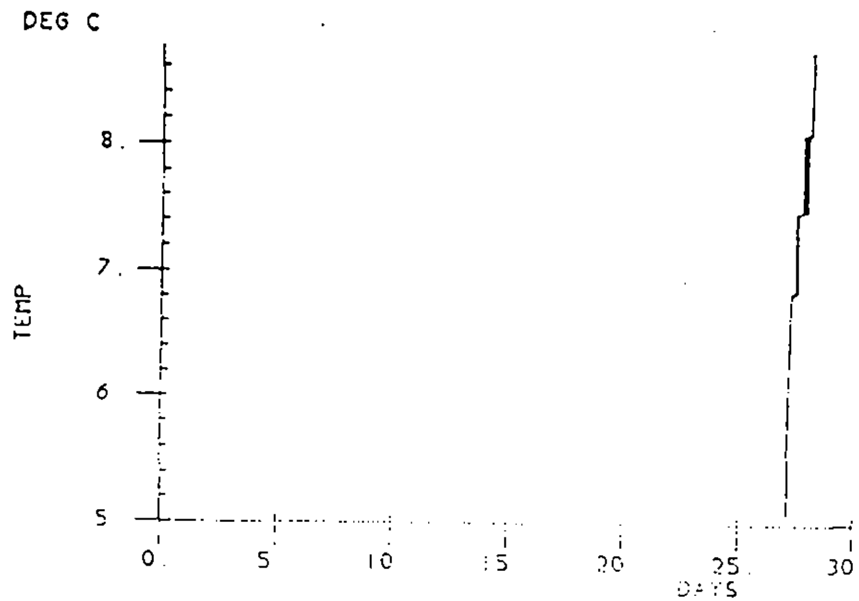
AUGUST CONTINUOUS DATA ST.LEONARDS 1987



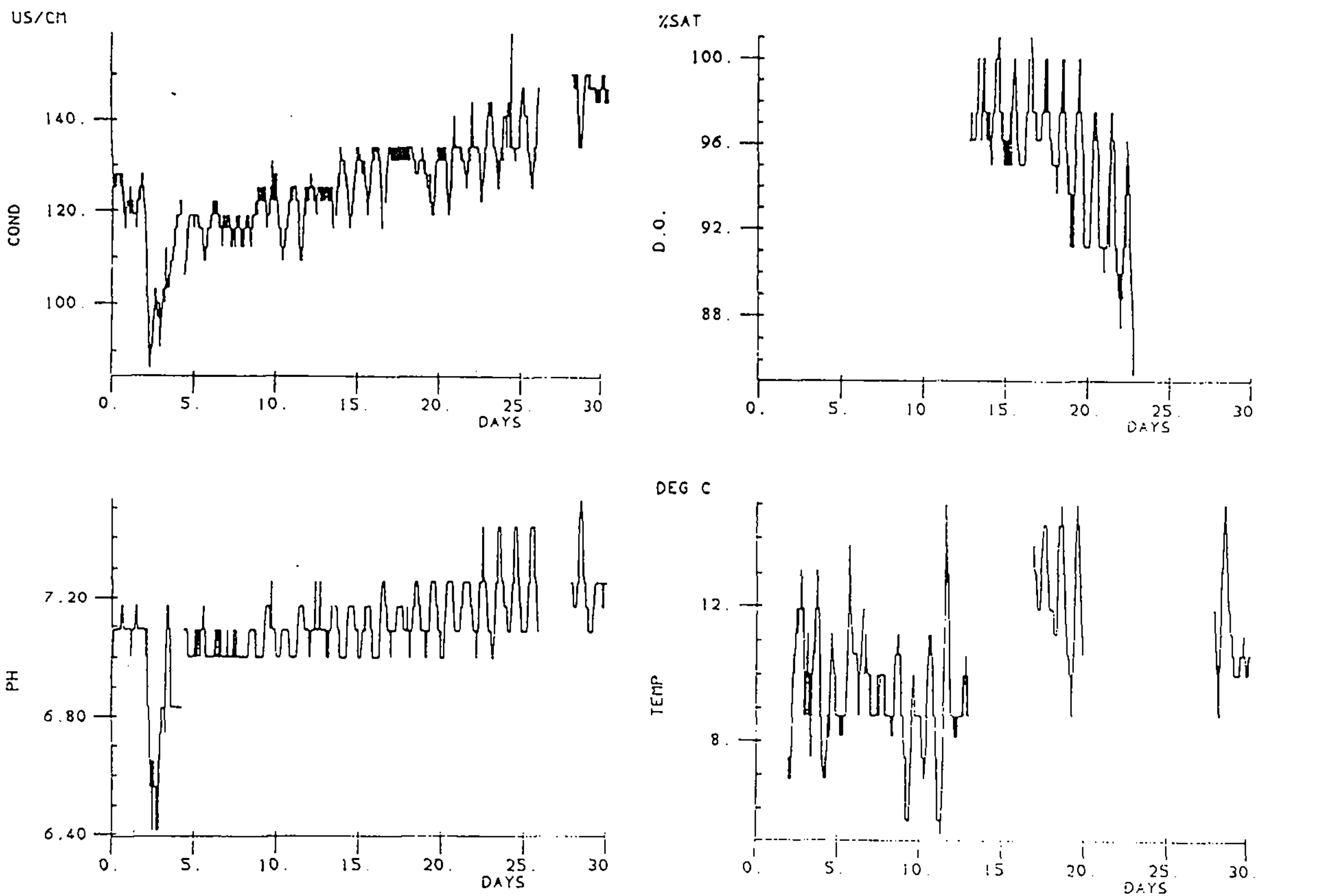
FEBRUARY 1987 LIFTON CONTINUOUS DATA







APRIL 1987 CONTINUOUS DATA LIFTON



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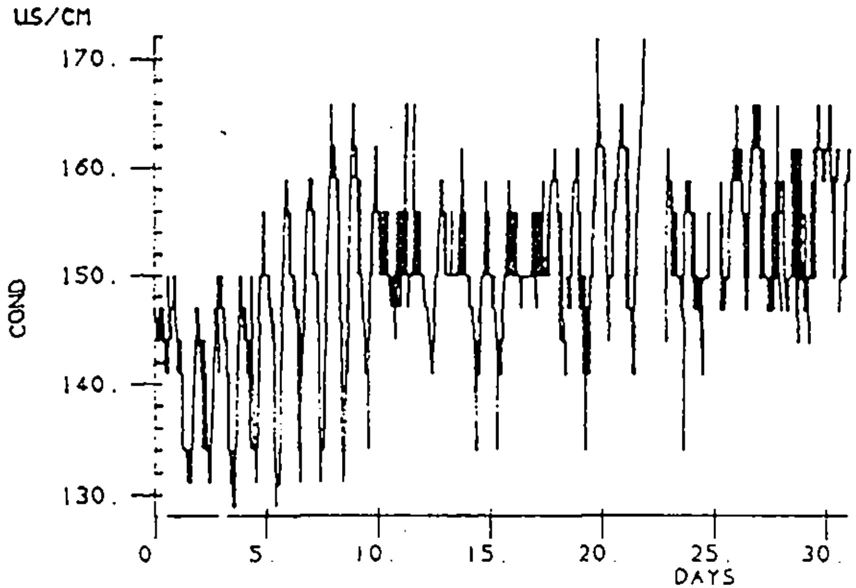

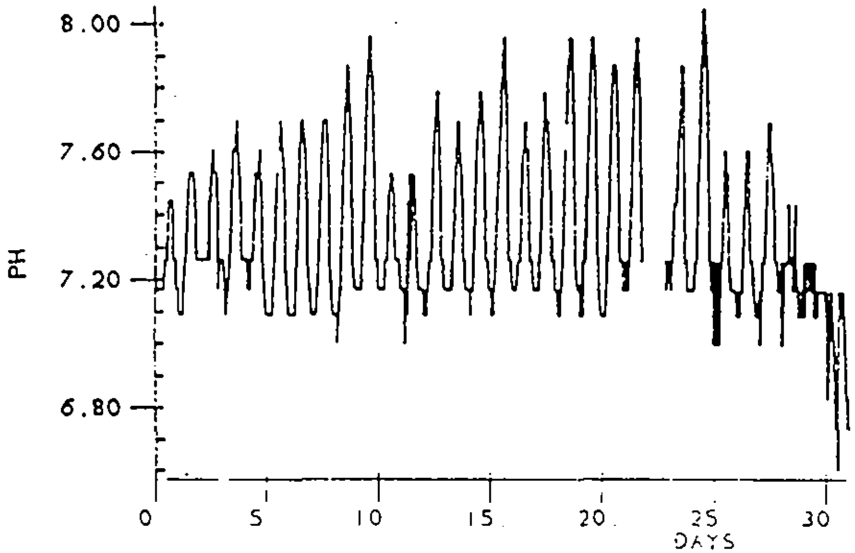

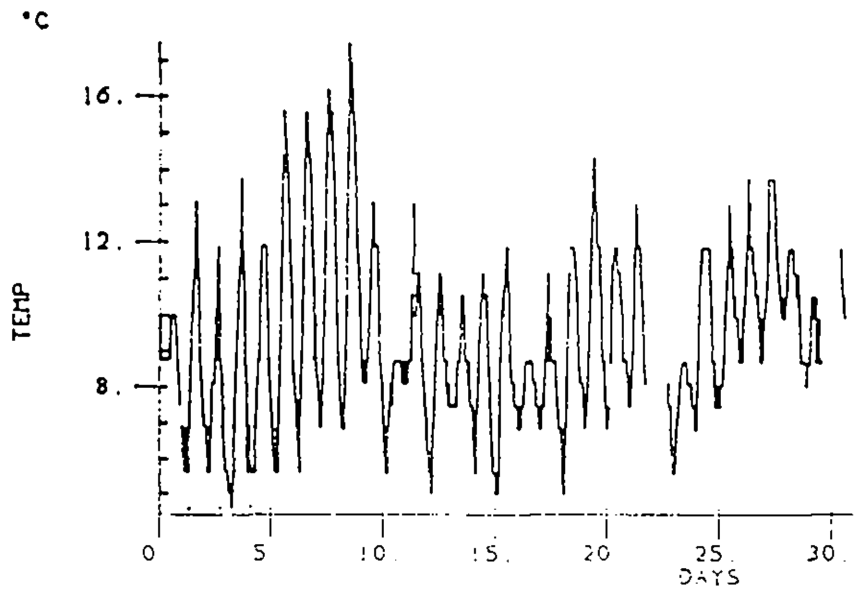

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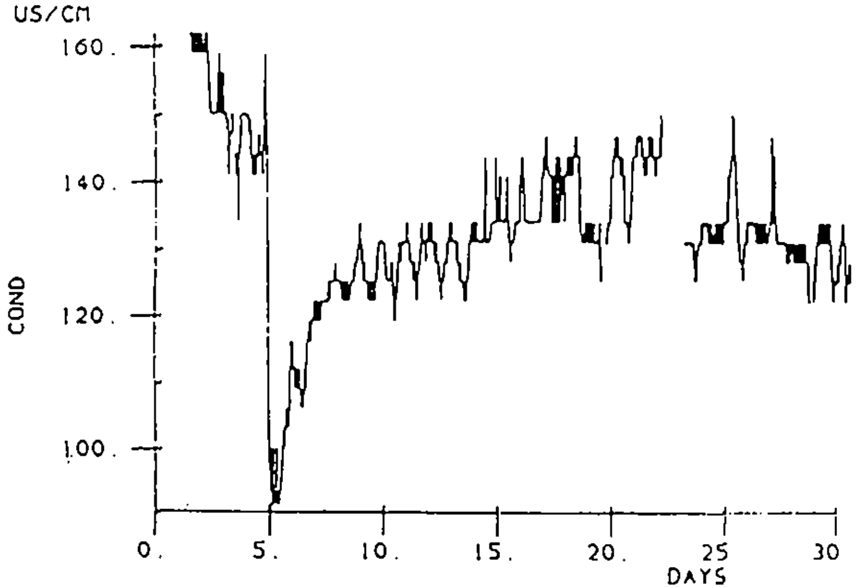
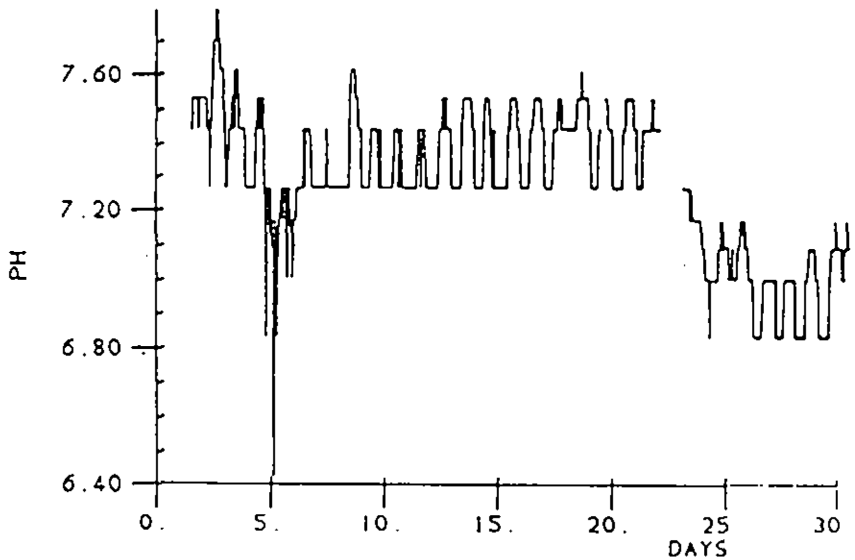
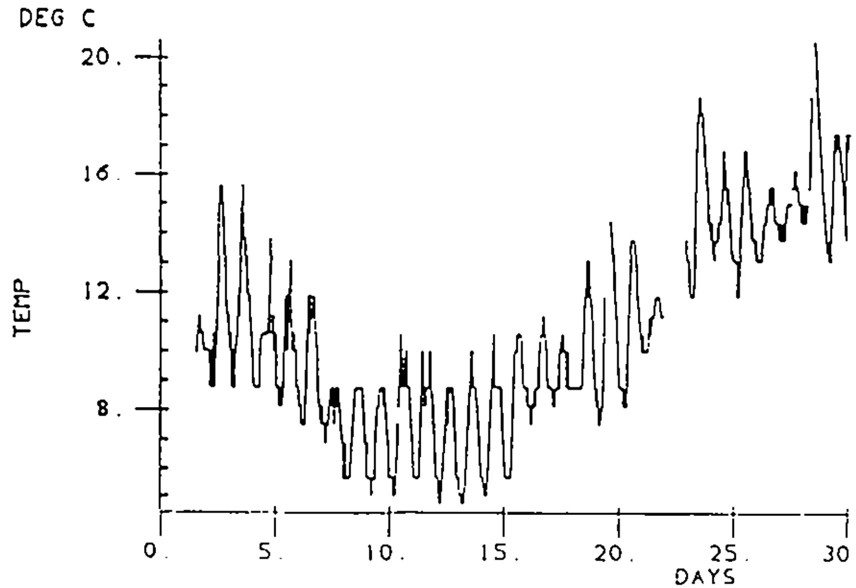
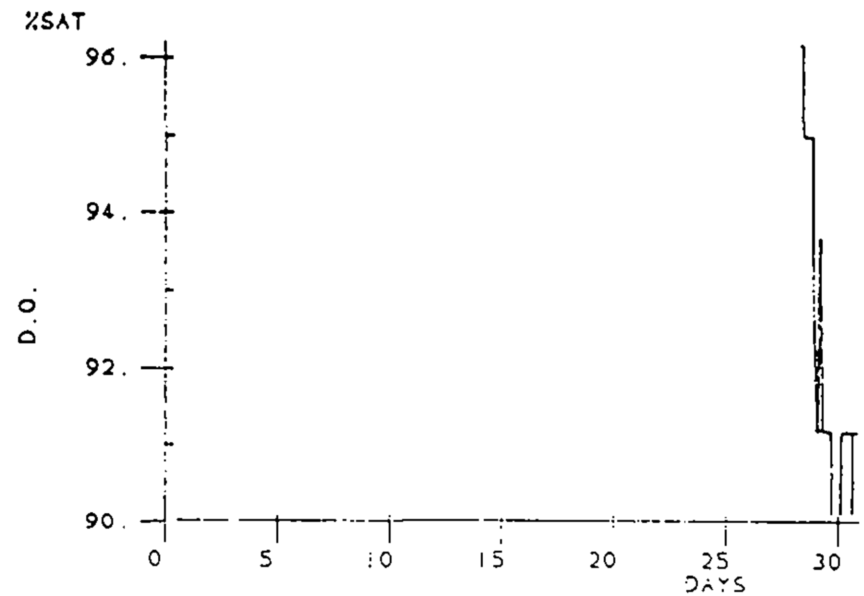
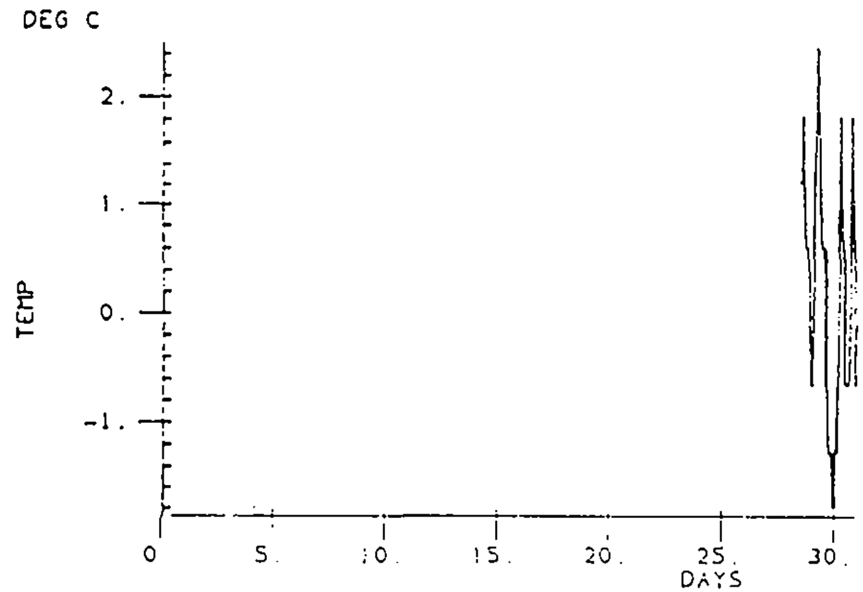




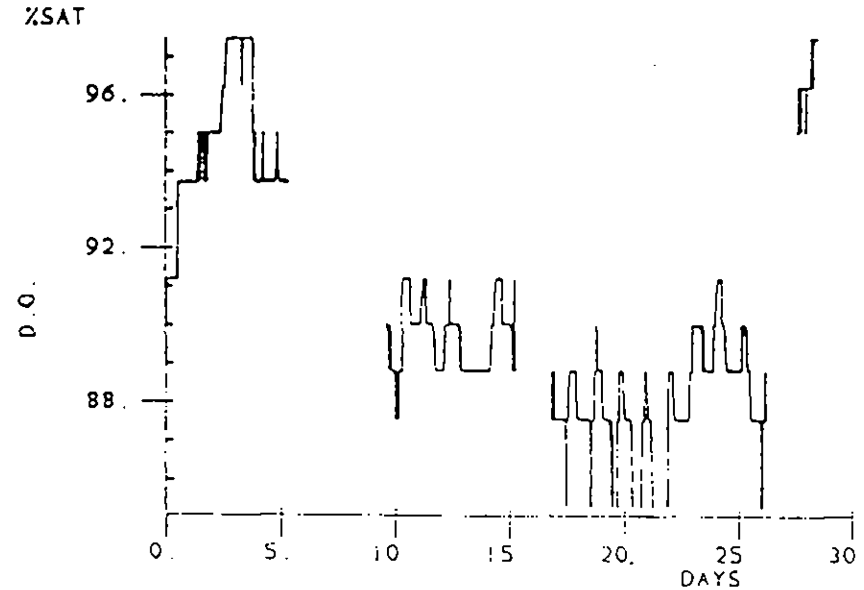


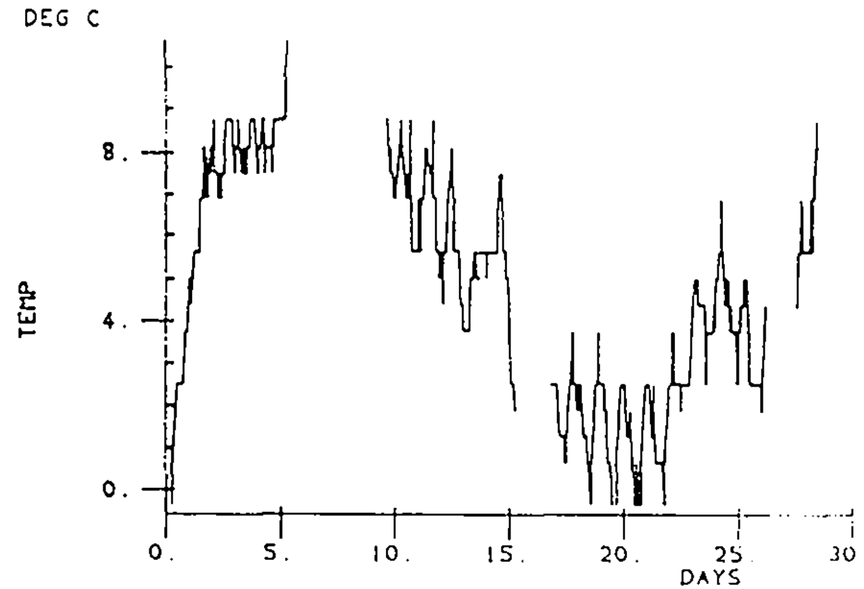
JANUARY 1987 CONTINUOUS DATA REXON



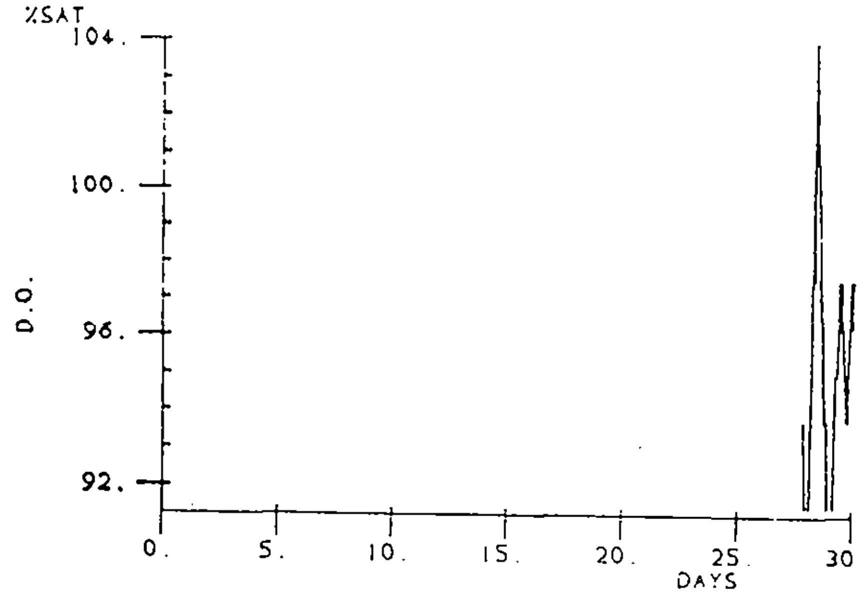


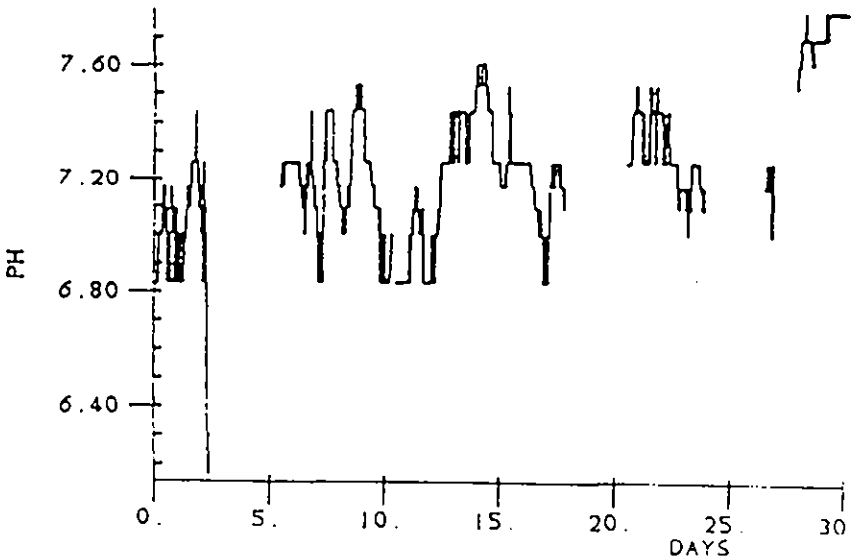
FEBRUARY REXON CONTINUOUS DATA 1987

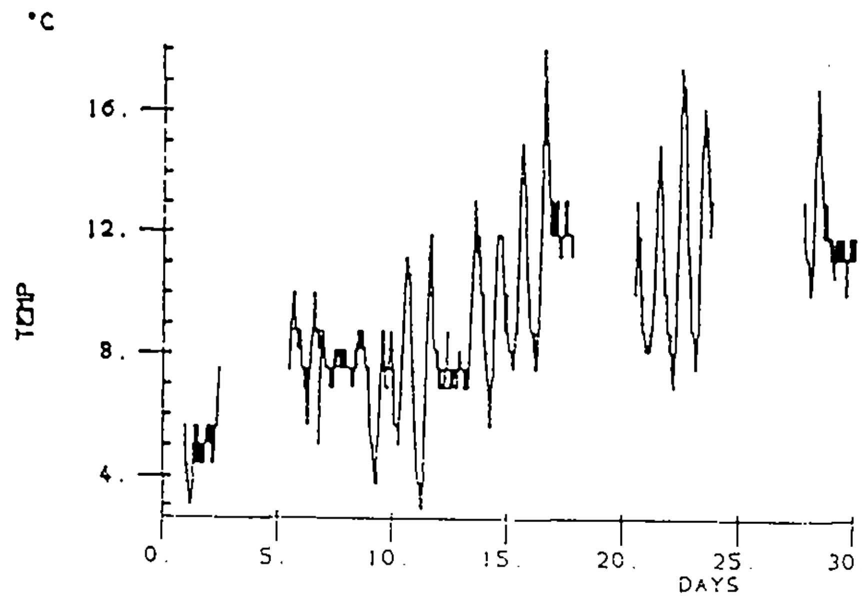




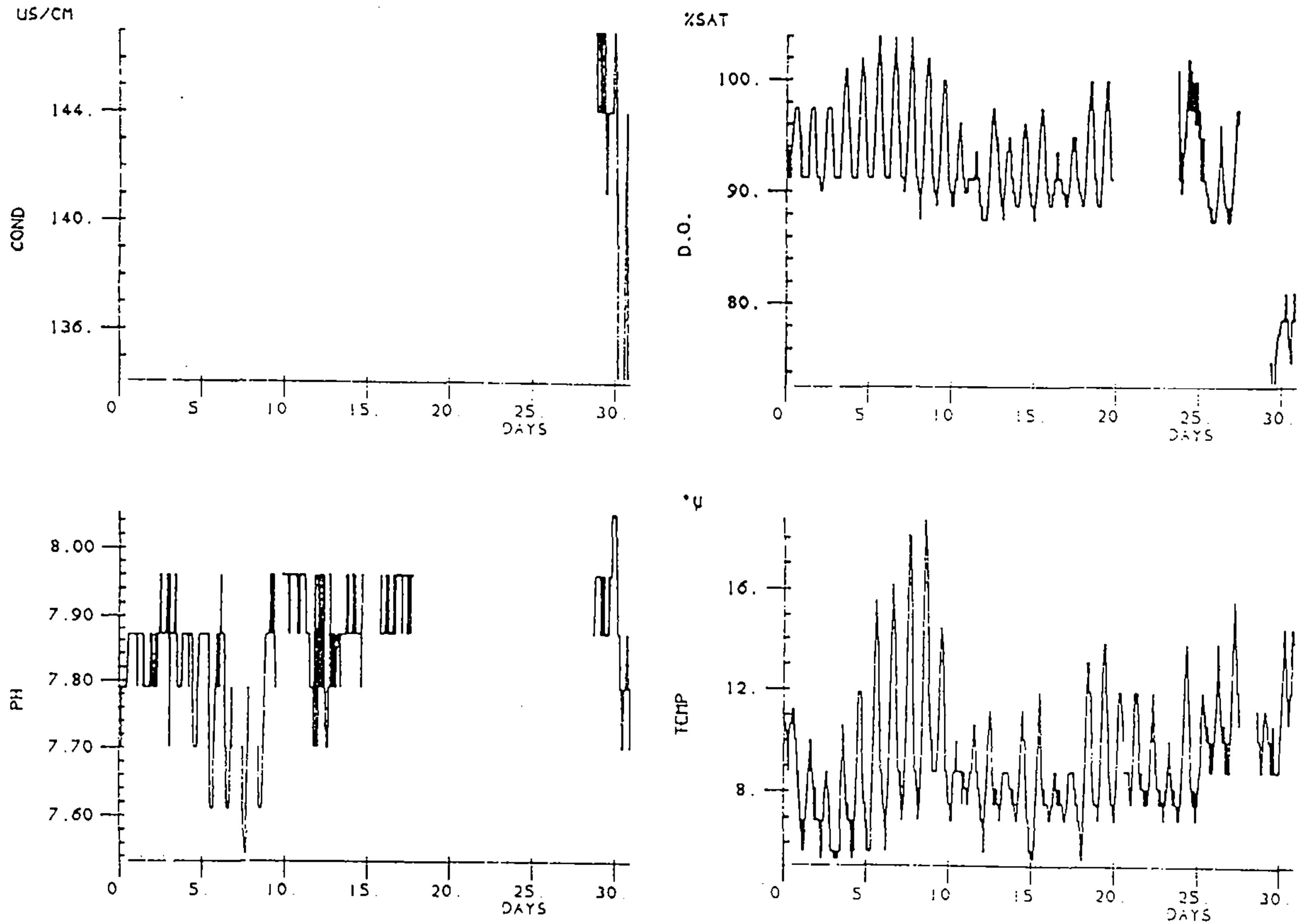
APRIL 1987 REXON CONTINUOUS DATA



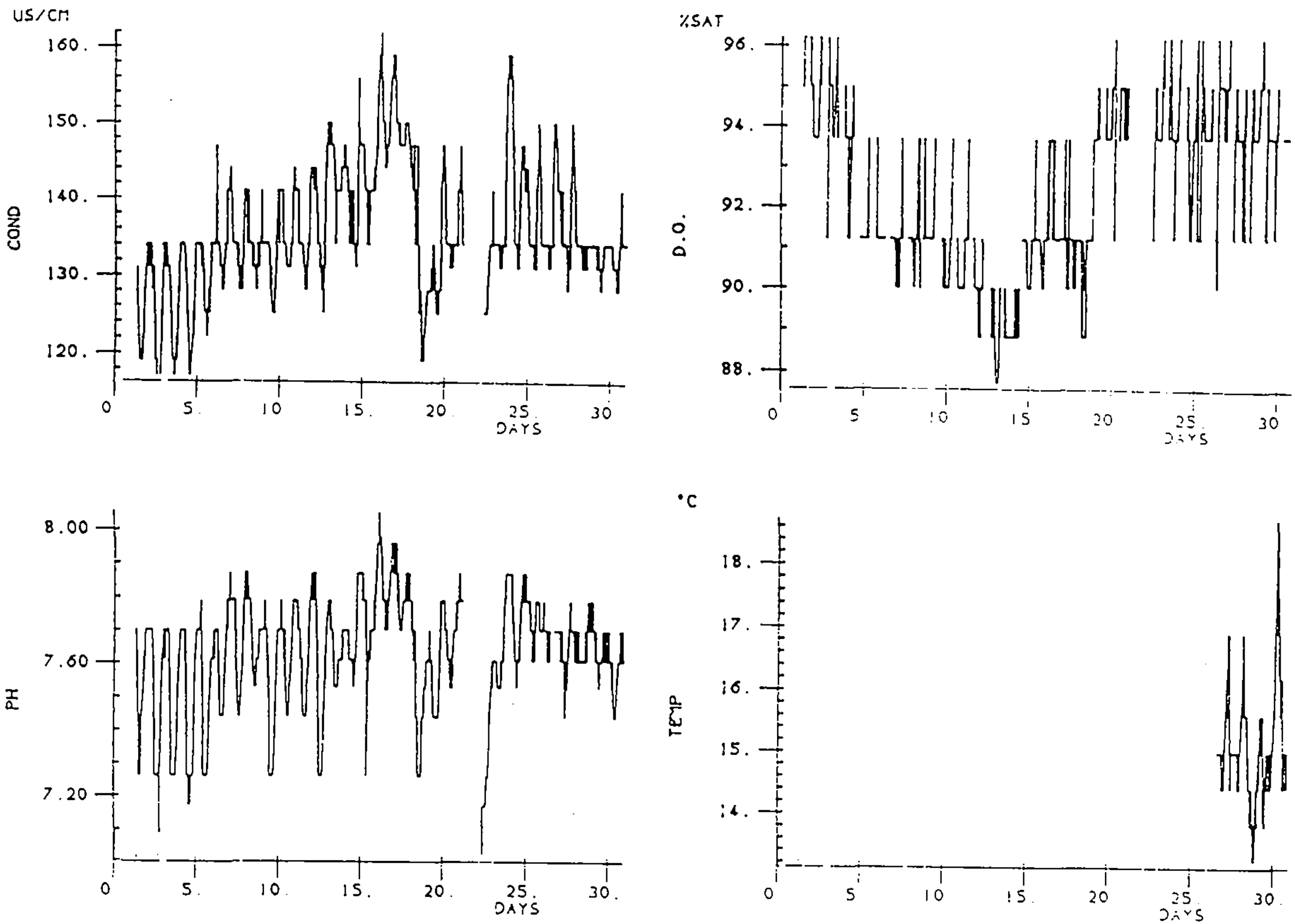




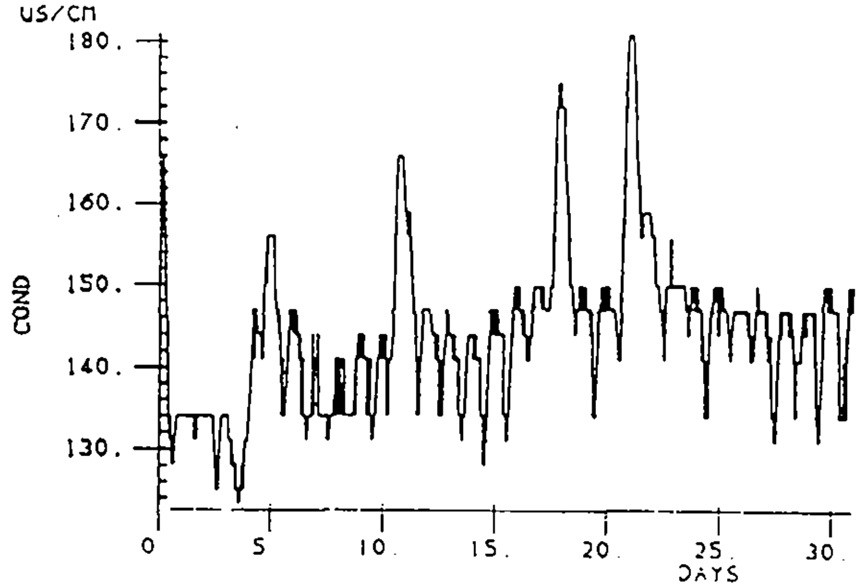
MAY 1987 REXON CONTINUOUS DATA

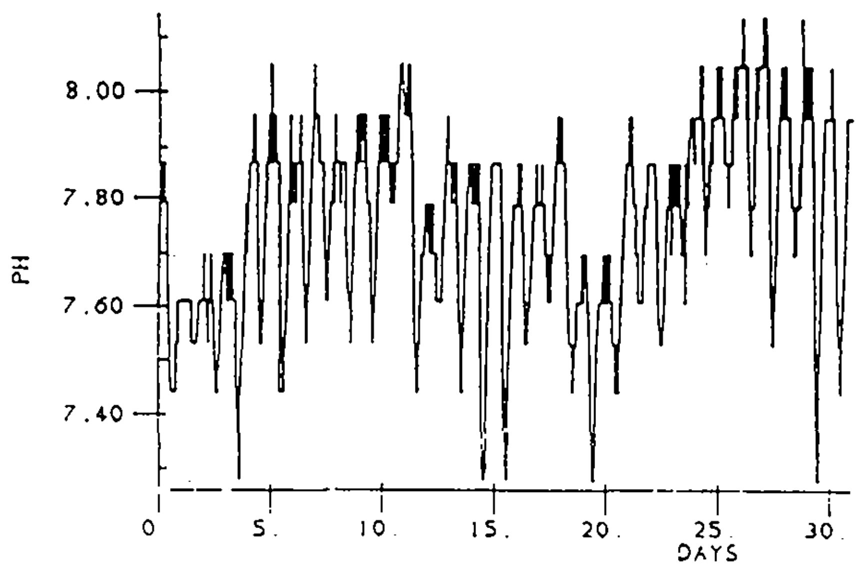


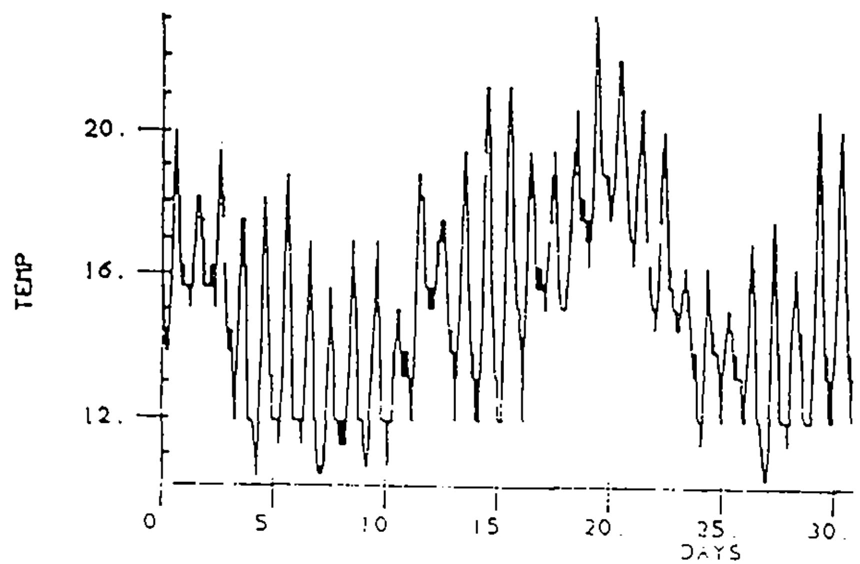
JULY 1987 REXON CONTINUOUS DATA



AUGUST 1987 REXON CONTINUOUS DATA







Appendix 2

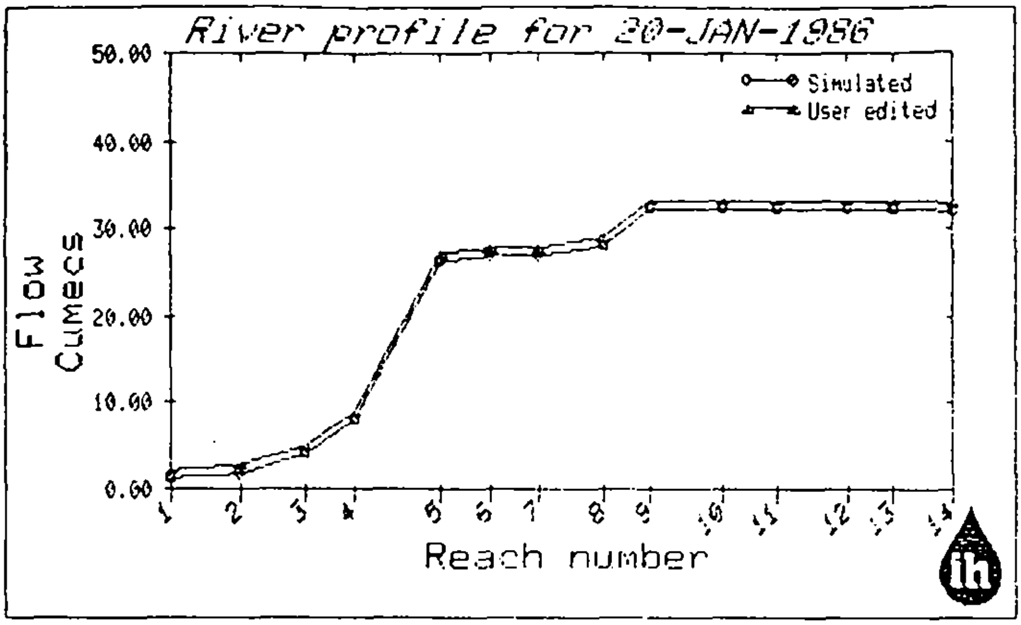
Plots of steady state flow conditions and user edited model runs to simulate releases of water from Roadford reservoir

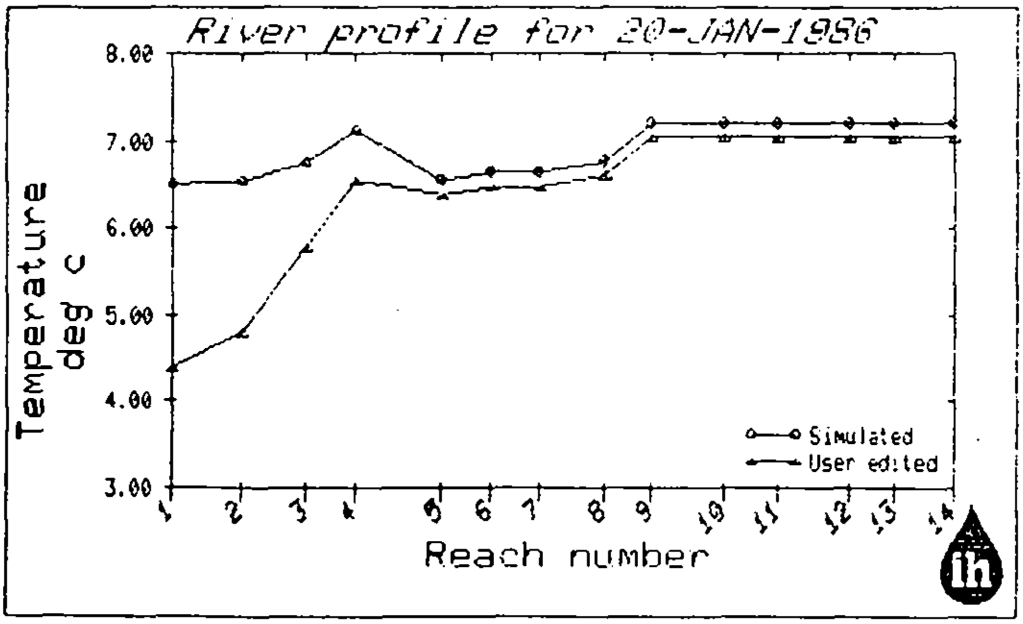
Three scenarios are depicted for each of the six model validation periods:-

1) Reservoir release rate = 1 cumec.
   Water quality high in BOD, NO_3 and NH_3 and at low temperature

2) Reservoir release rate = 1 cumec.
   Water quality typical of observed data taken from Wimbleball resevoir.

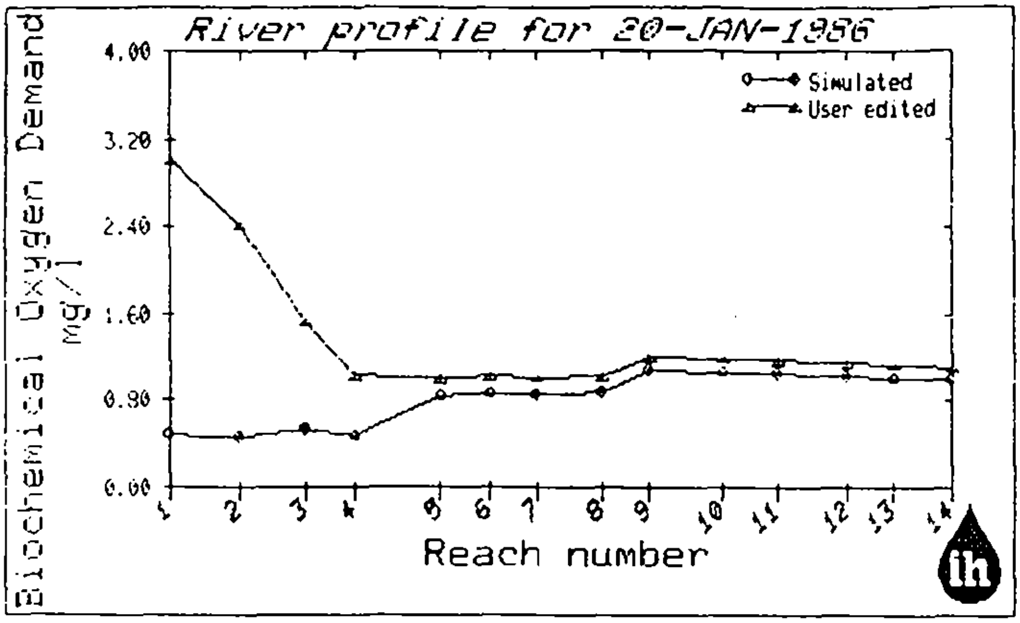
3) Reservoir release rate = 0.1 cumec.
   Water quality high in BOD, NO_3 and NH_3 and at low temperature.

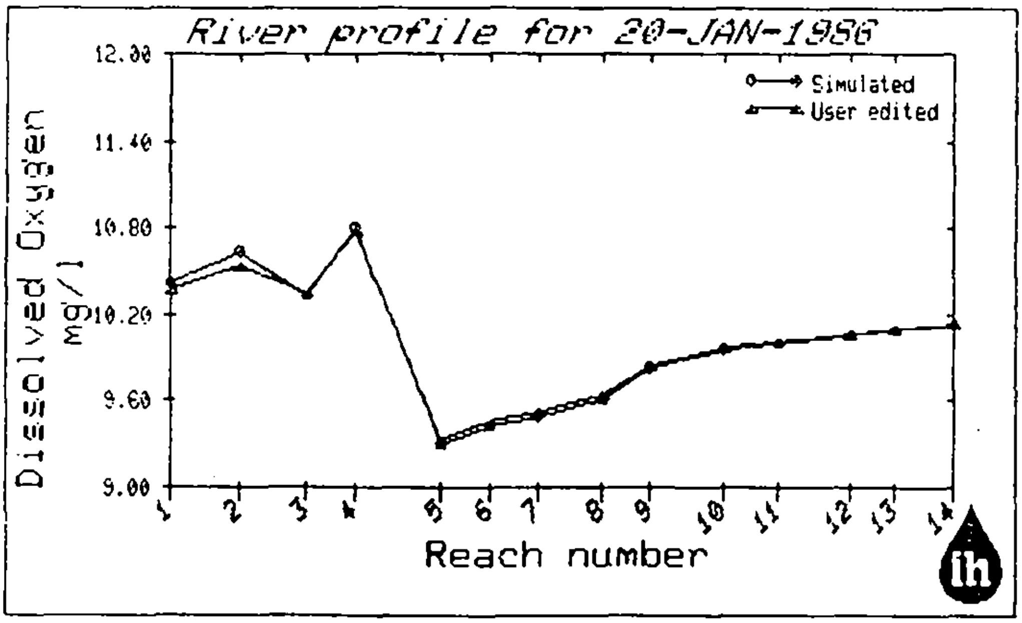




Flow = 1 cumec

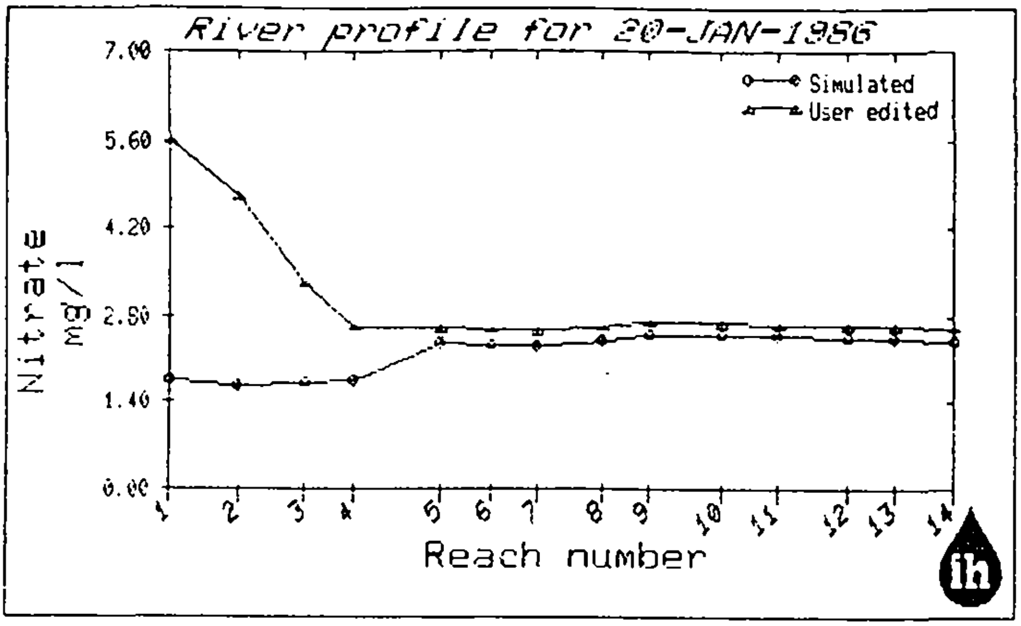
Temperature 2°c

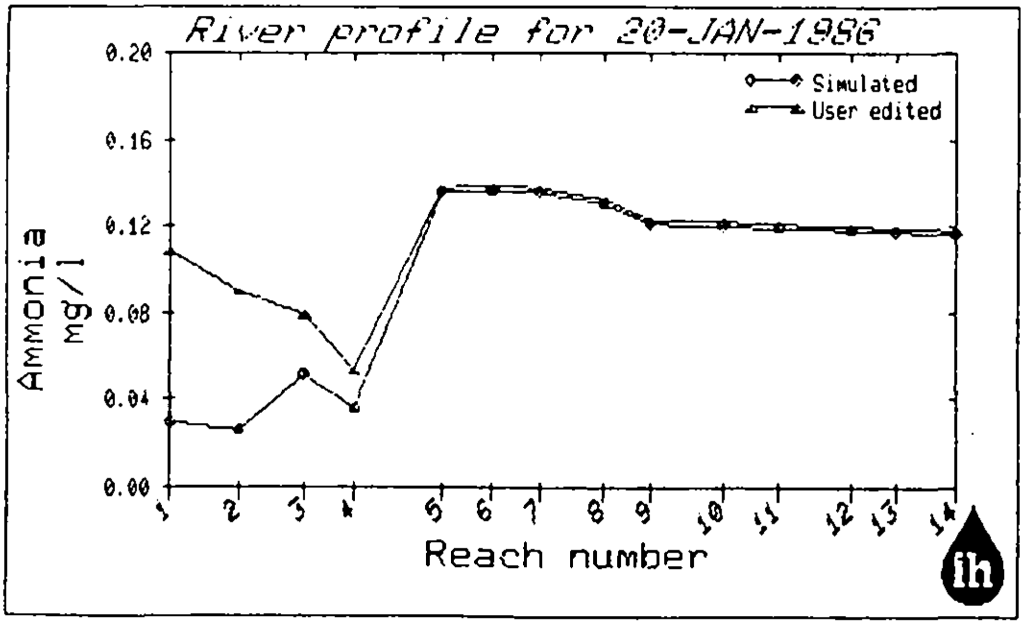




Flow = 1 cumec

BOD = 6 mg/L

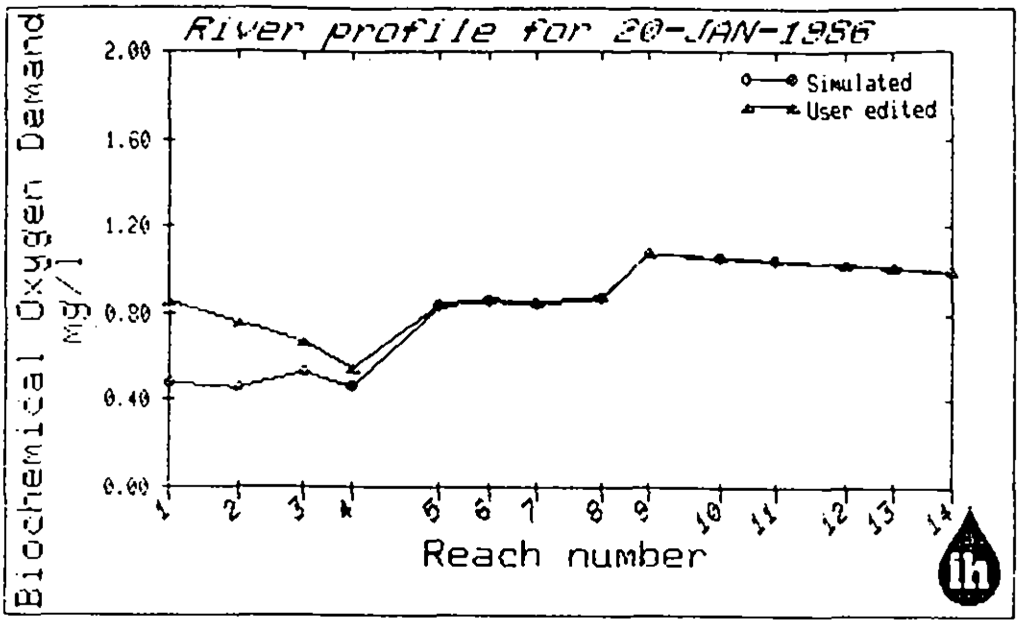


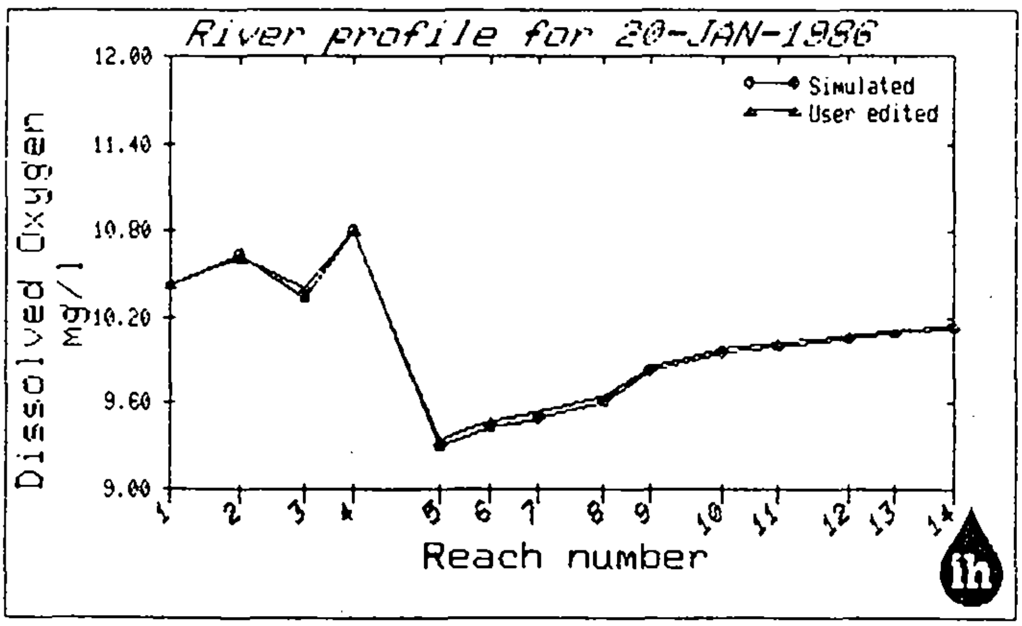


Flow = 1 cumec

Nitrate = 10 mg/L

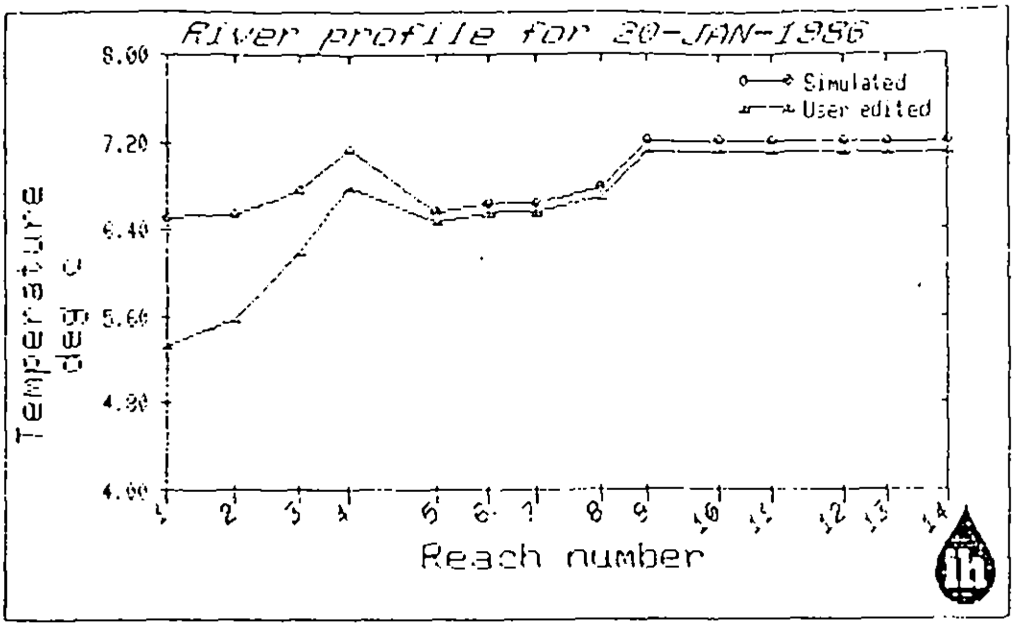
Ammonia = 0.2 mg/L

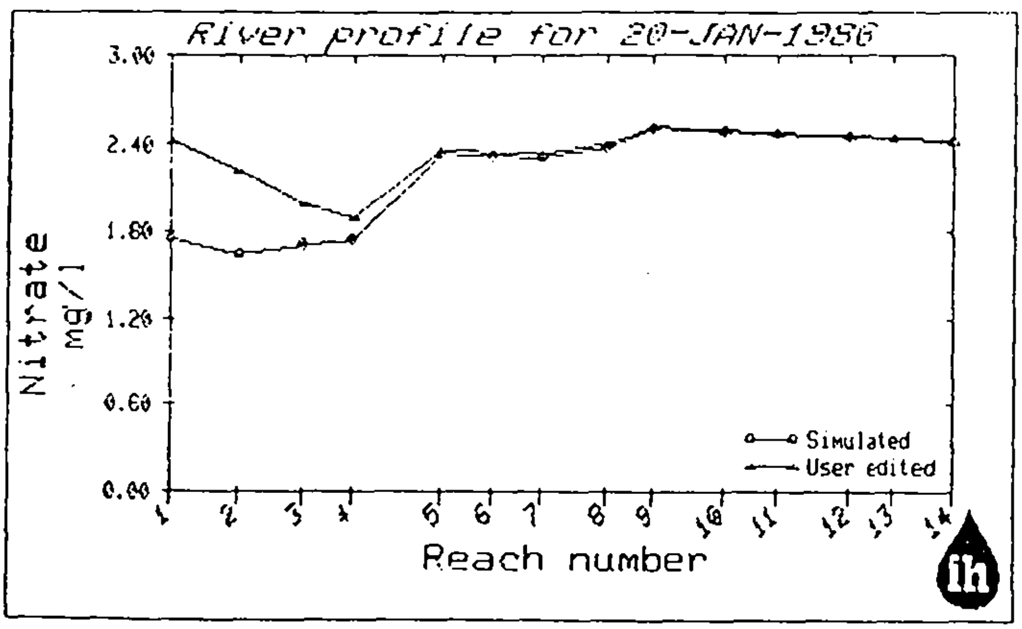


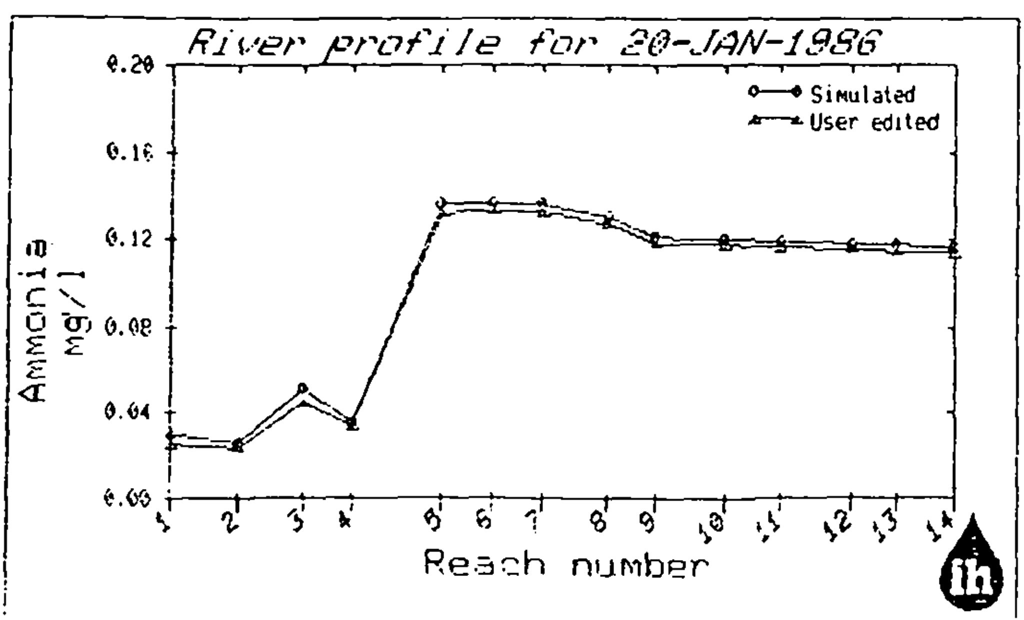


Flow = 1 cumec

BOD = 1.3 mg/L

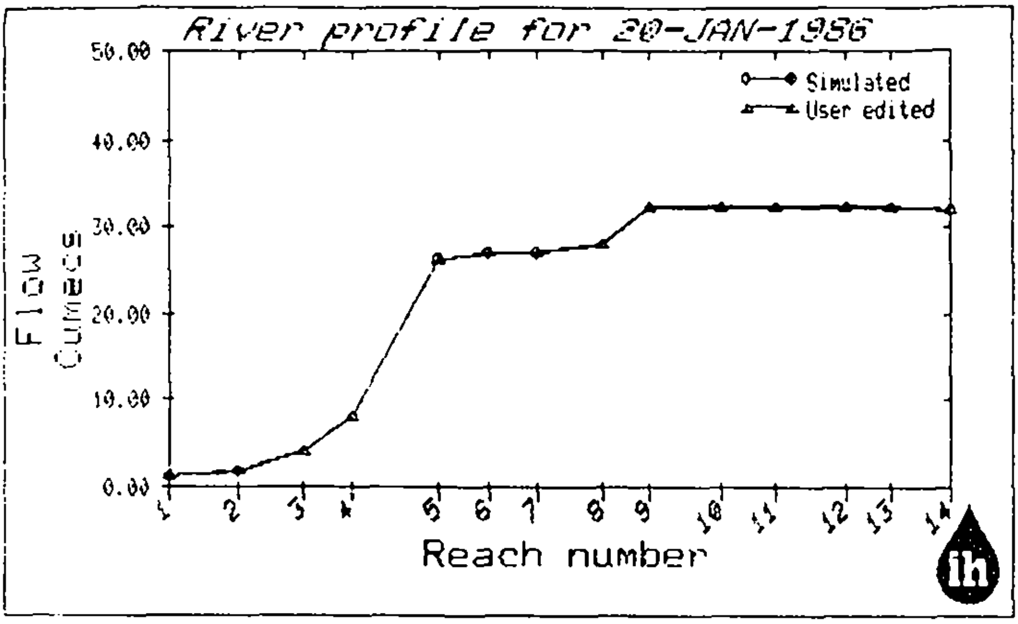


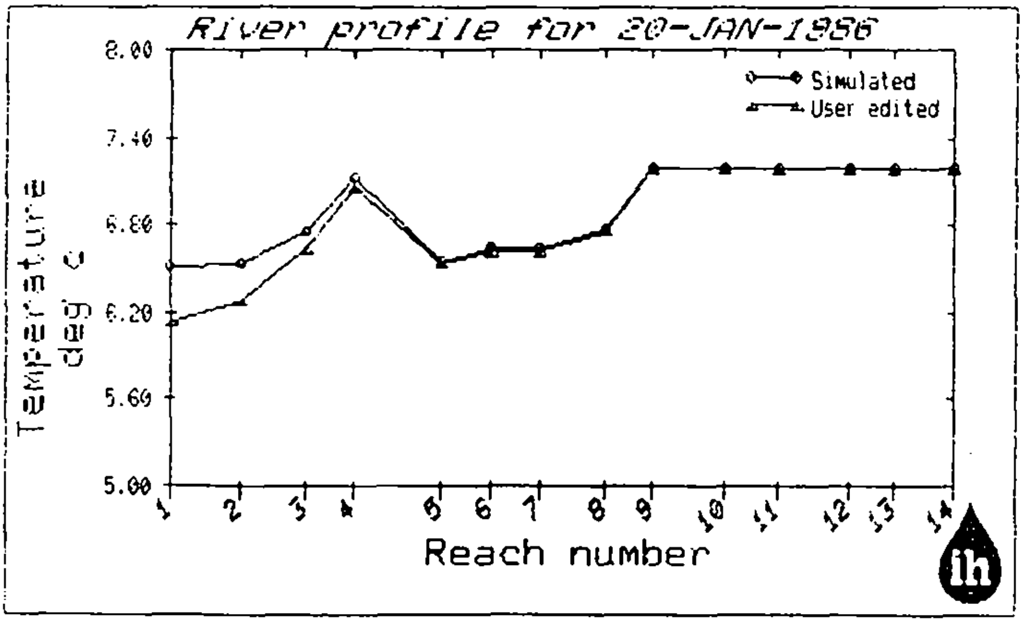




Flow = 1 Cumec   Temperature = 5°C

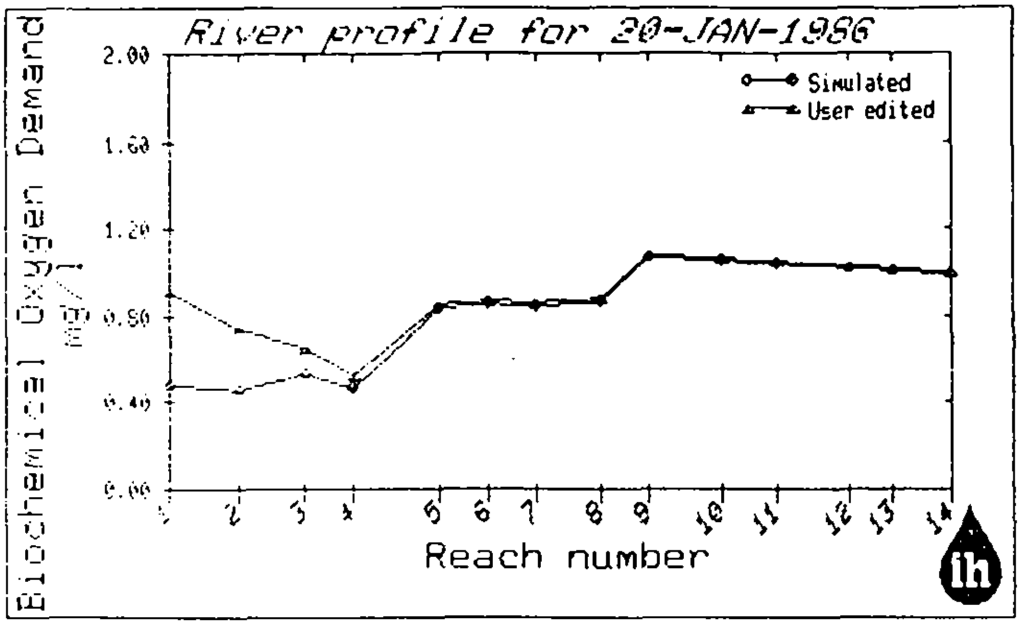
Nitrate = 3.2 mg/L   Ammonia = 0.02 mg/L

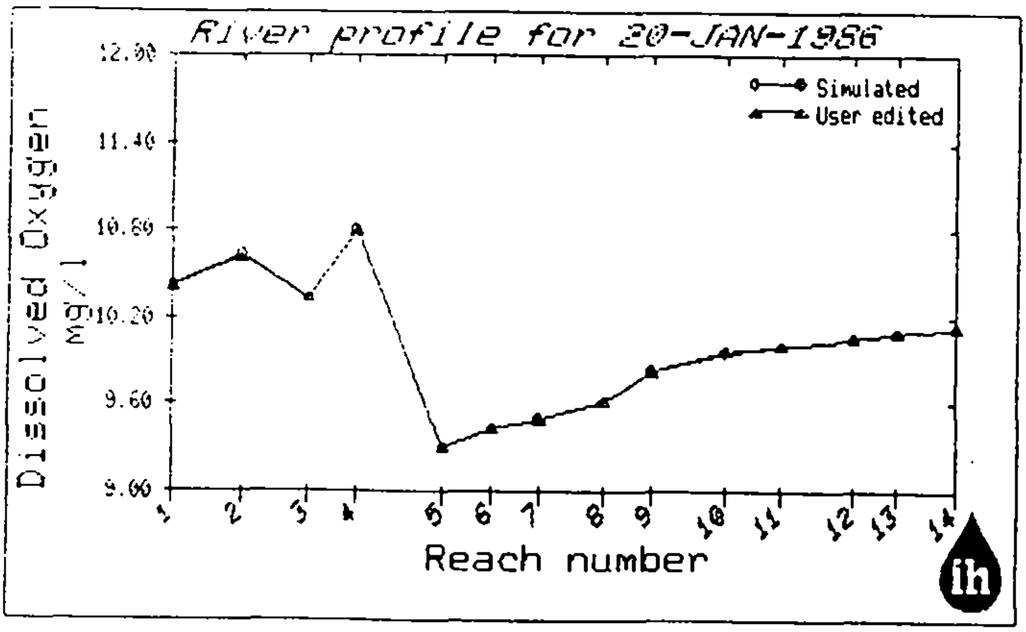




Flow = 0.1 cumec

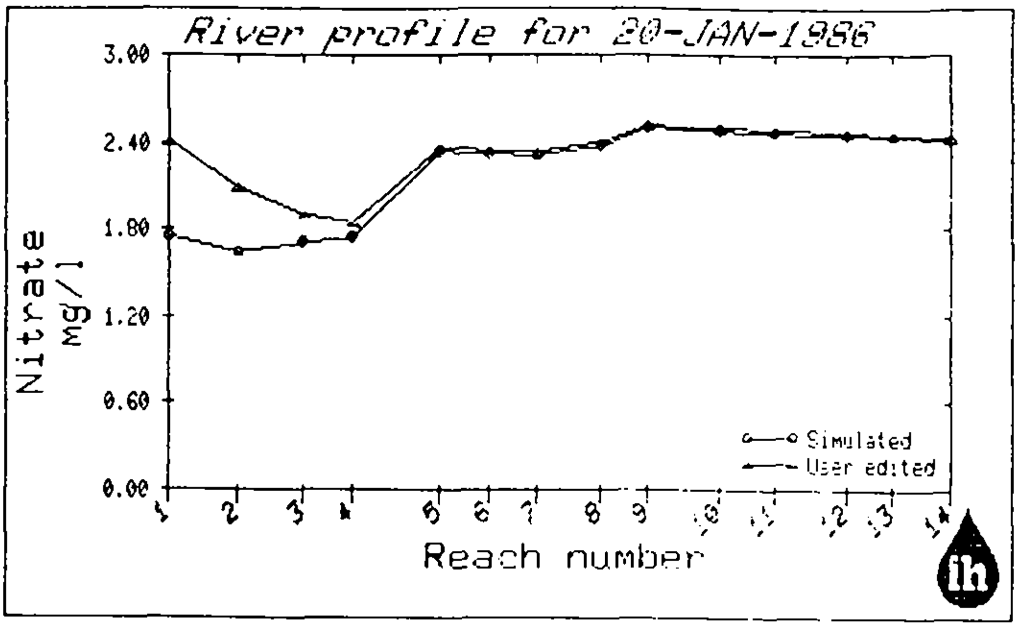
Temperature = 2°C

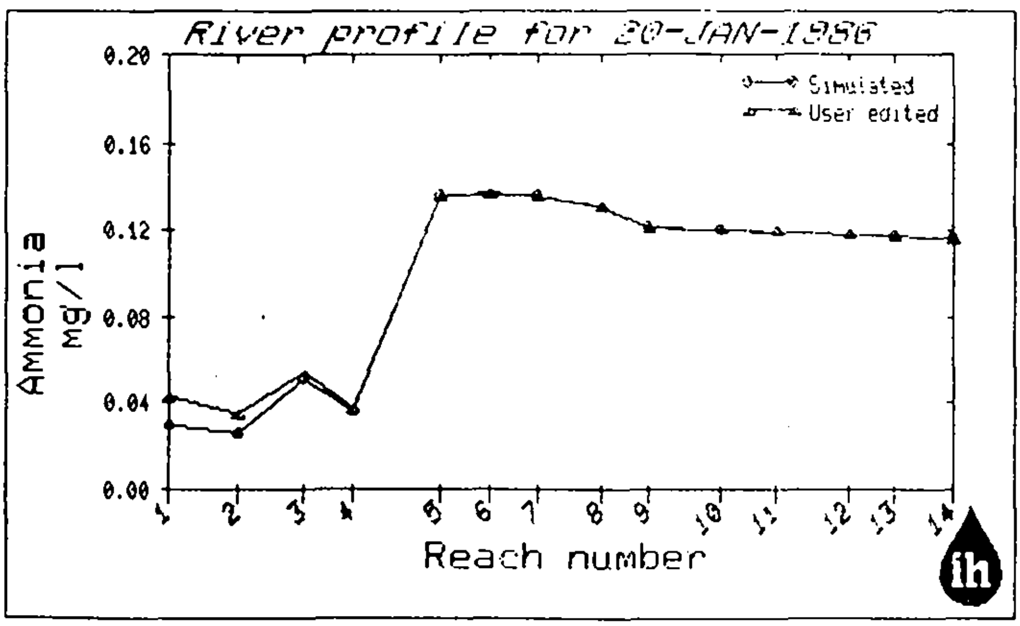




Flow = 0.1 cumec

BOD = 6 mg/L

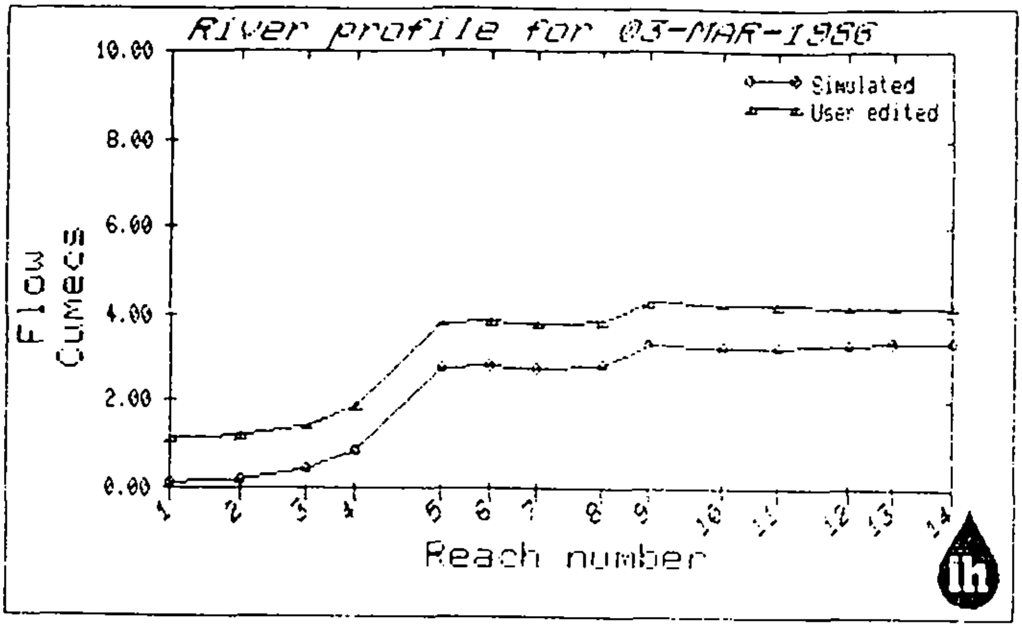


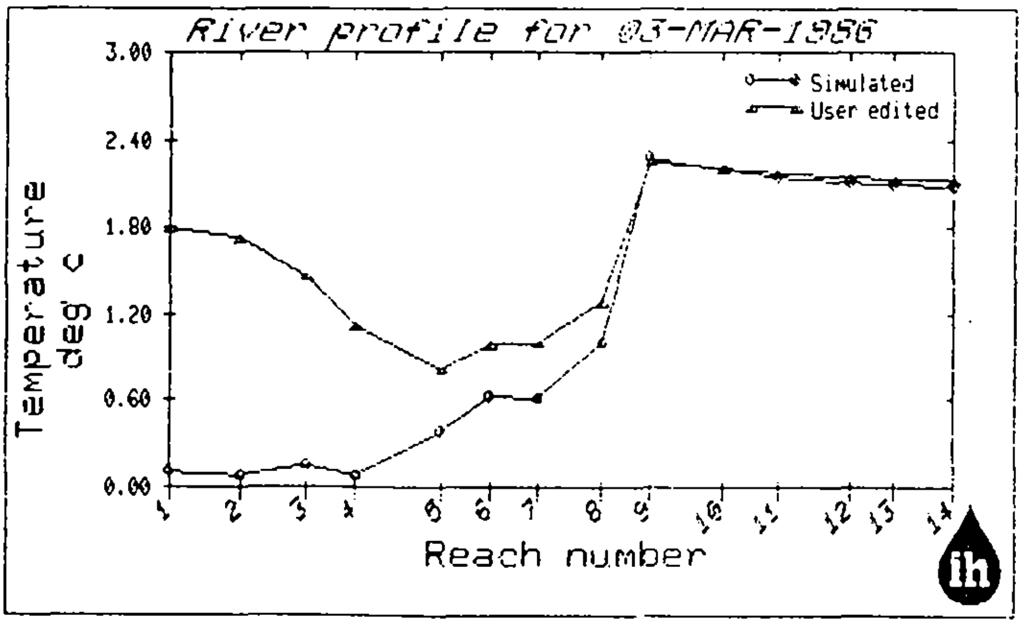


Flow = 0.1 cumec

Nitrate = 10 mg/L

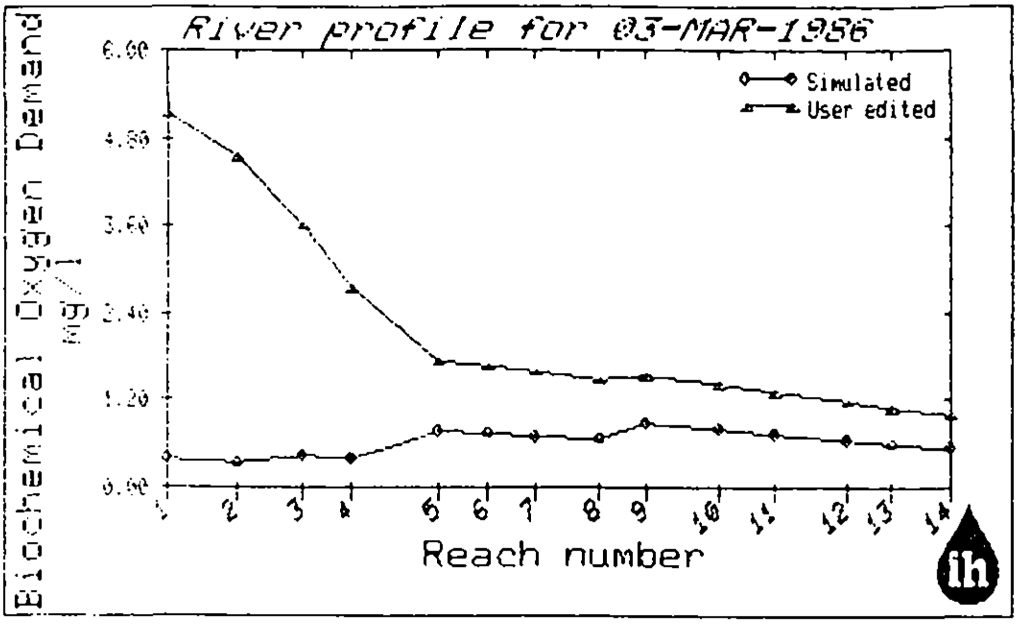
Ammonia = 0.2 mg/L

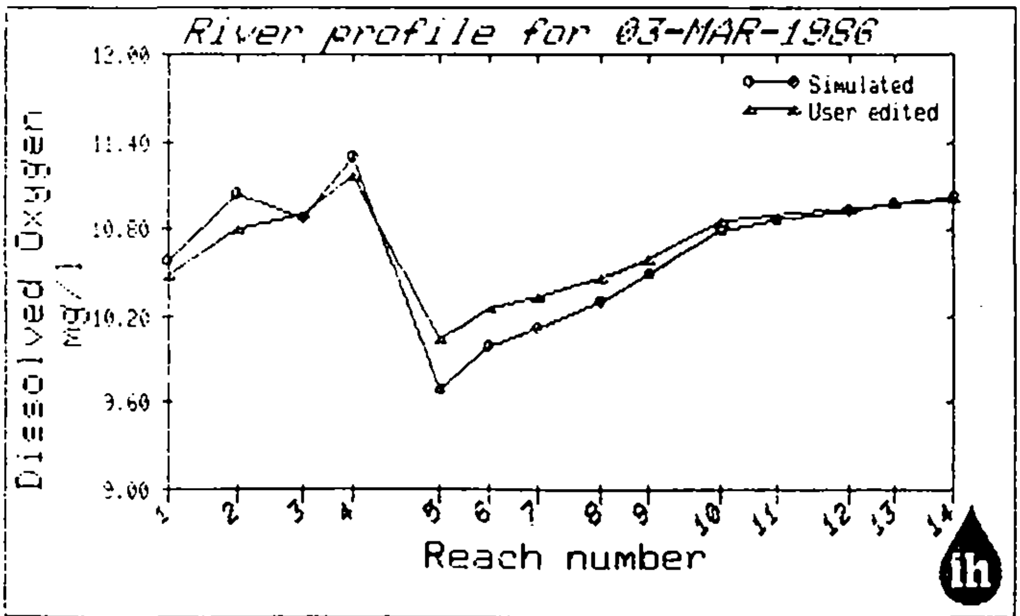




Flow = 1 cumec

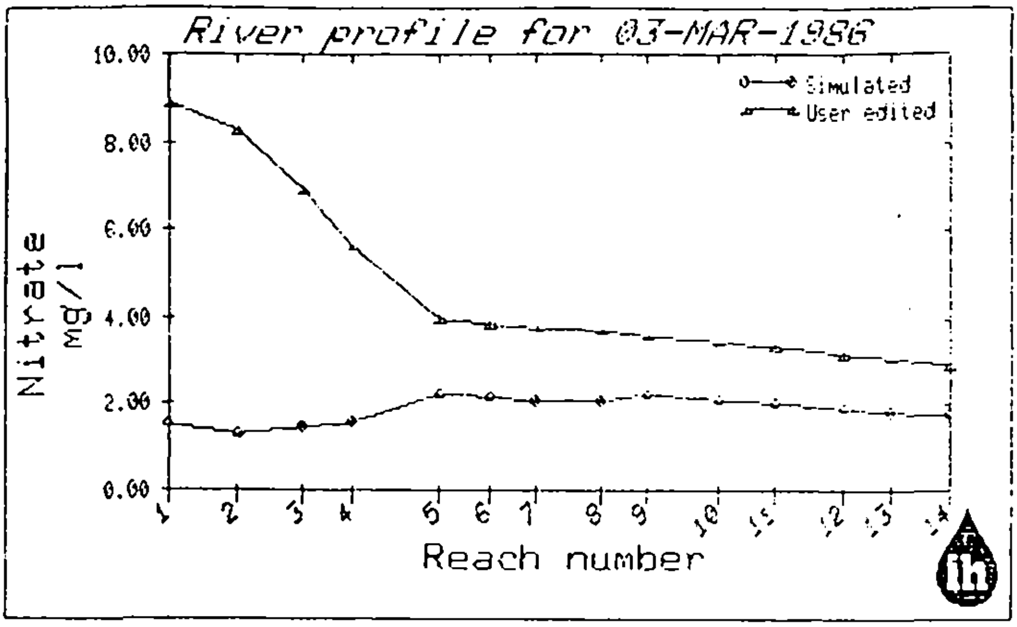
Temperature = 2°C

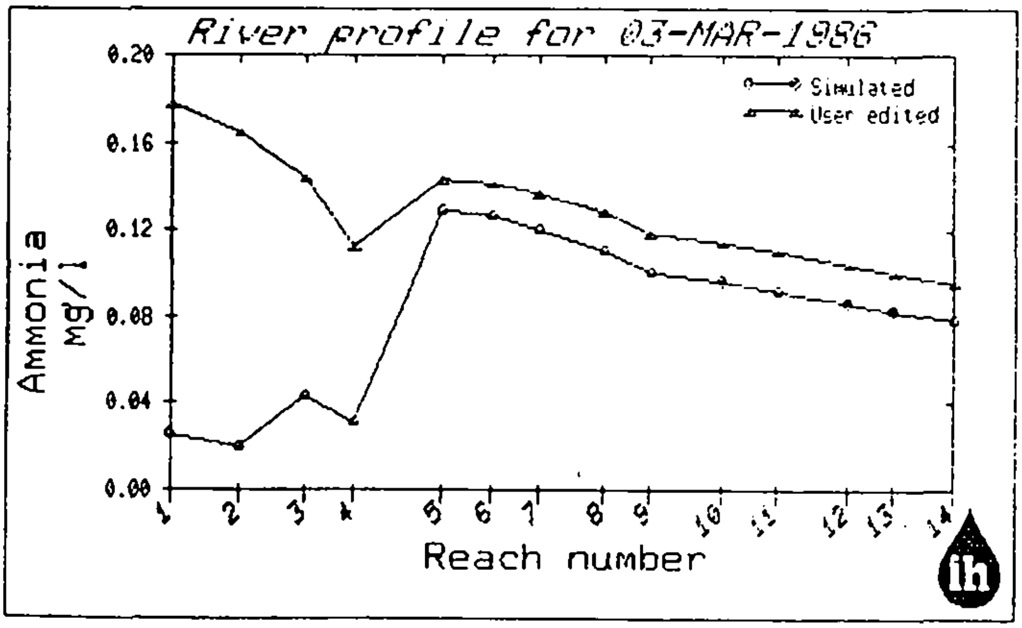




Flow = 1 cumec

BOD = 6 mg/L

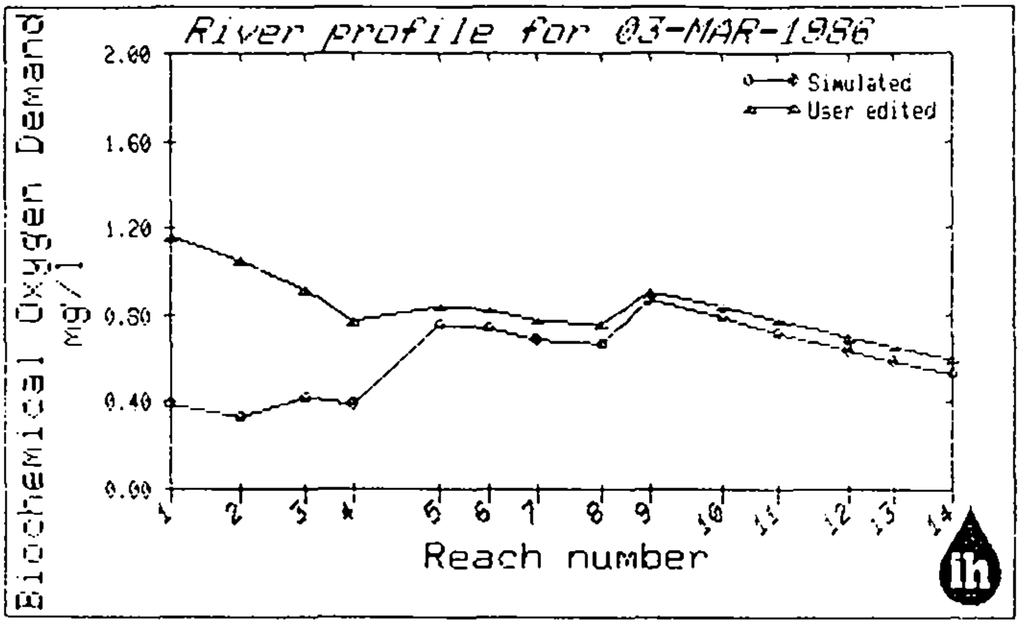


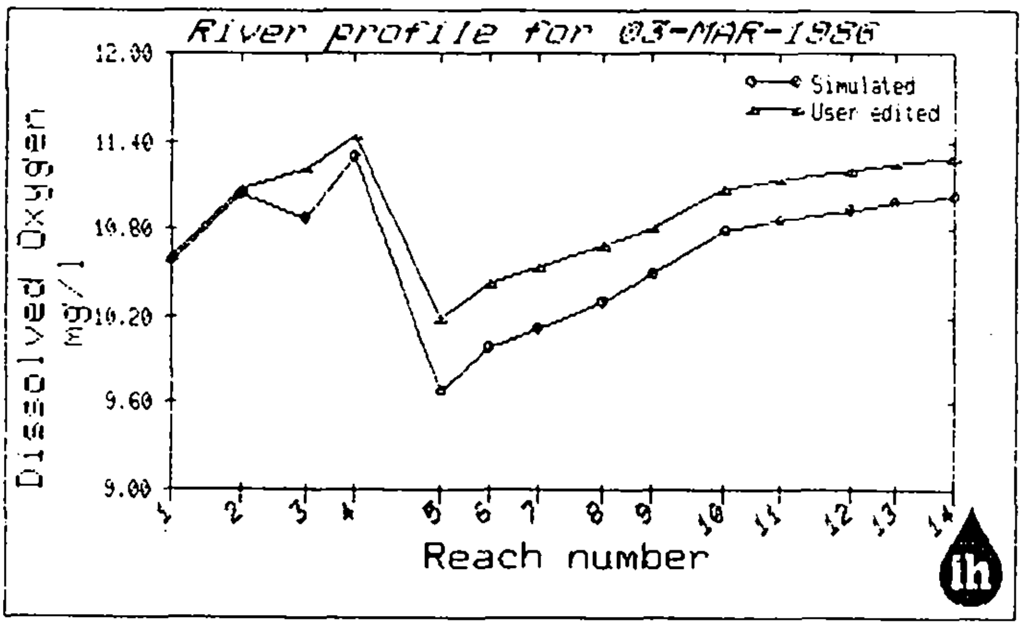


Flow = 1 cumec

Nitrate = 10 mg/L

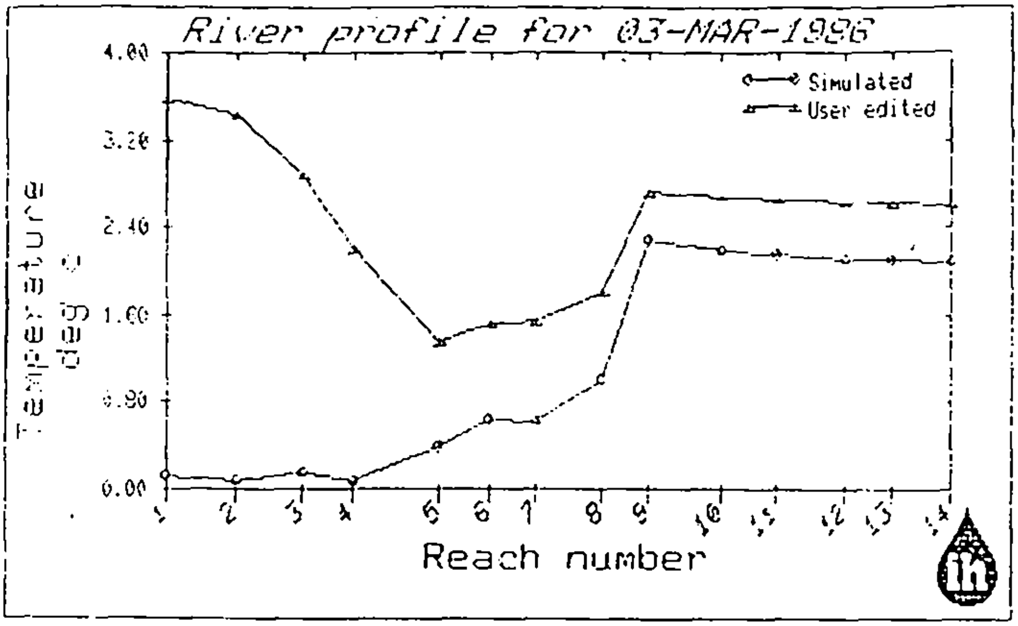
Ammonia = 0.2 mg/L

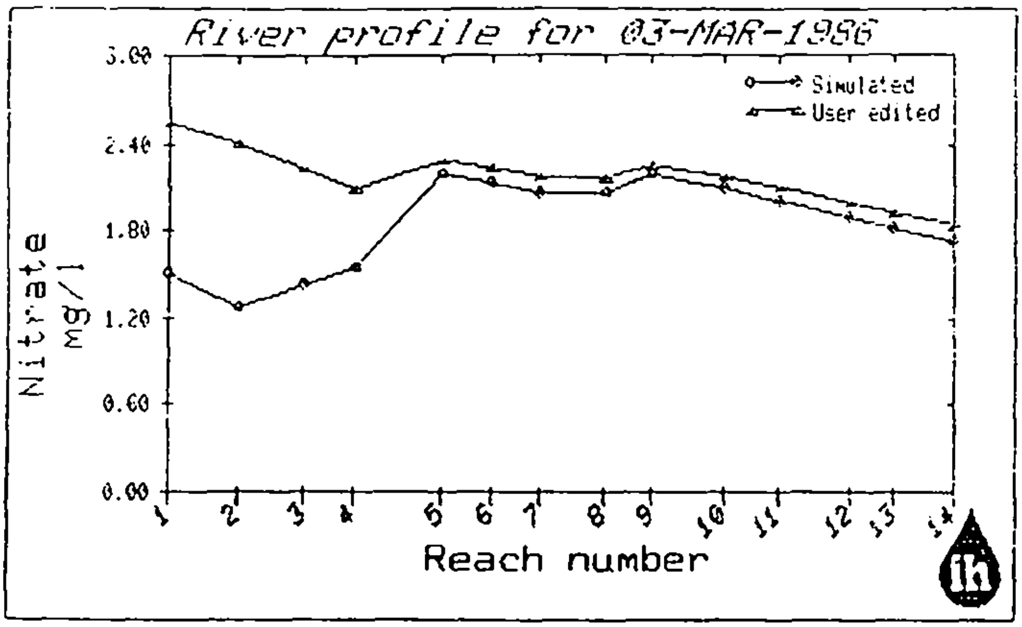


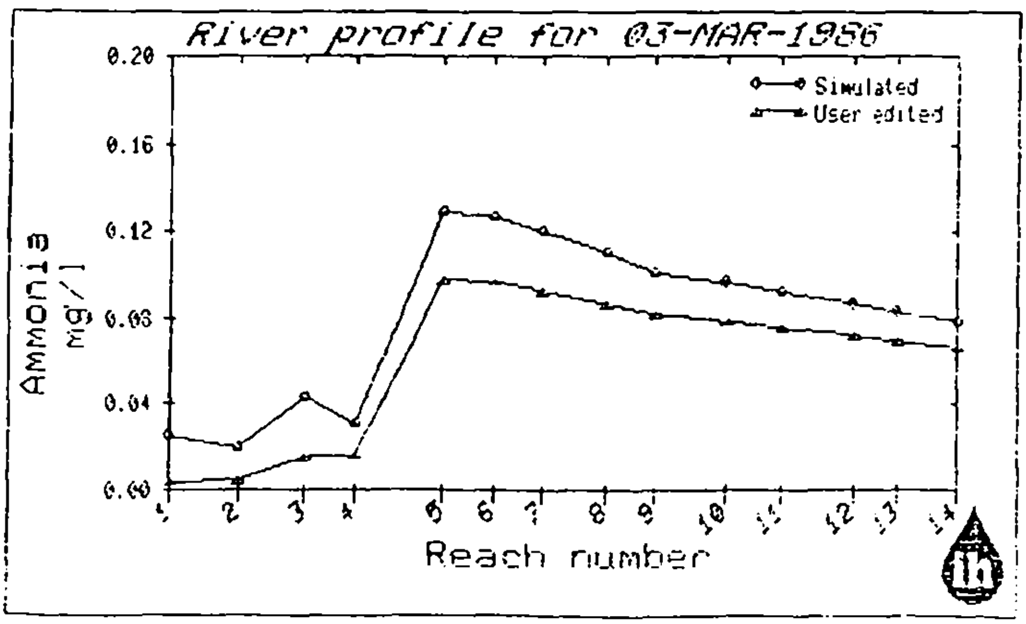


Flow = 1 cumec

BOD = 1.3 mg/L

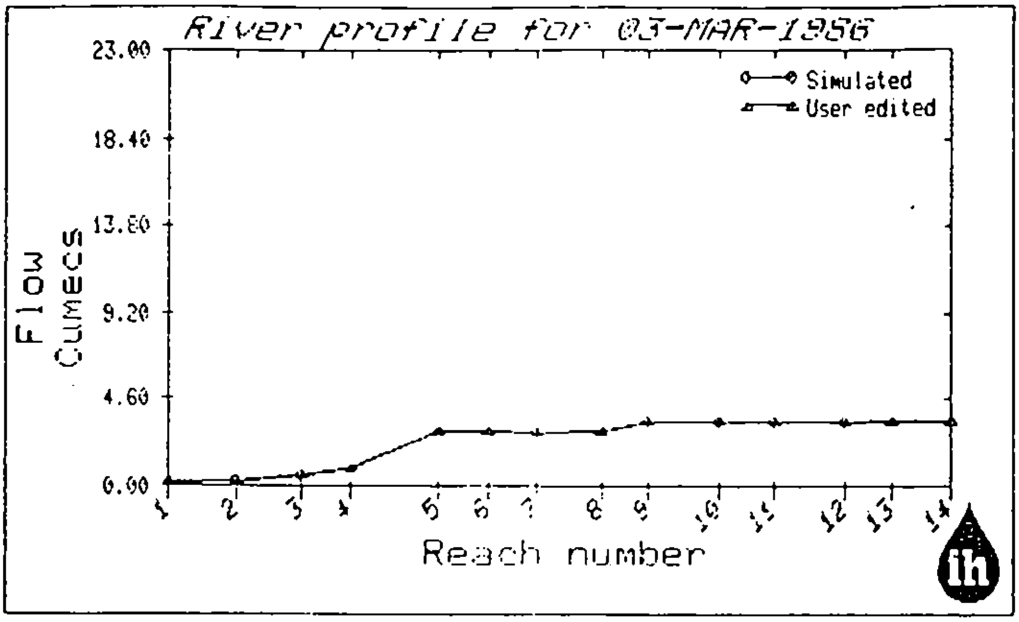


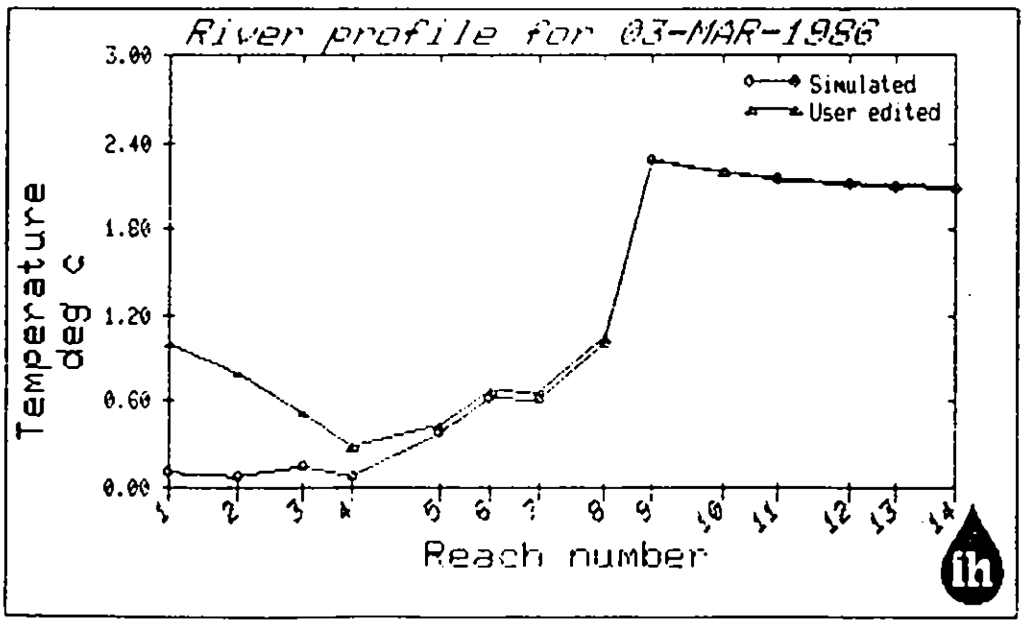




Flow = 1 cumec   Temperature = 4°C

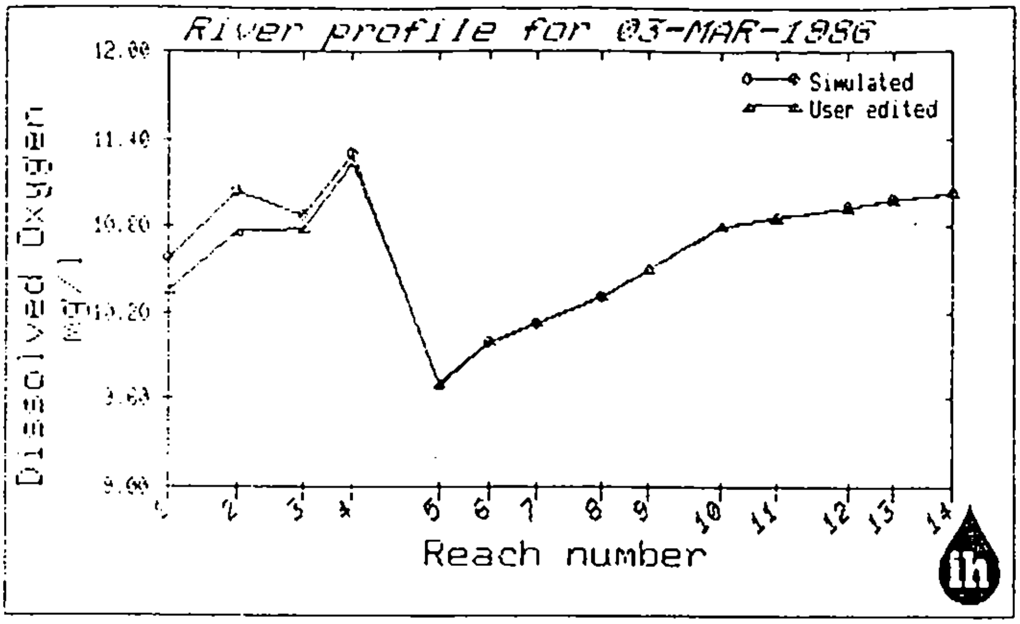
Nitrate = 2.7 mg/L   Ammonia = 0.01 mg/l

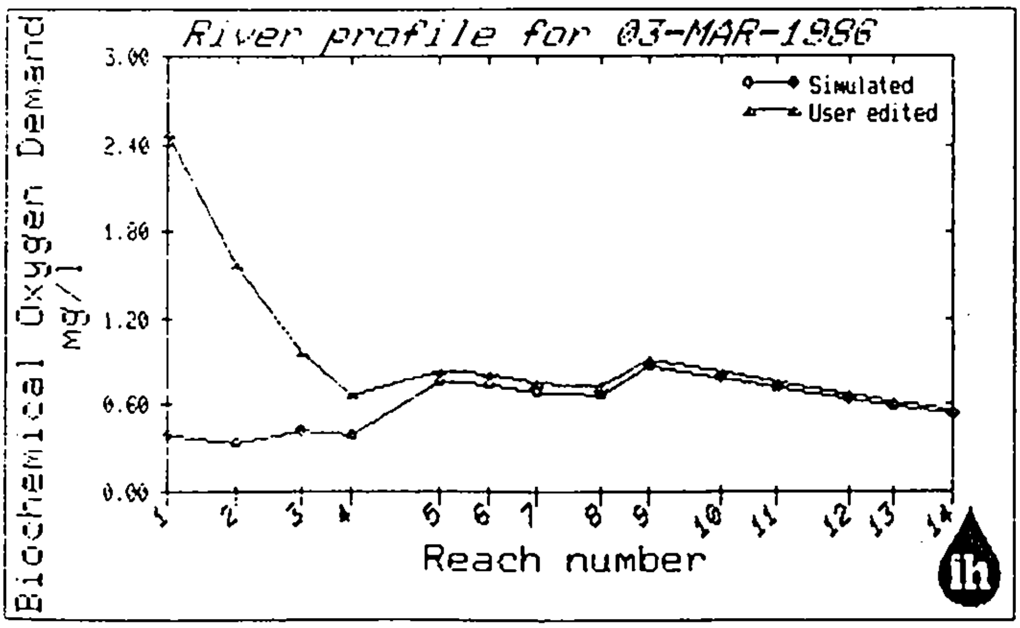




Flow = 0.1 cumec

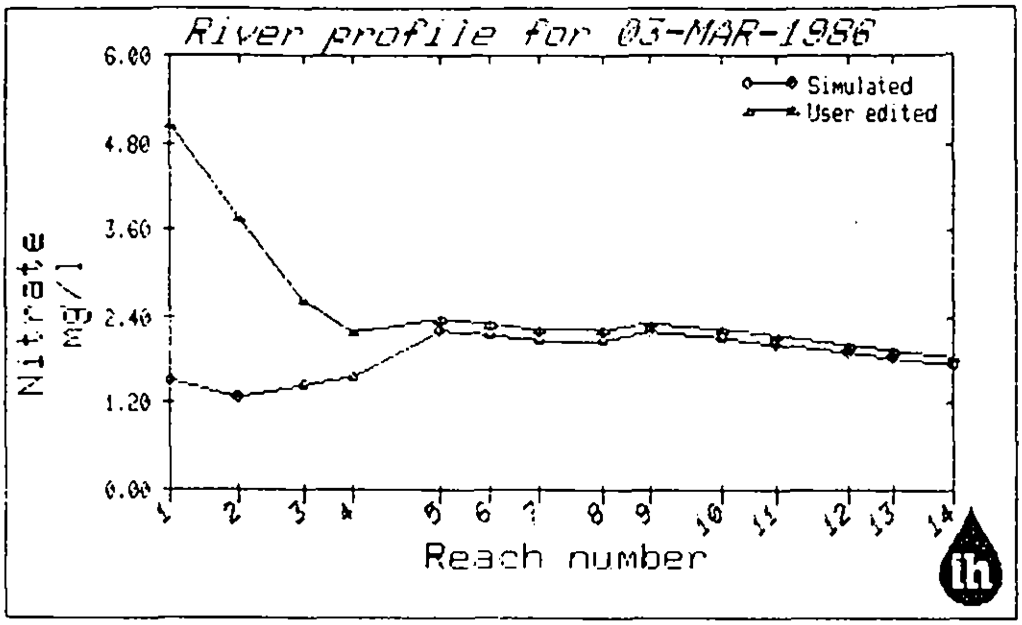
Temperature = 2°C

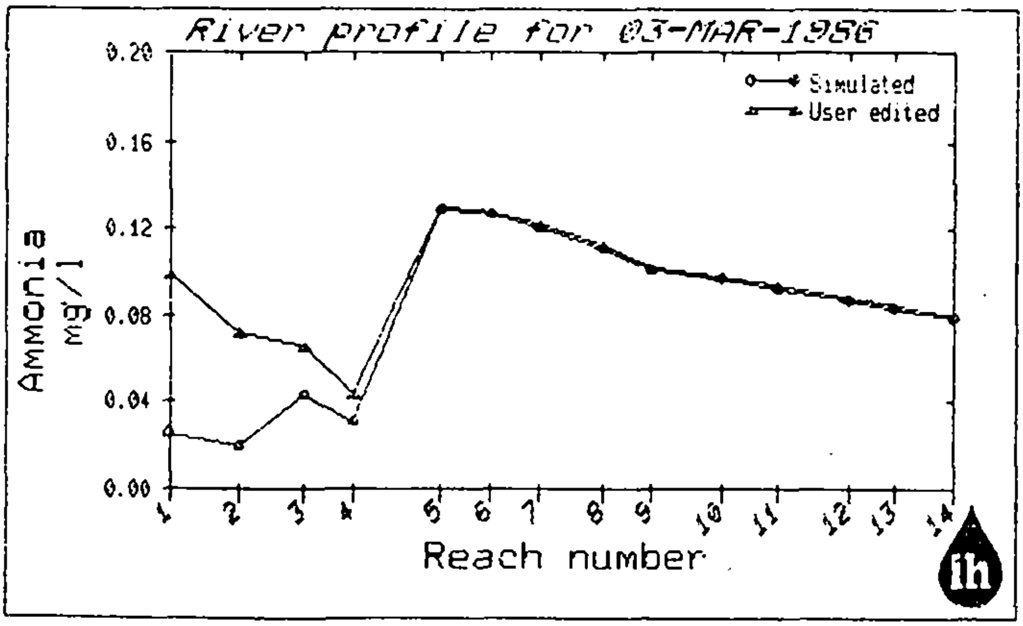




Flow = 0.1 cumec

BOD = 6 mg/L

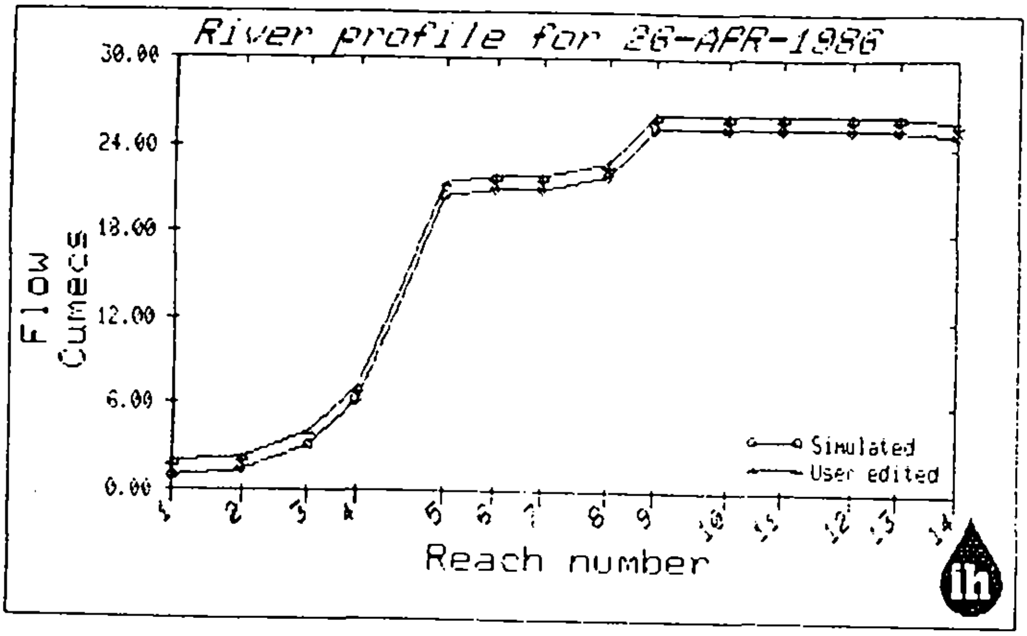


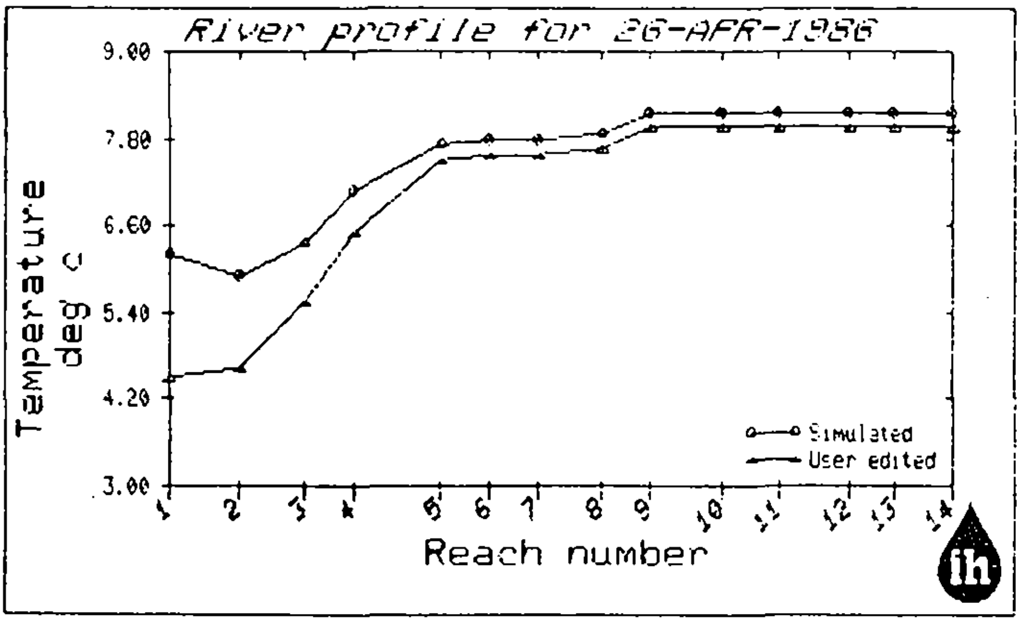


Flow = 0.1 cumec

Nitrate = 10 mg/L

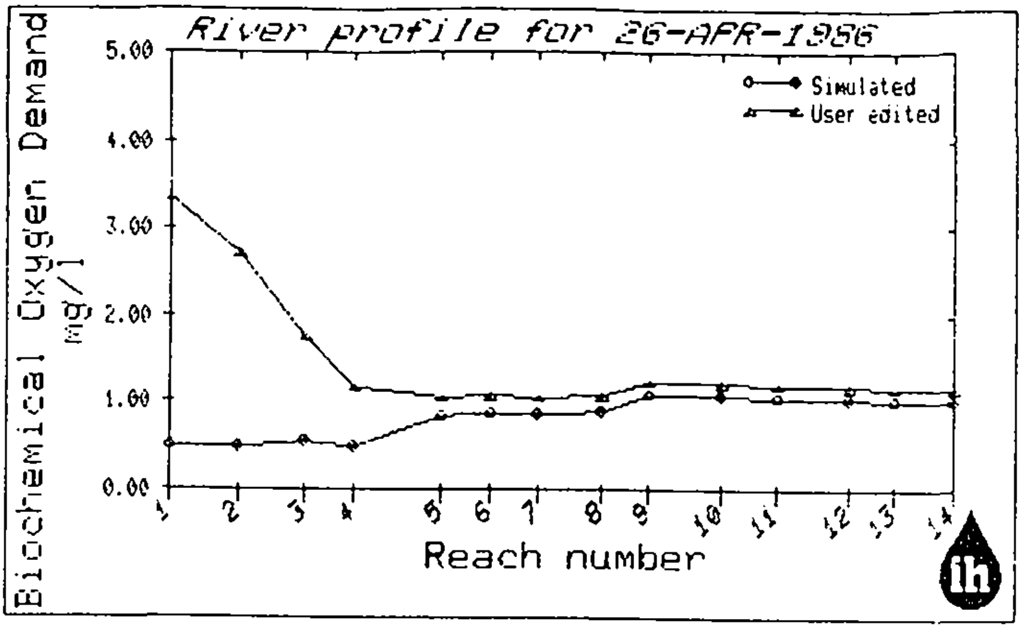
Ammonia = 0.2 mg/L

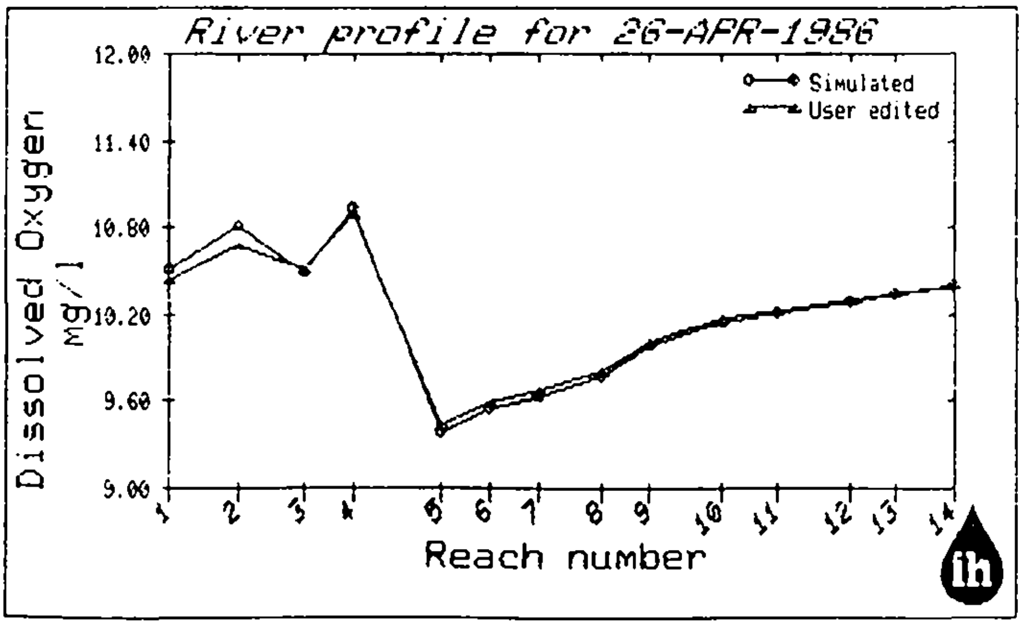




Flow = 1 cumec

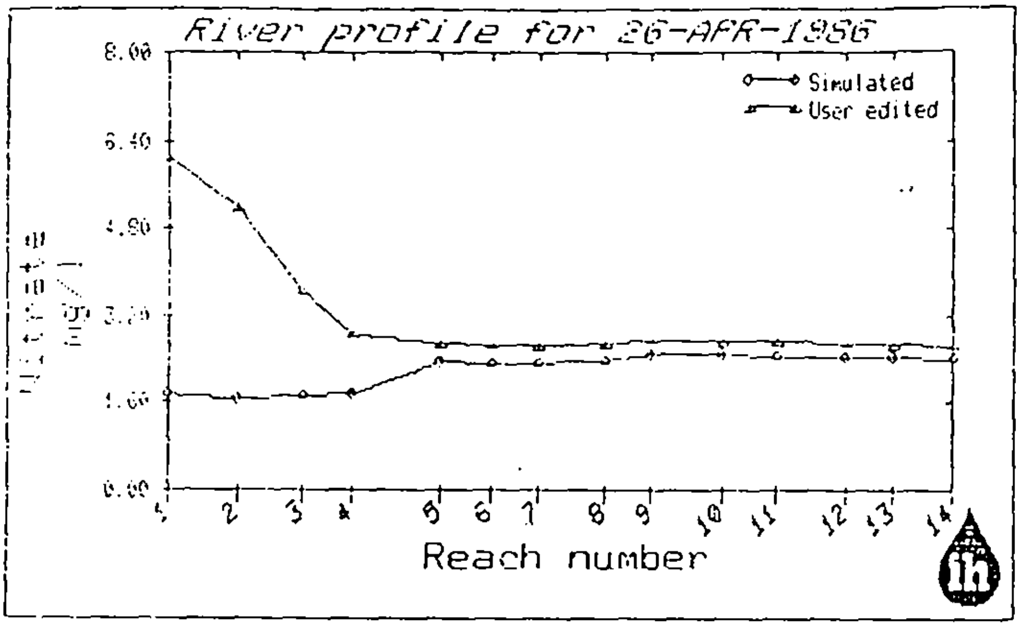
Temperature = 3°C

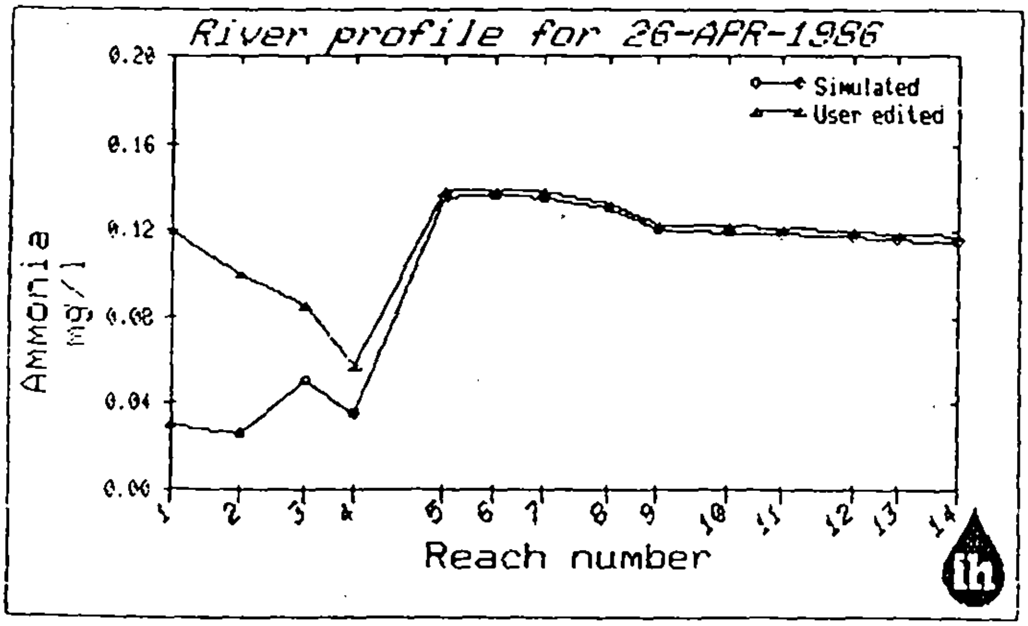




Flow = 1 cumec

BOD = 6 mg/L

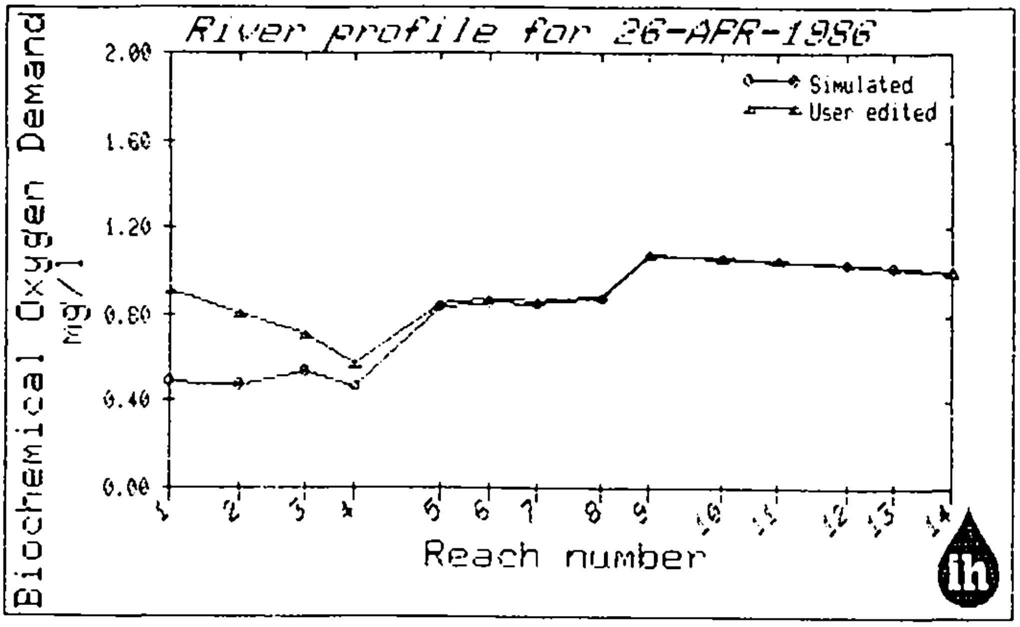


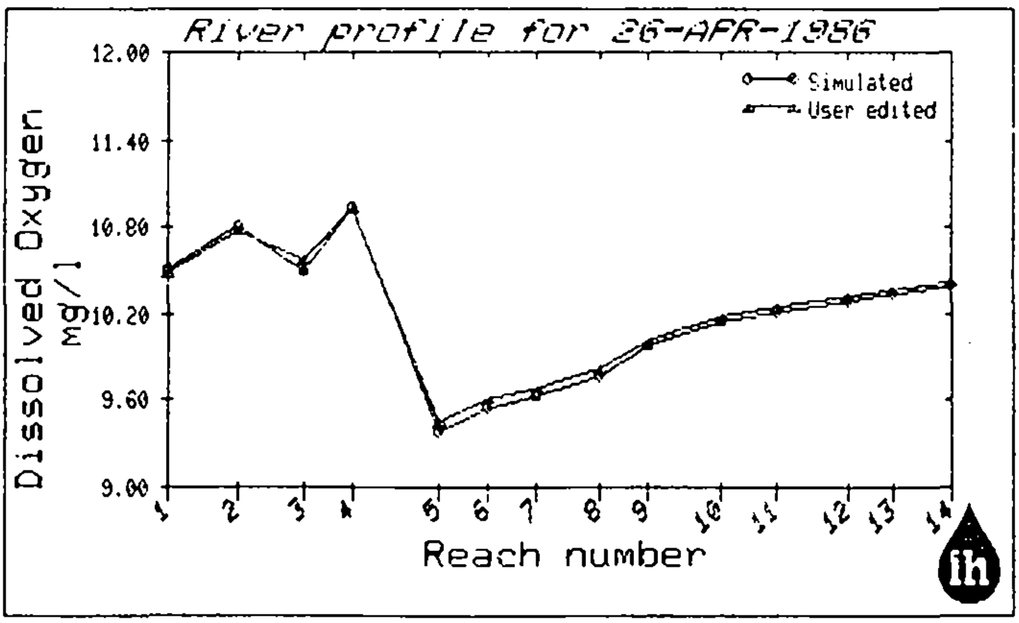


Flow = 1 cumec

Nitrate = 10 mg/L

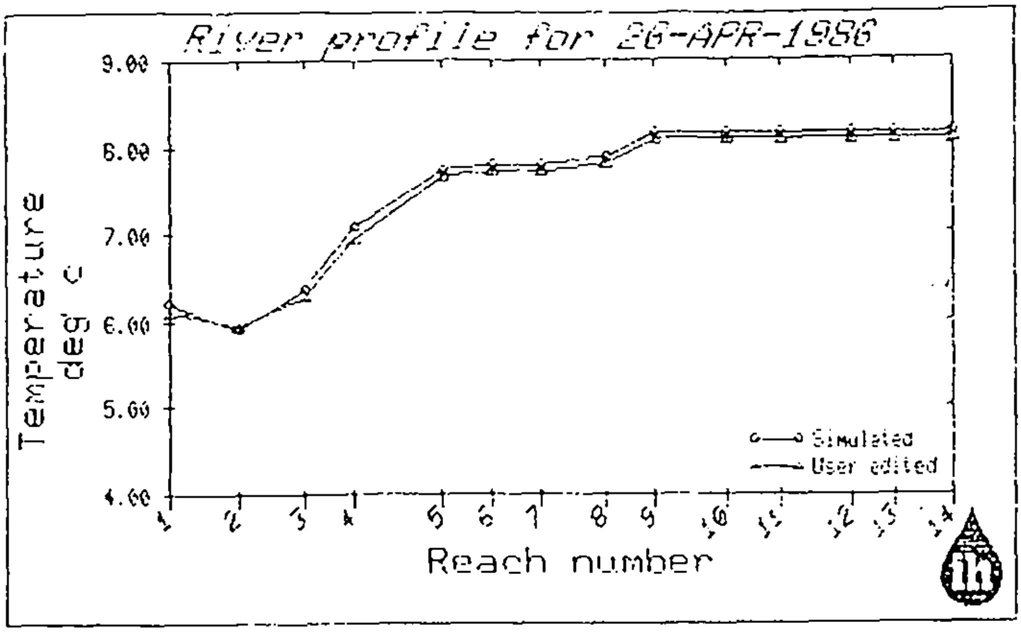
Ammonia = 0.2 mg/L

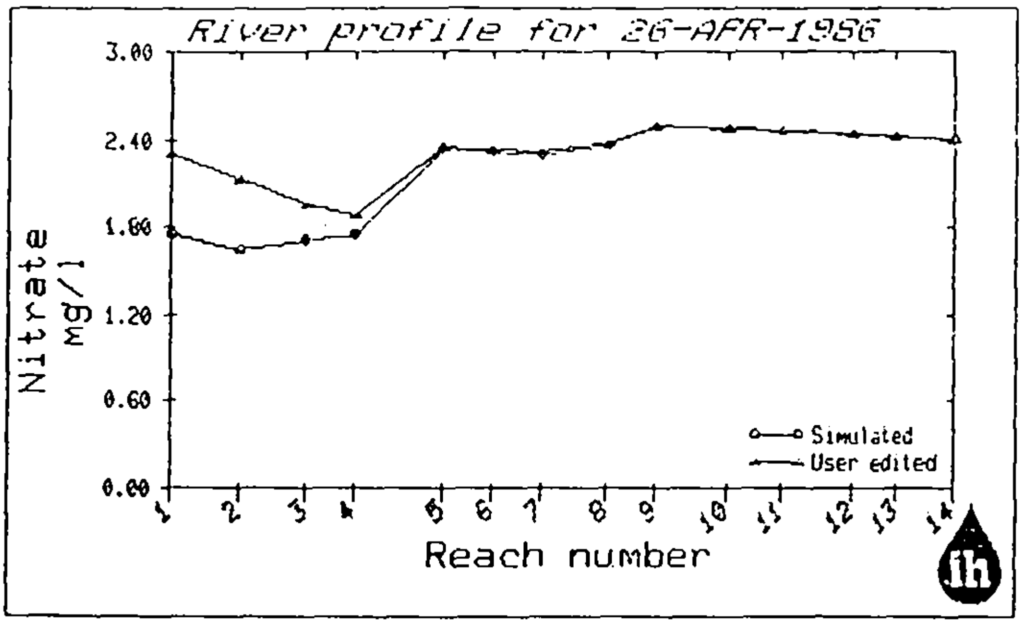


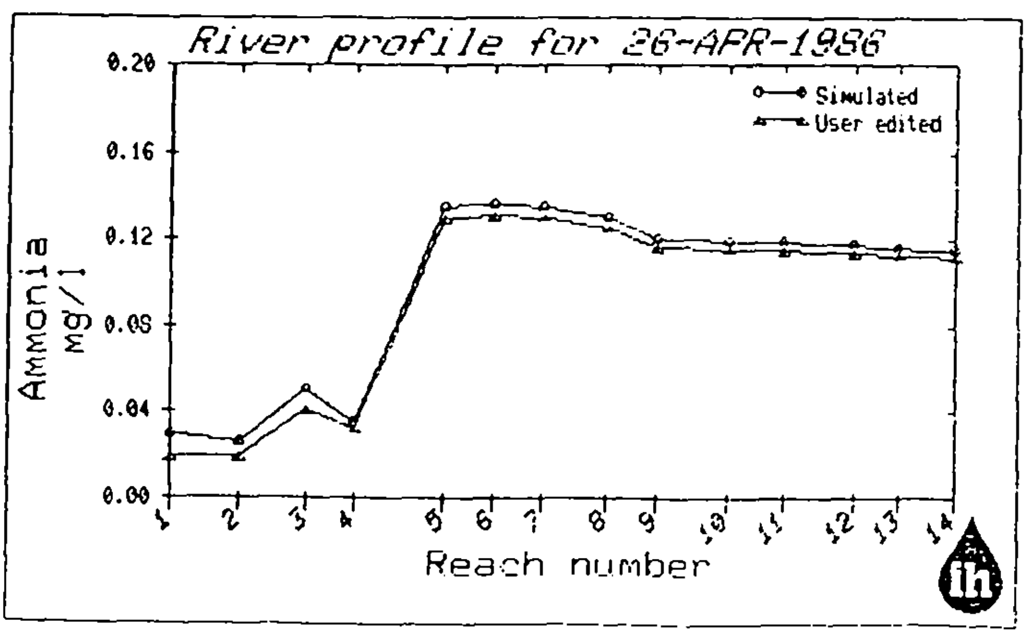


Flow = 1 cumec

BOD = 1.3 mg/L

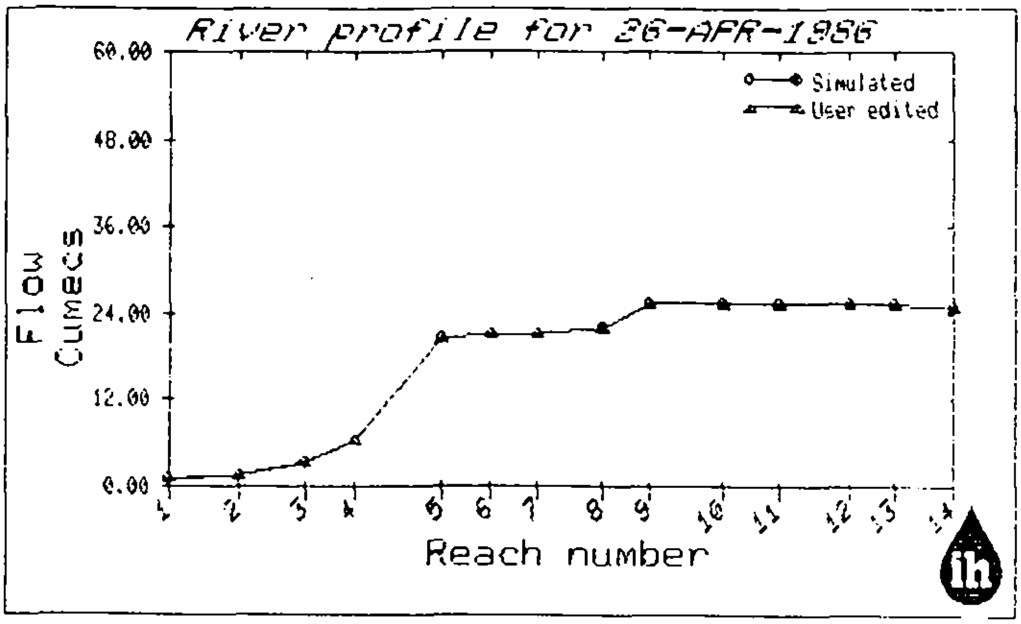


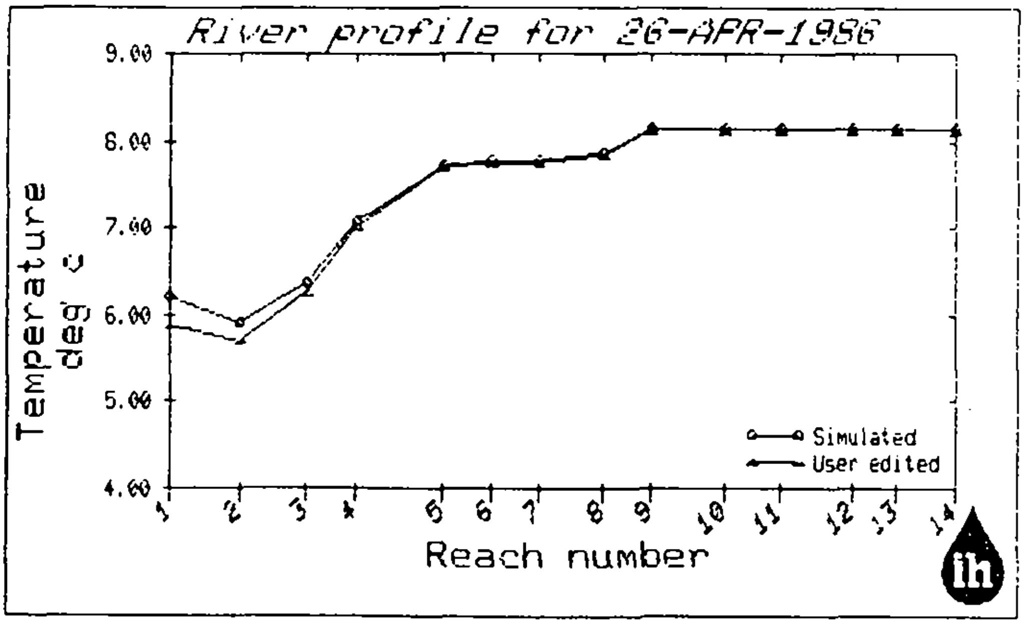




Flow = 1 cumec   Temperature = 6°C

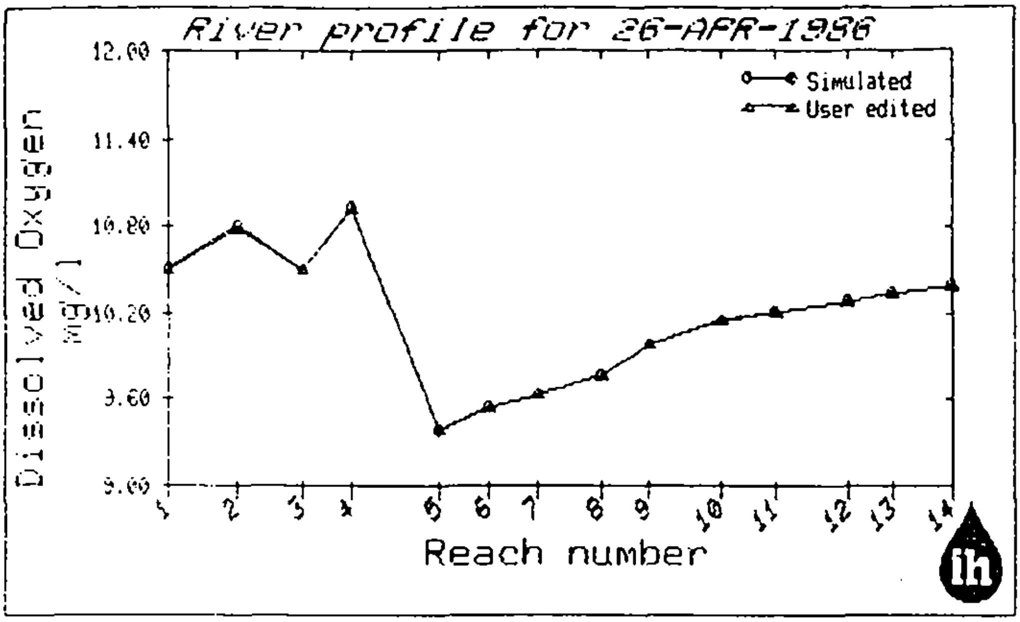
Nitrate = 2.8 mg/L   Ammonia = 0.01 mg/L

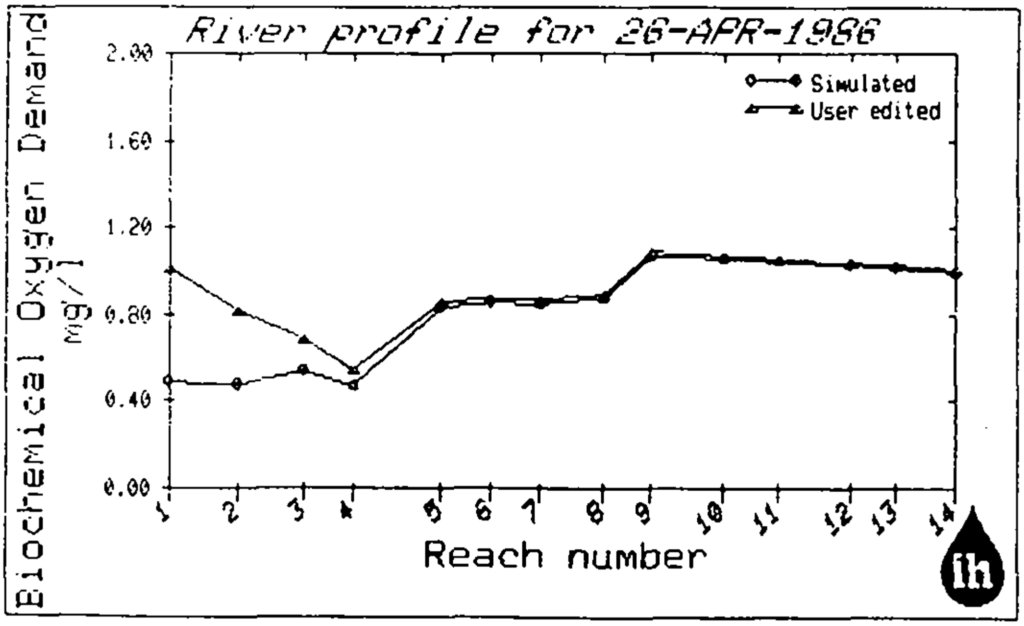




Flow = 0.1 cumec

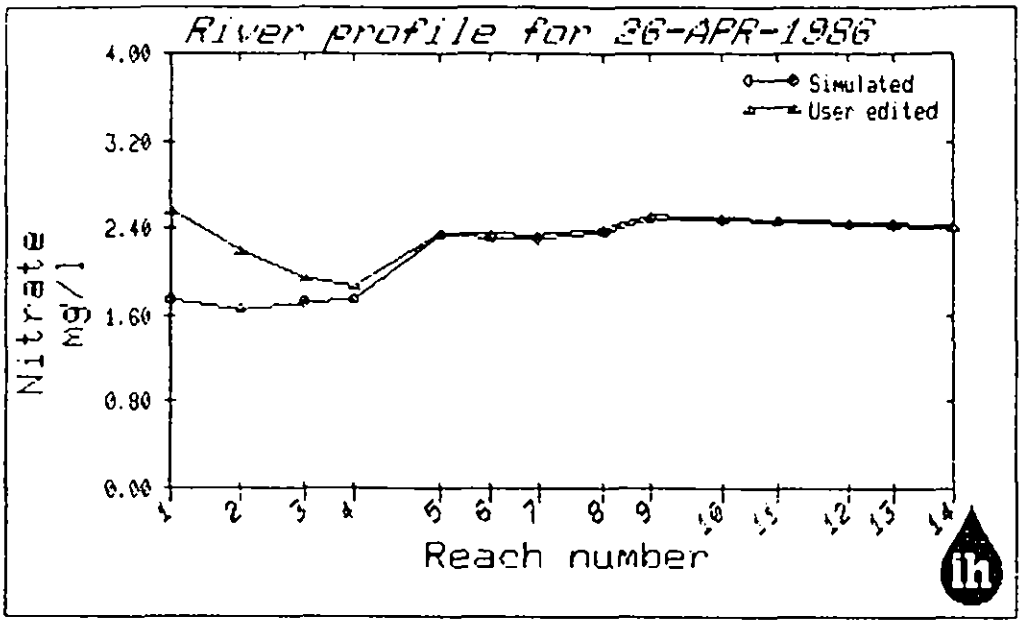
Temperature = 3°C

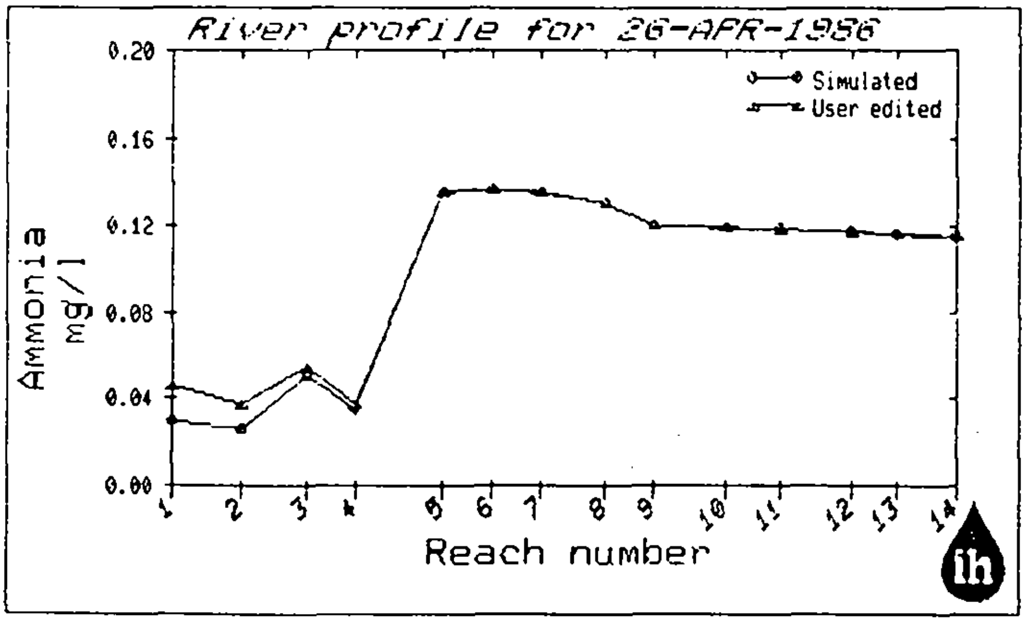




Flow = 0.1 cumec

BOD = 6 mg/L

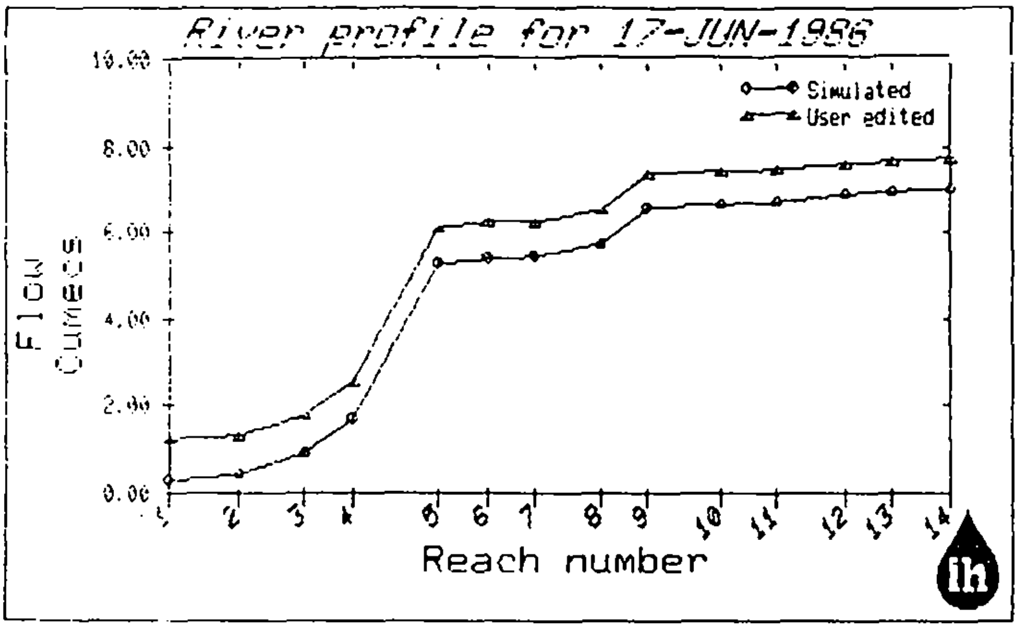


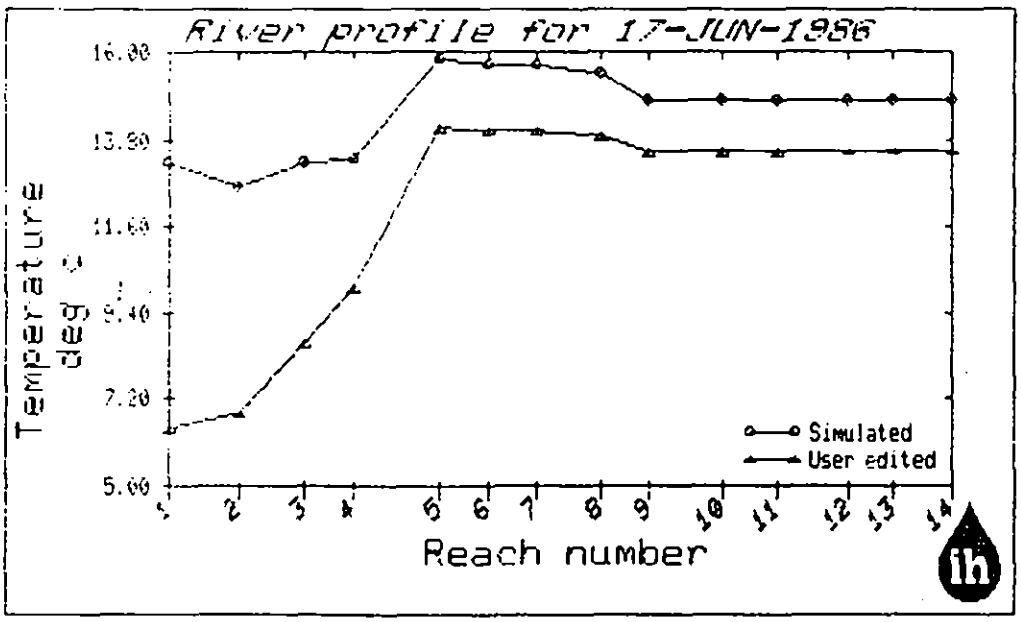


Flow = 0.1 cumec

Nitrate = 10 mg/L

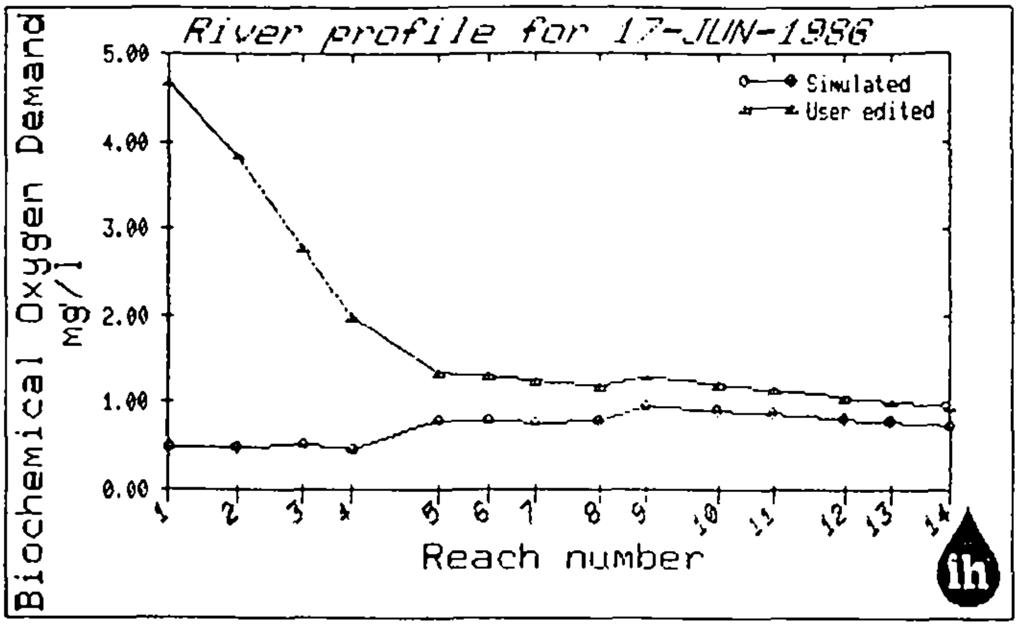
Ammonia = 0.2 mg/L

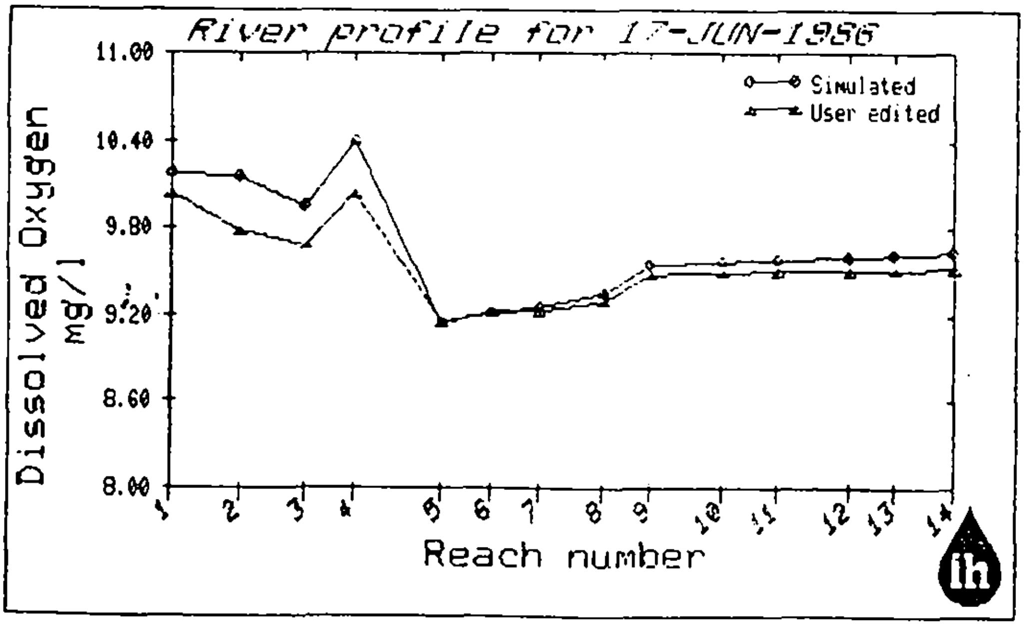




Flow = 1 cumec

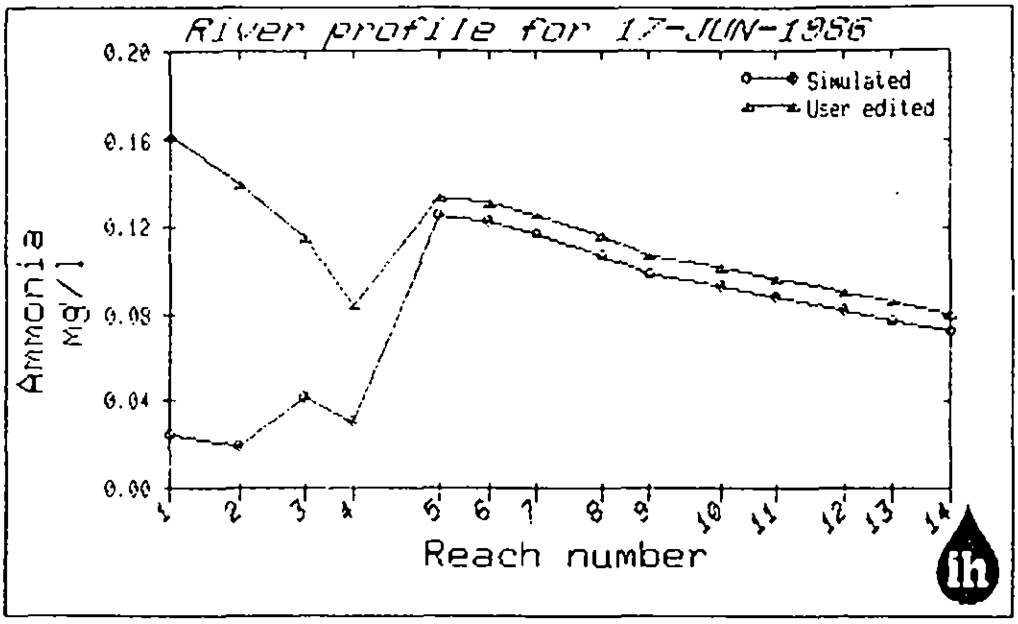
Temperature = 5°C

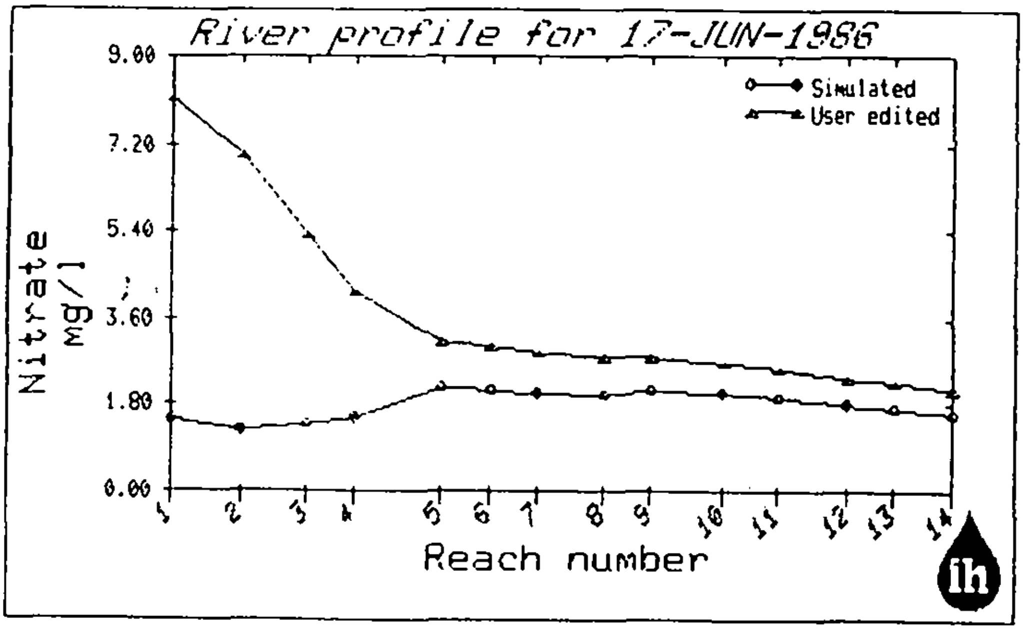




Flow = 1 cumec

BOD = 6 mg/L

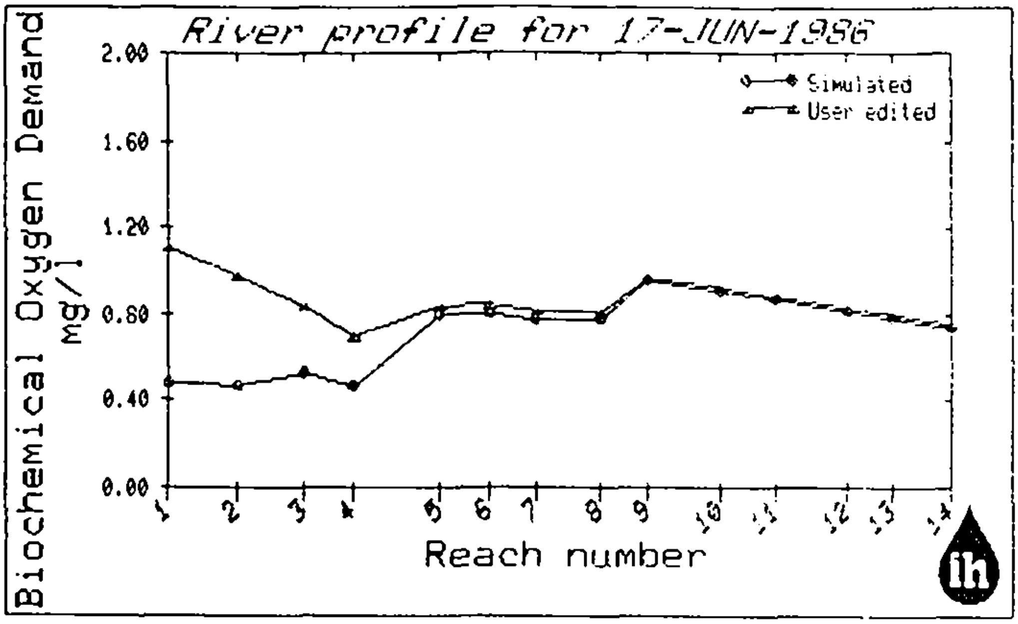


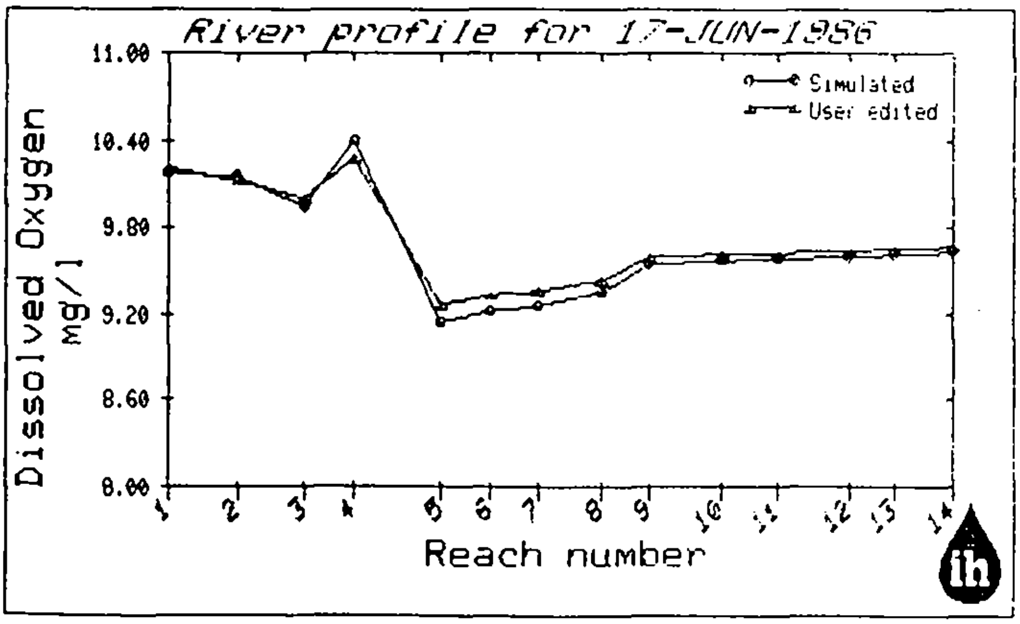


Flow = 1 cumec

Nitrate = 10 mg/L

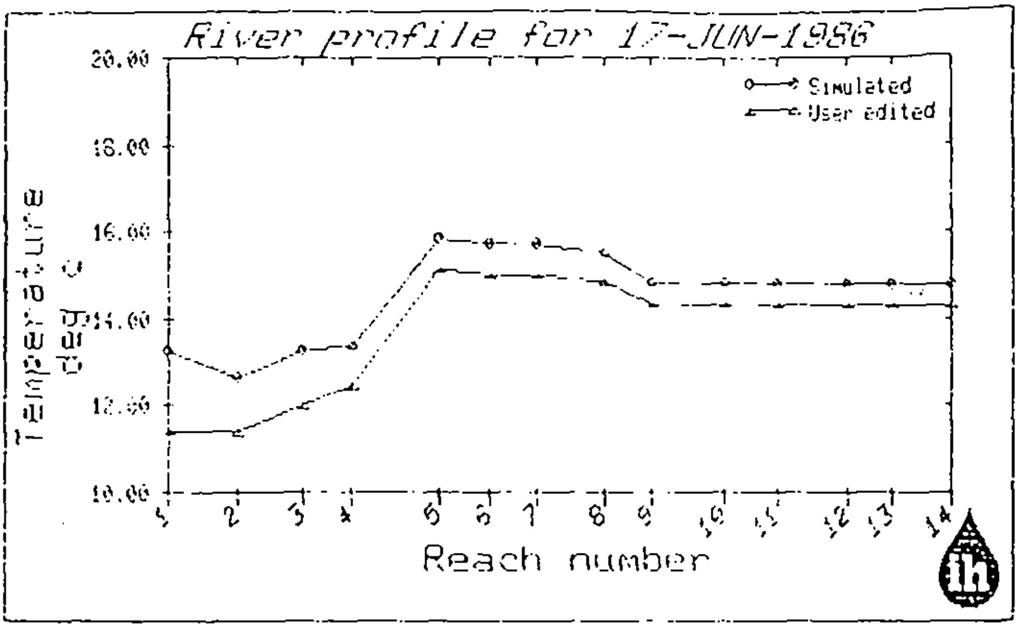
Ammonia = 0.2 mg/L

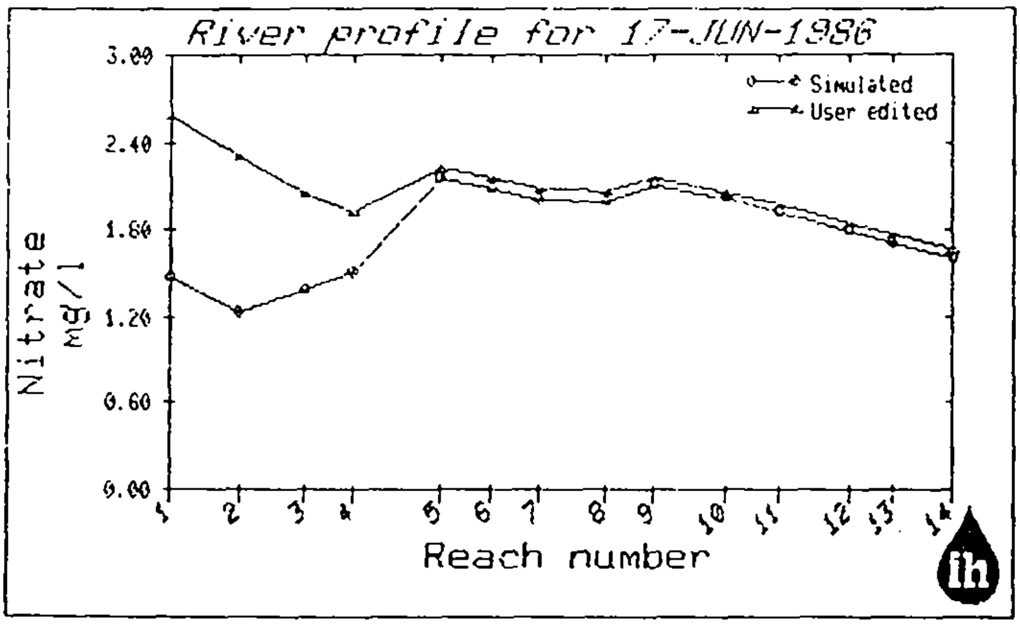


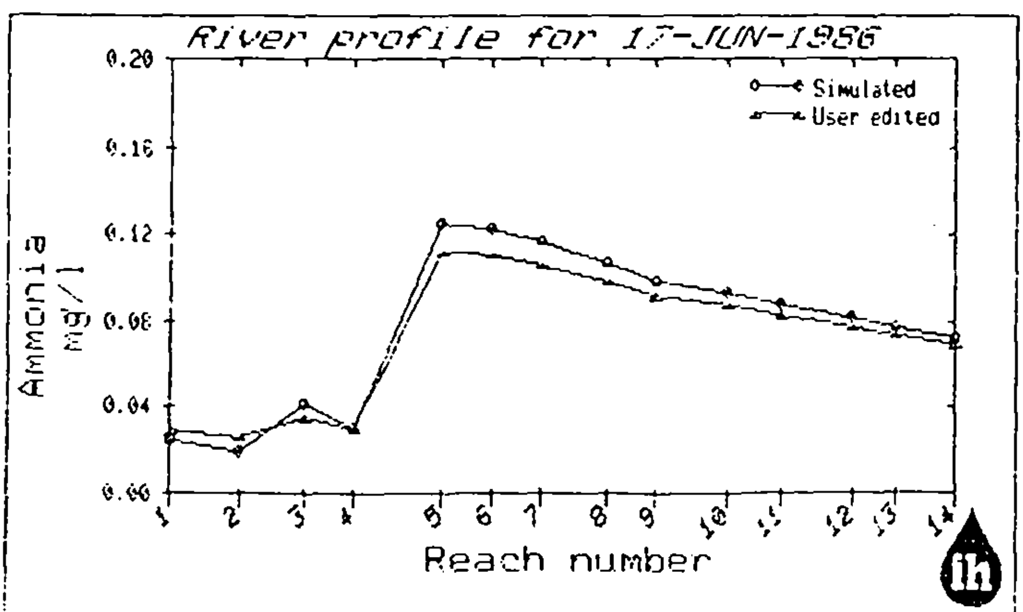


Flow = 1 cumec

BOD = 1.3 mg/L

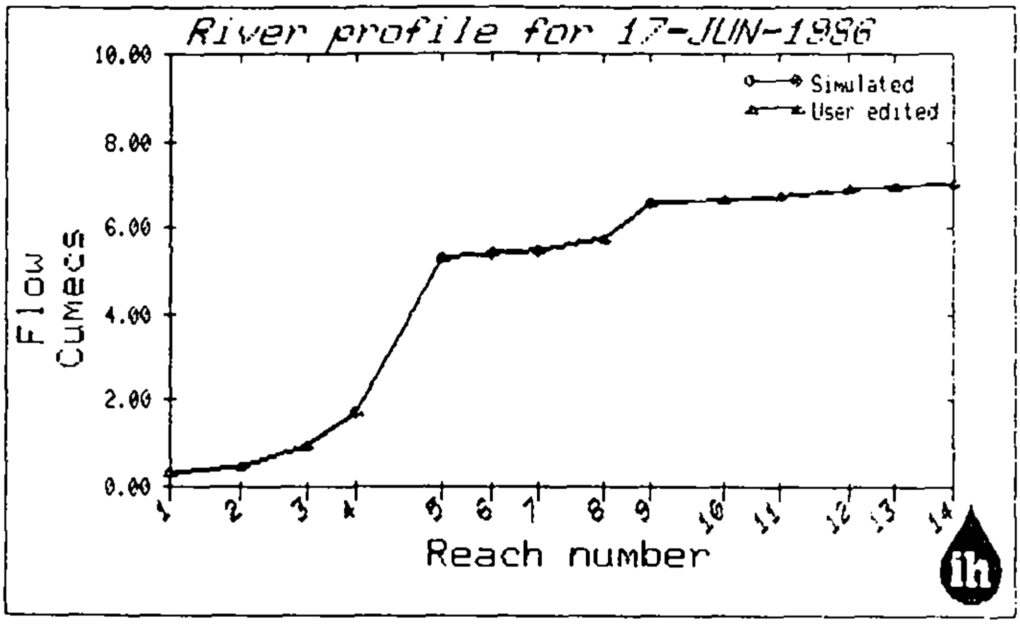


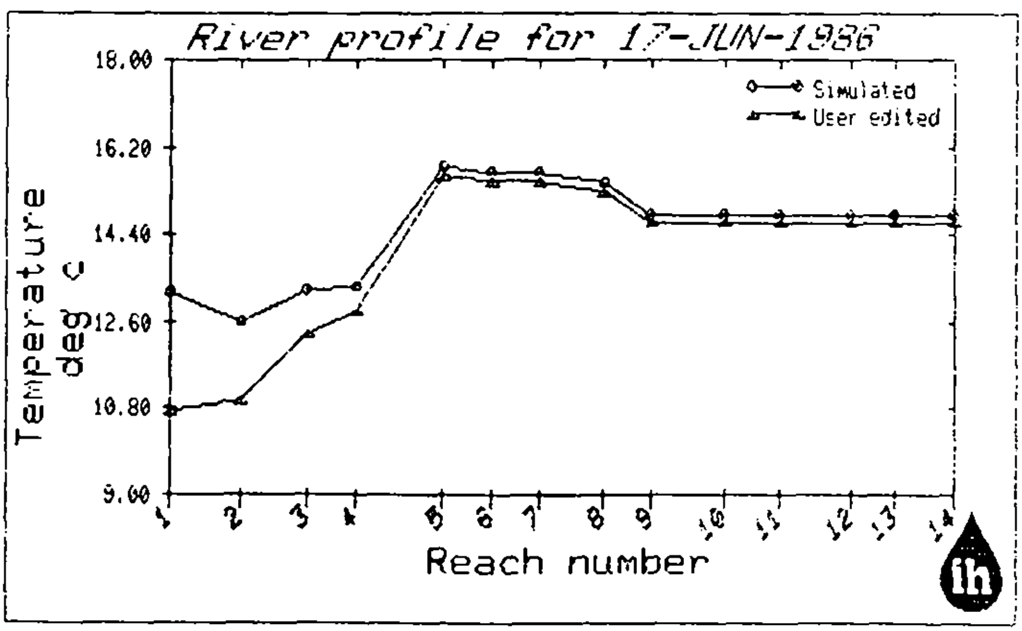




Flow = 1 cumec   Temperature = 11°C

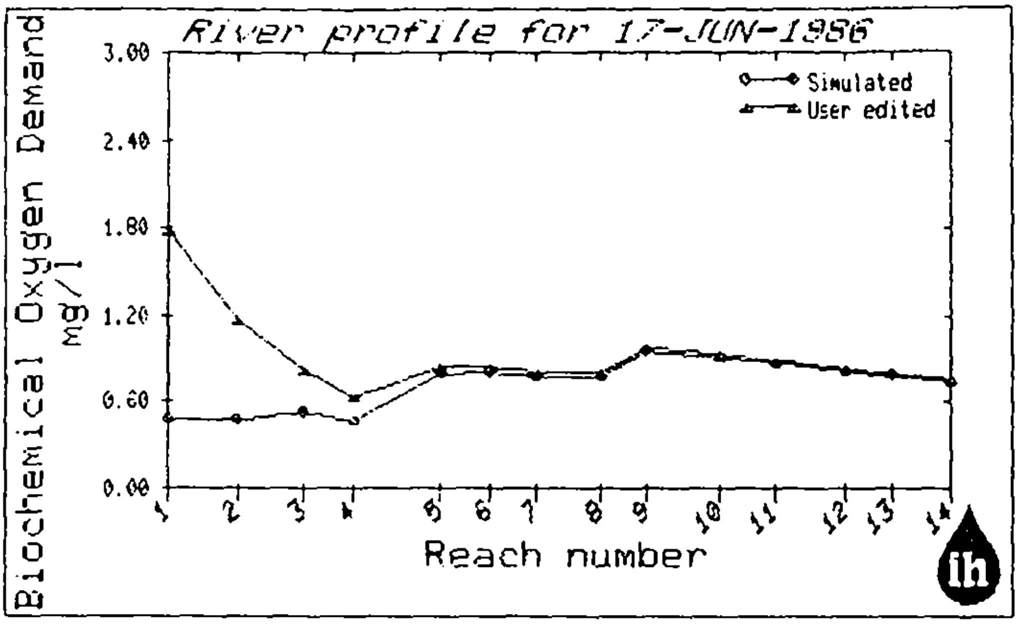
Nitrate = 2.9 mg/L   Ammonia = 0.03 mg/L

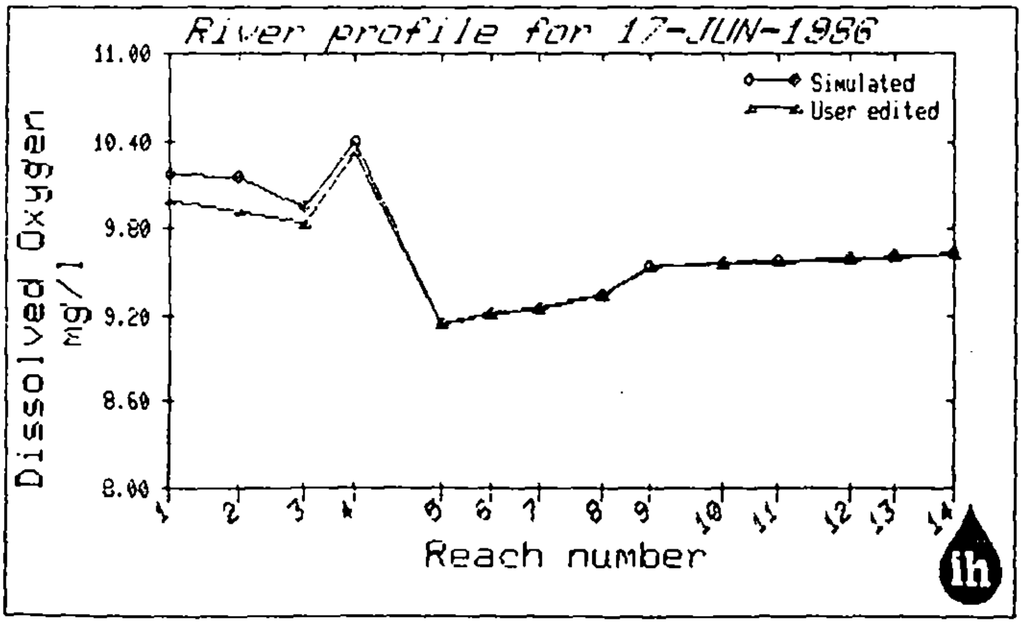




Flow = 0.1 cumec

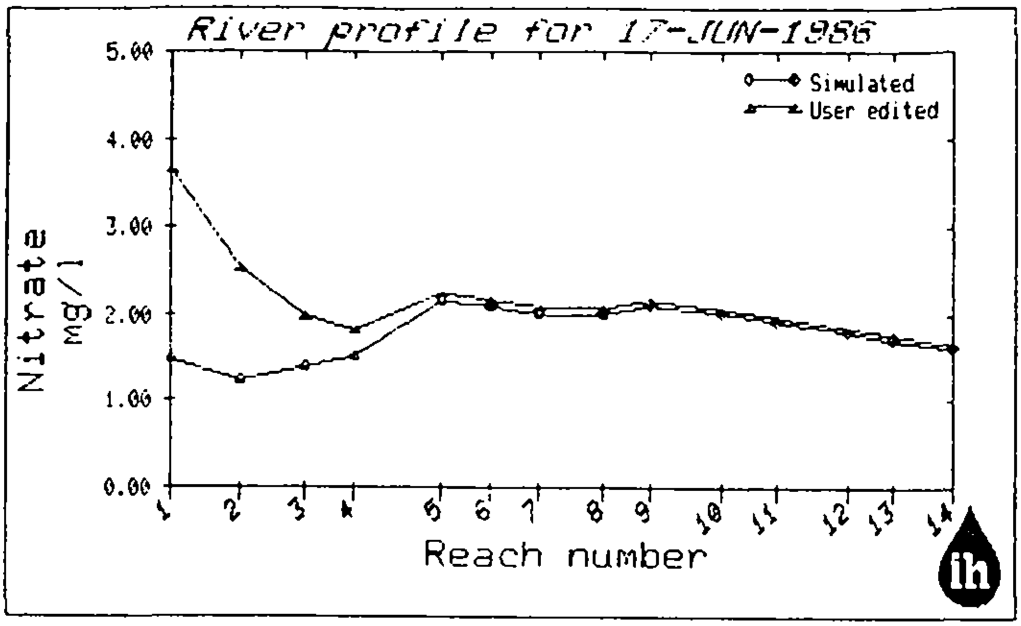
Temperature = 5°C

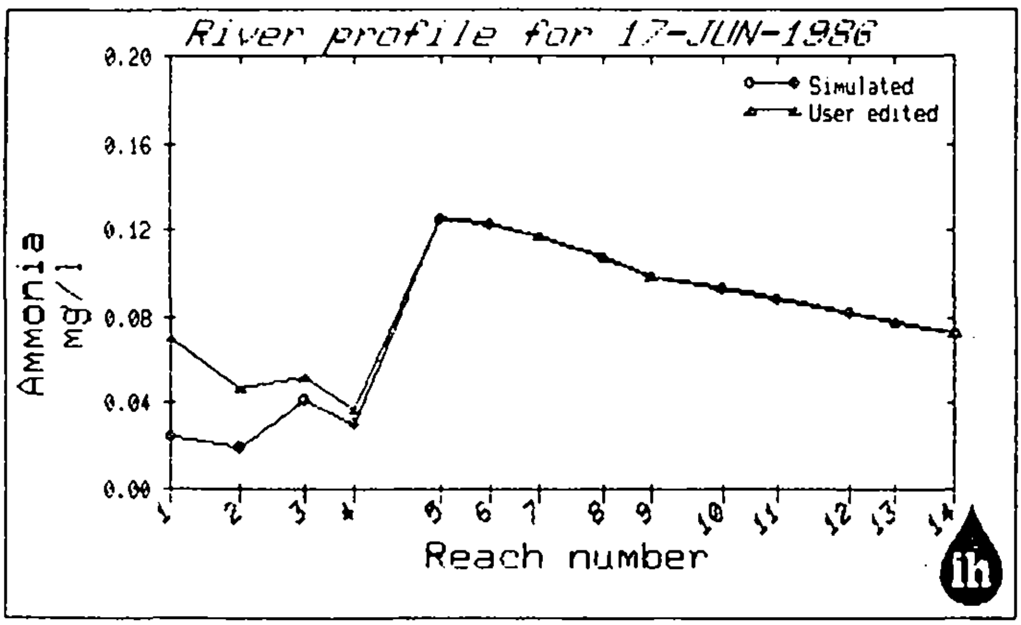




Flow = 0.1 cumec

BOD = 6 mg/L

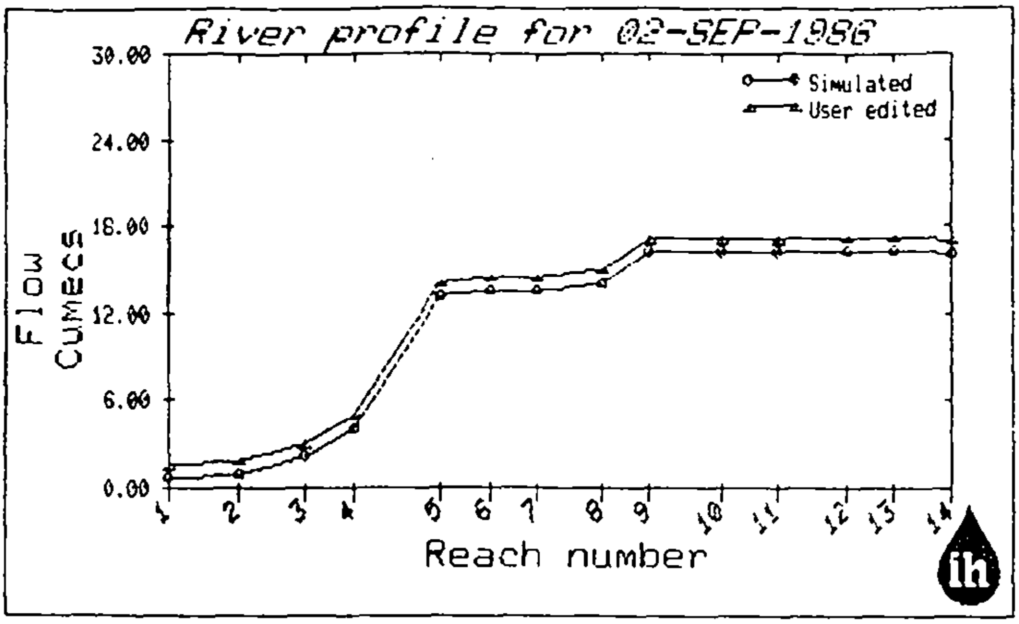


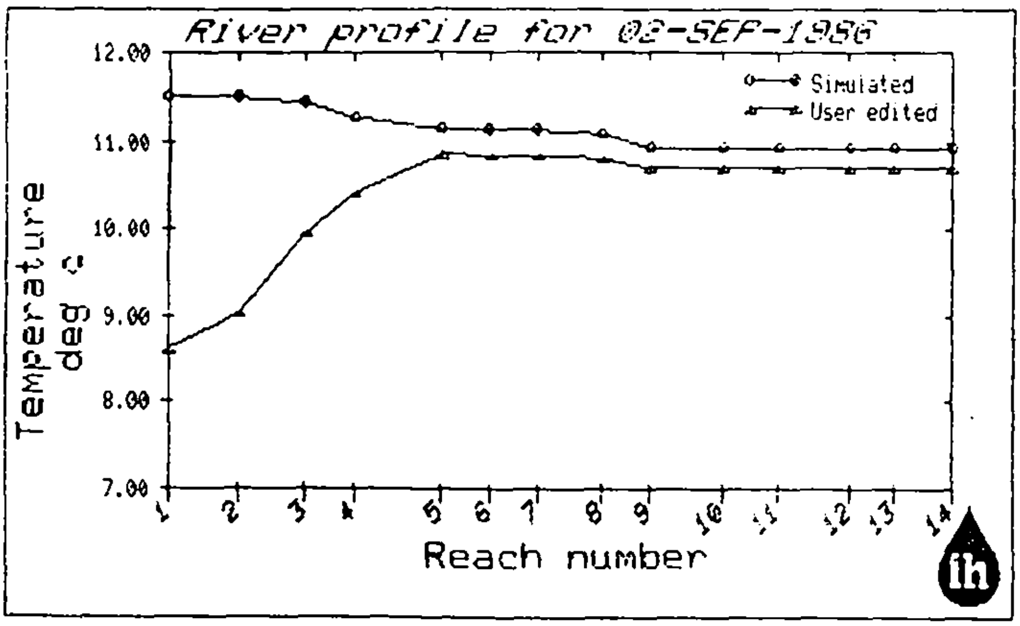


Flow = 0.1 cumec

Nitrate = 10 mg/L

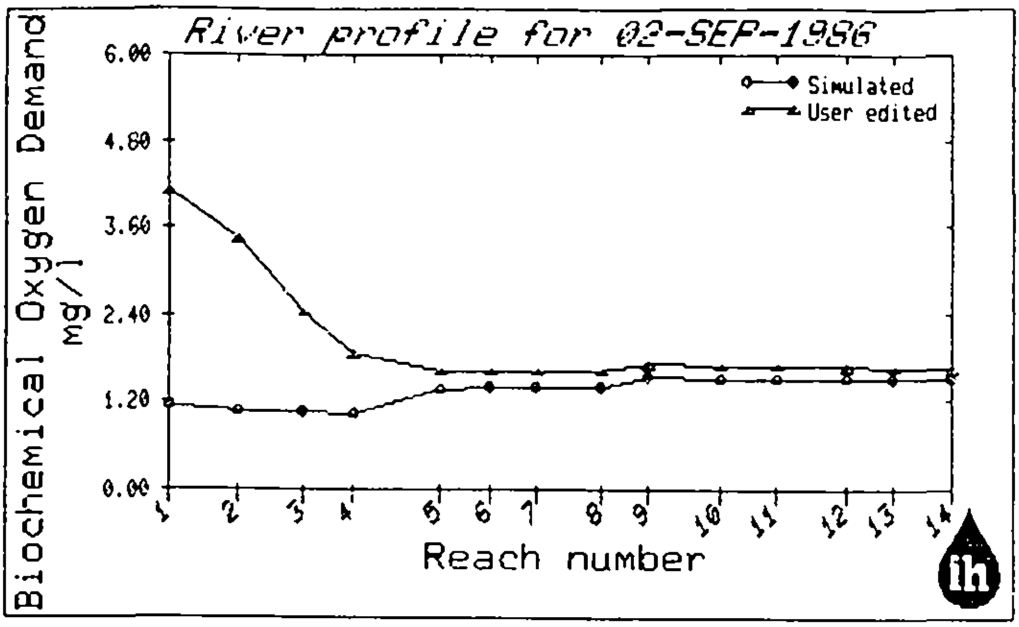
Ammonia = 0.2 mg/L

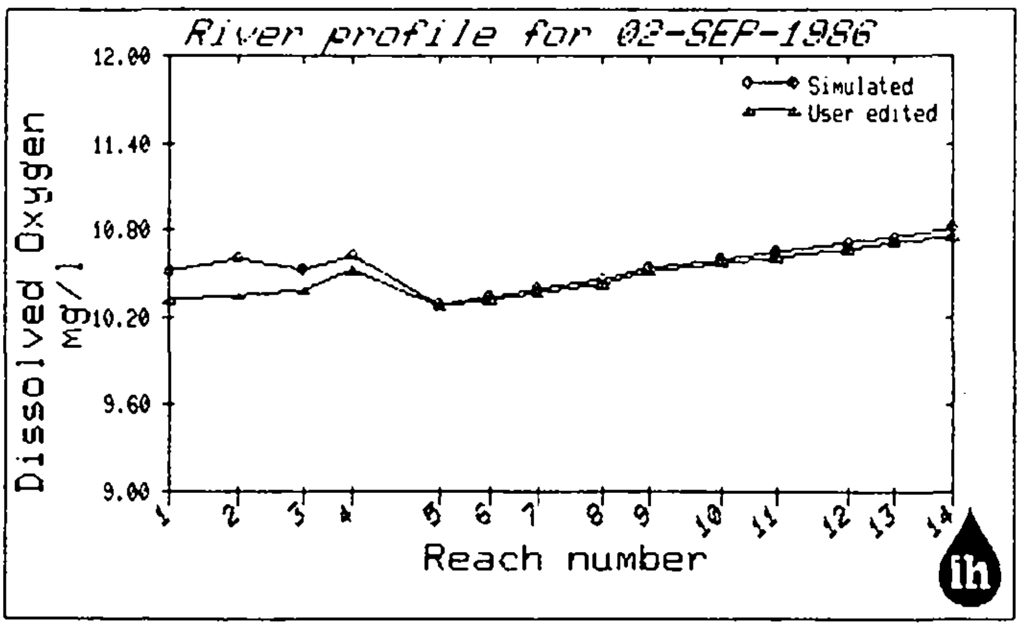




Flow = 1 cumec

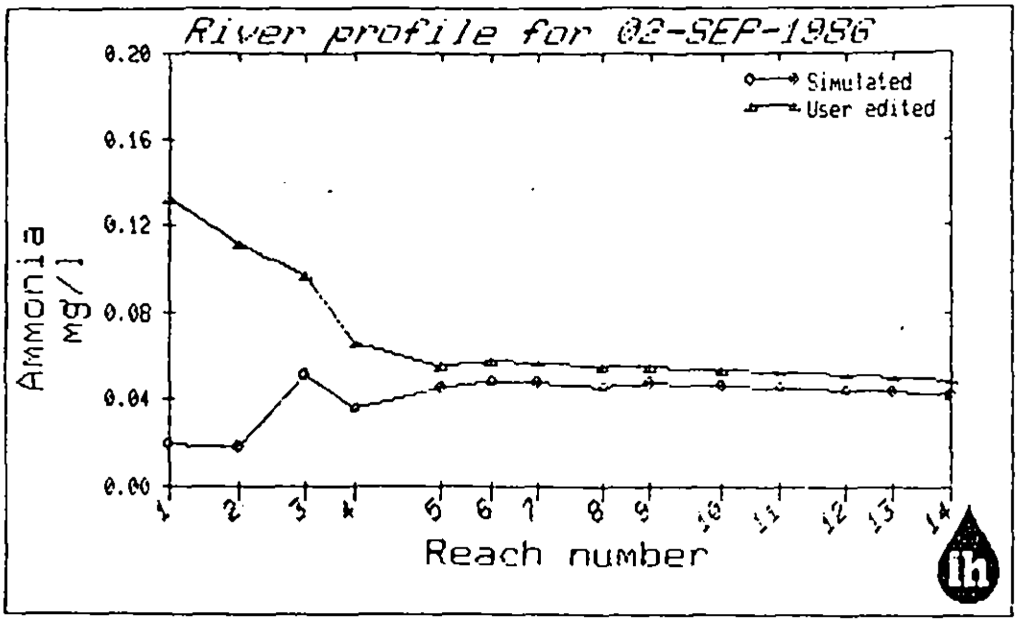
Temperature = 7°C

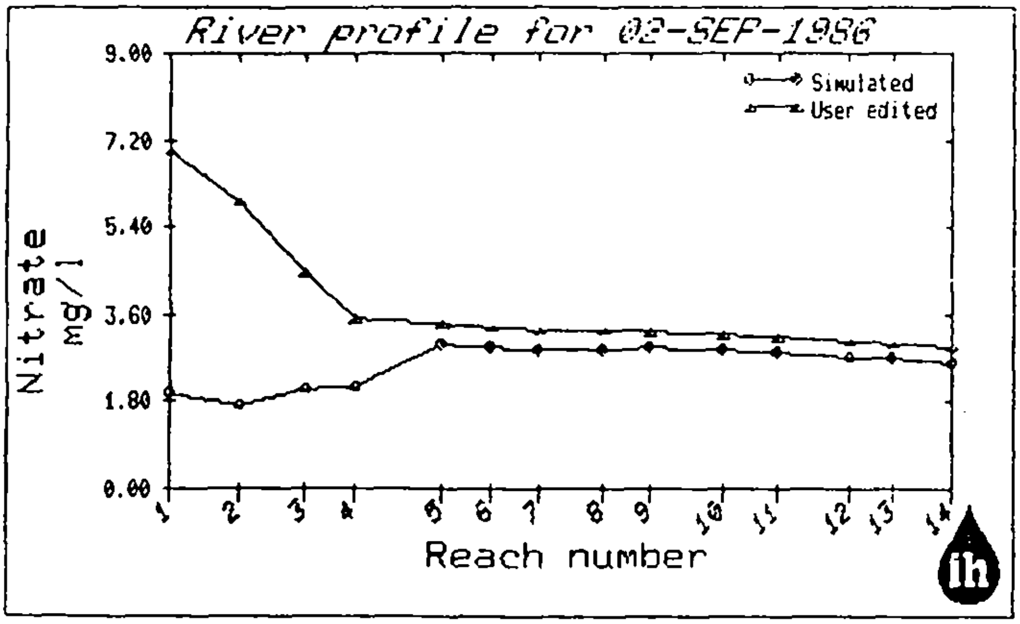




Flow = 1 cumec

BOD = 6 mg/L

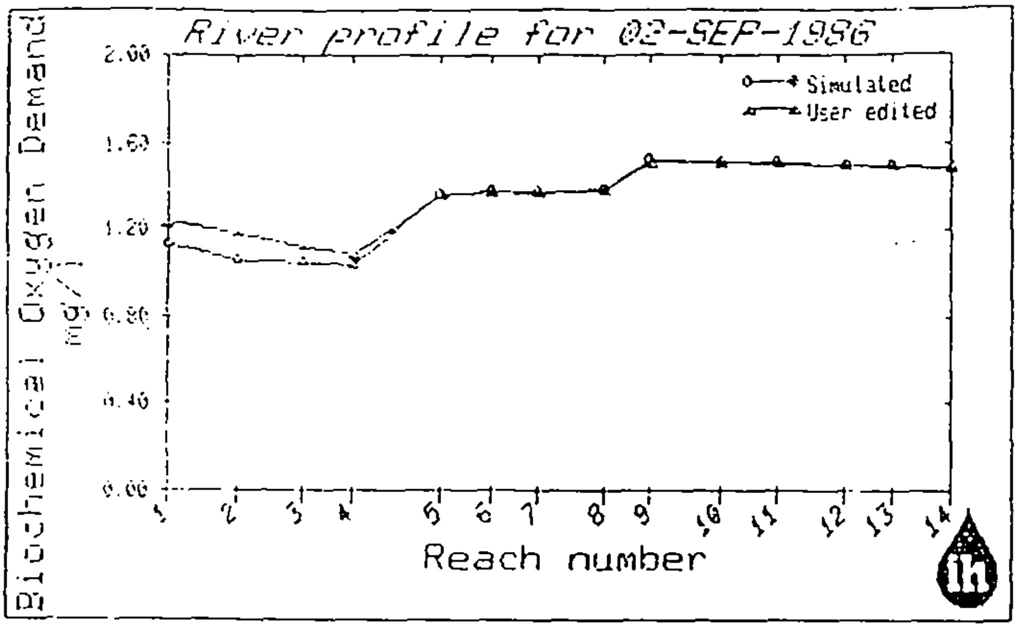


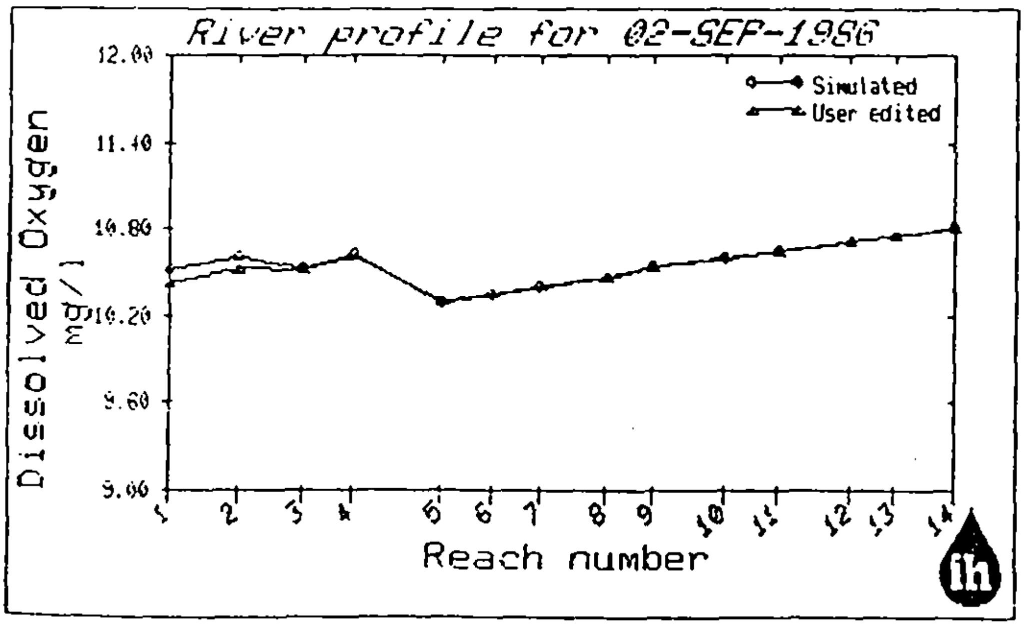


Flow = 1 cumec

Nitrate = 10 mg/L

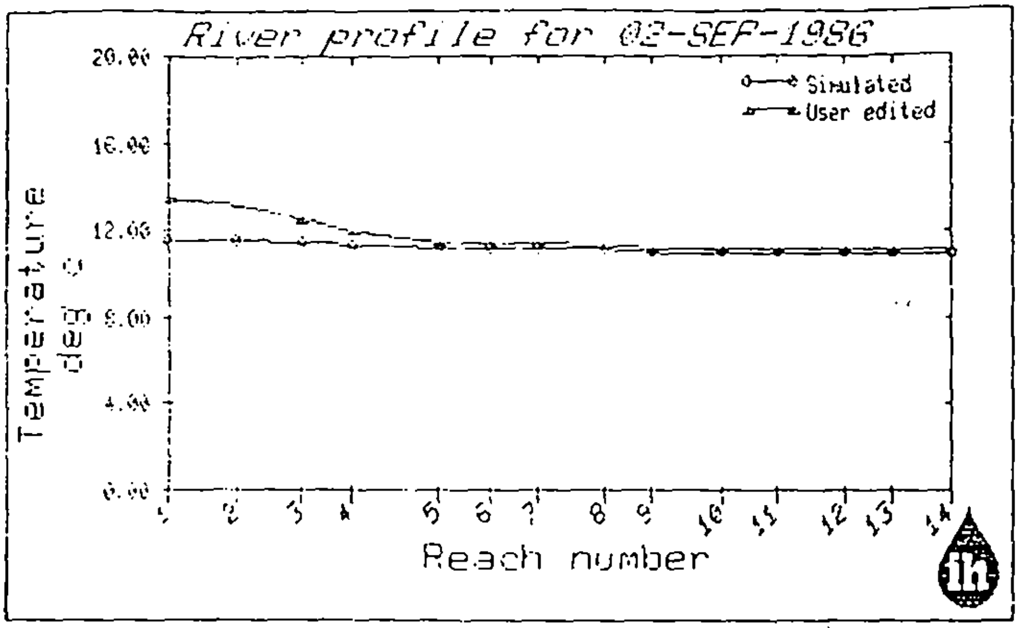
Ammonia = 0.2 mg/L

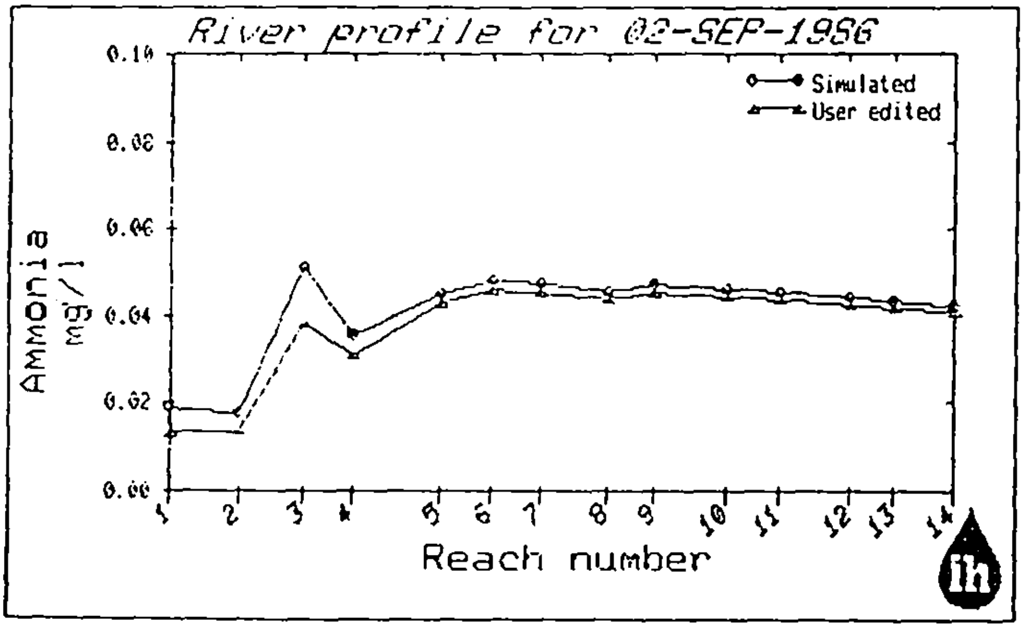


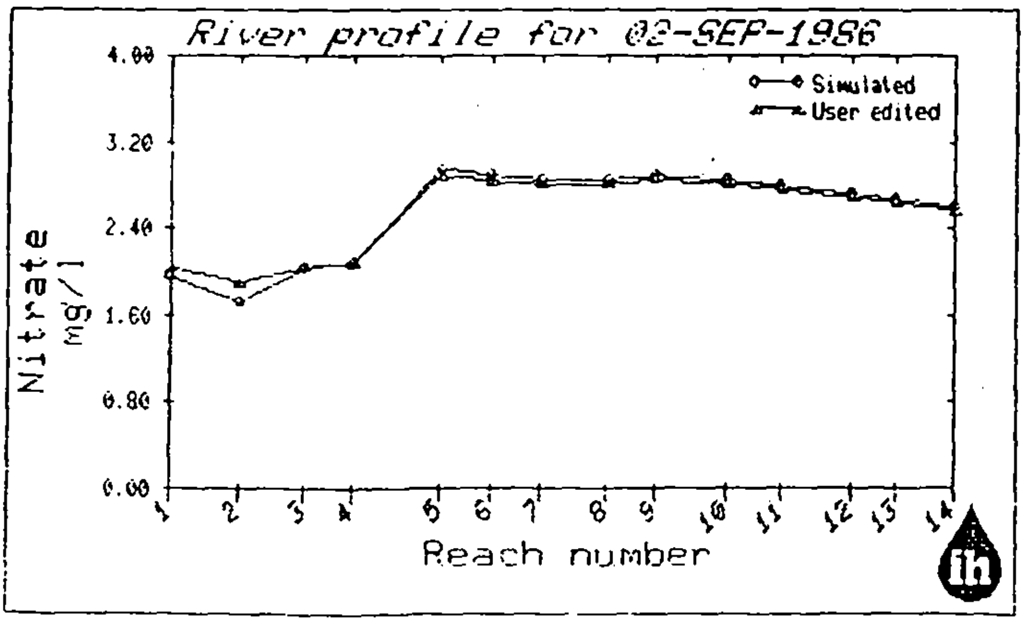


Flow = 1 cumec

BOD = 1.3 mg/L

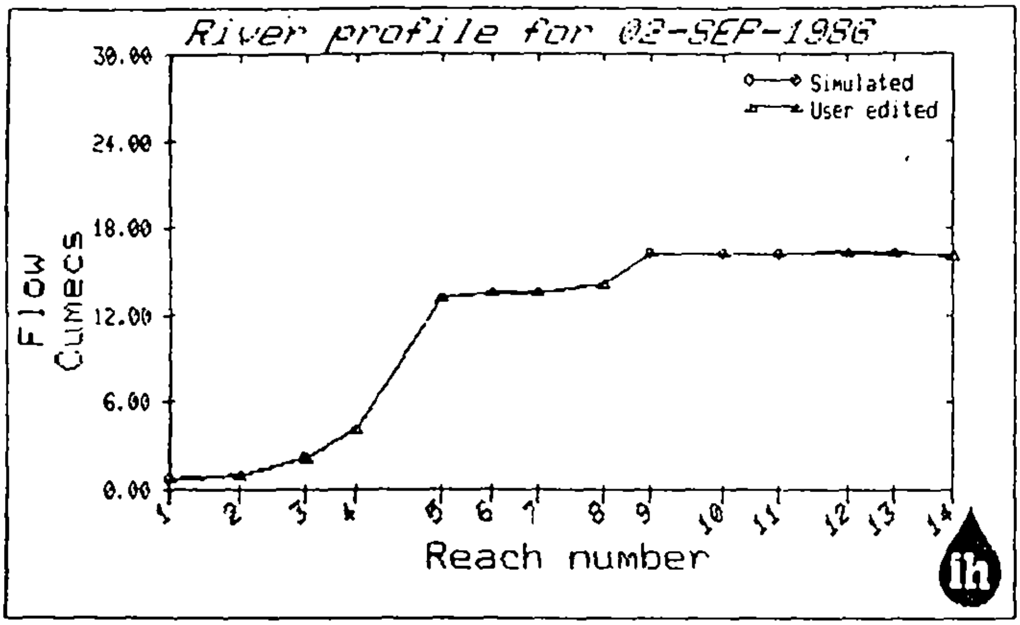


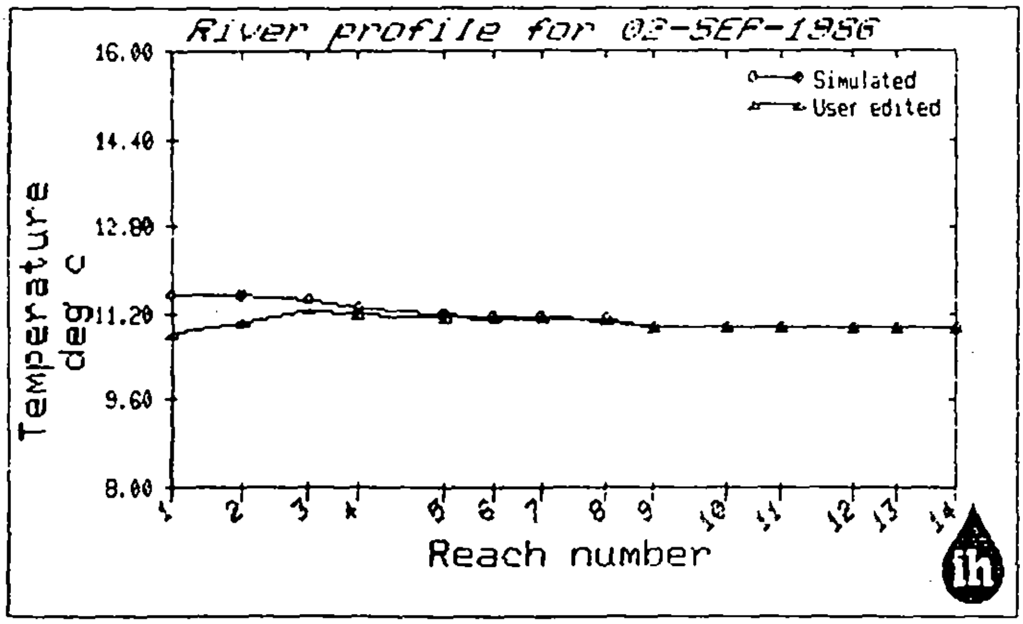




Flow = 1 cumec Temperature = 14.5°C

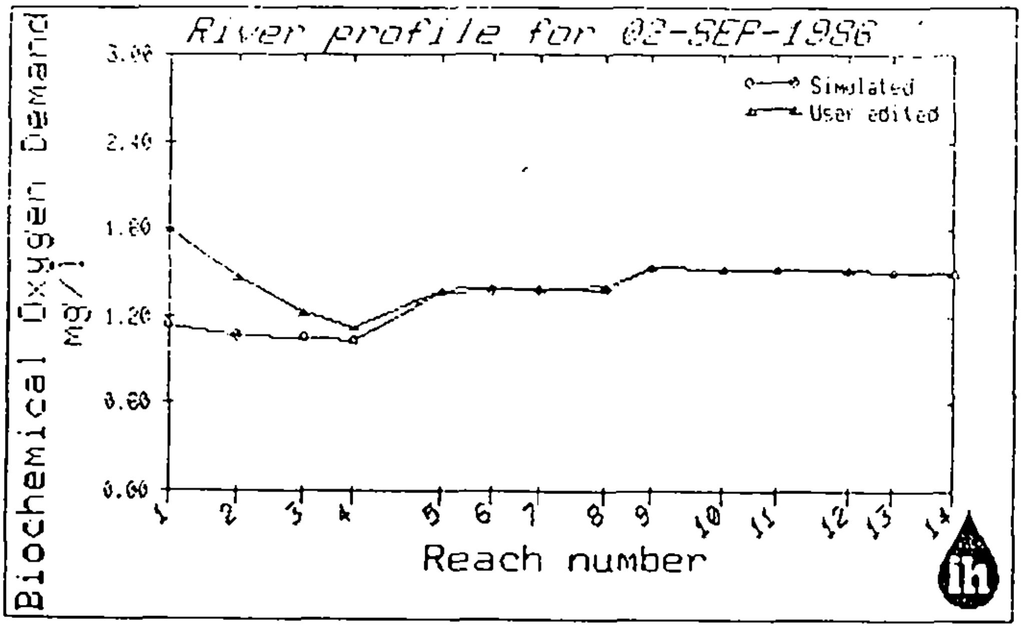
Nitrate = 2.1 mg/L Ammonia = 0.01 mg/L

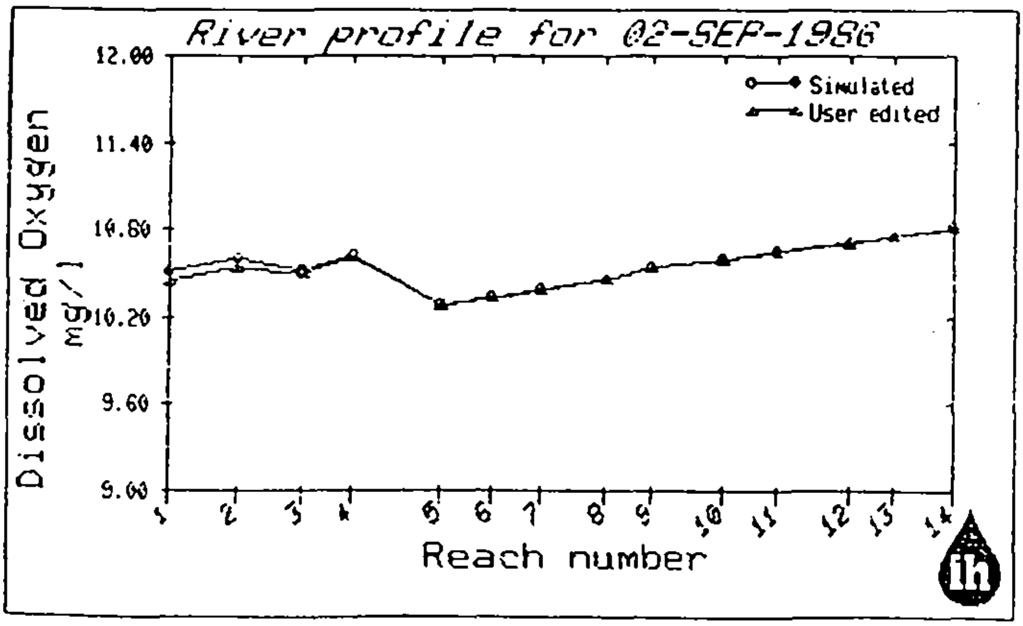




Flow = 0.1 cumec

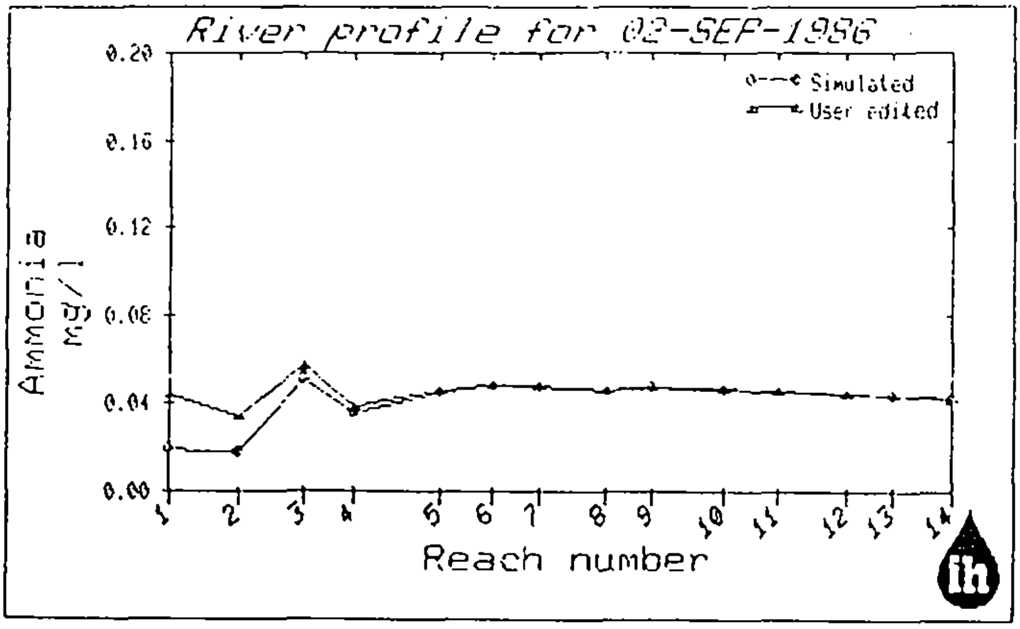
Temperature = 7°C

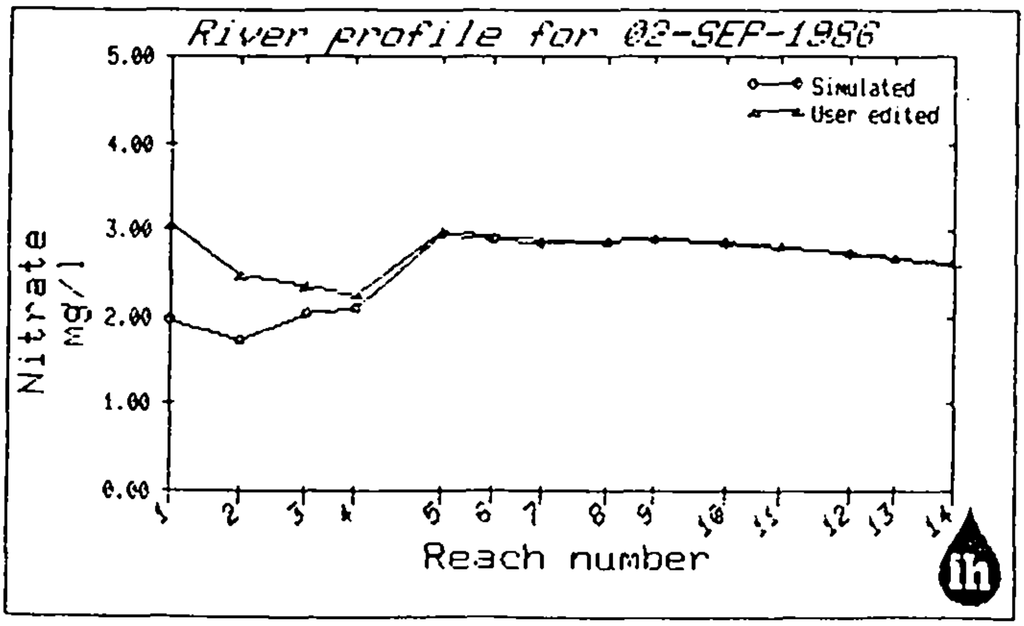




Flow = 0.1 cumec

BOD = 6 mg/L

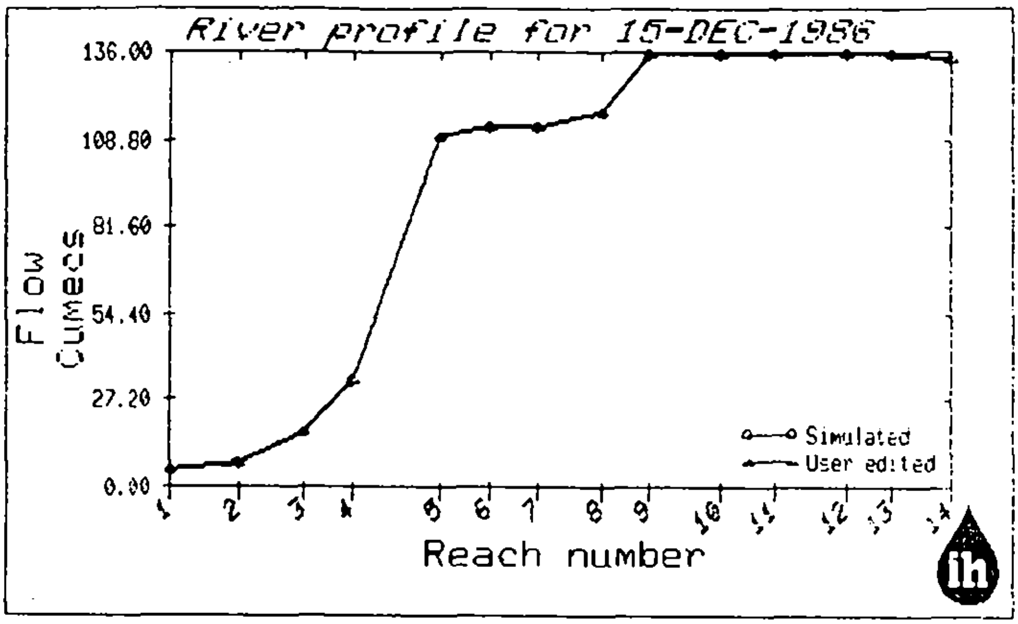


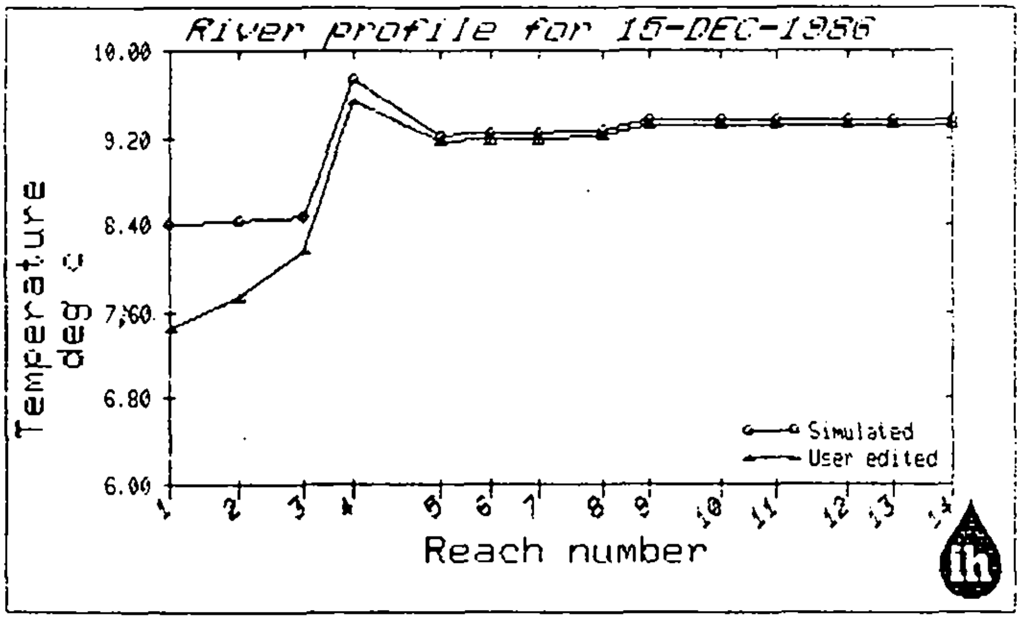


Flow = 0.1 cumec

Nitrate = 10 mg/L

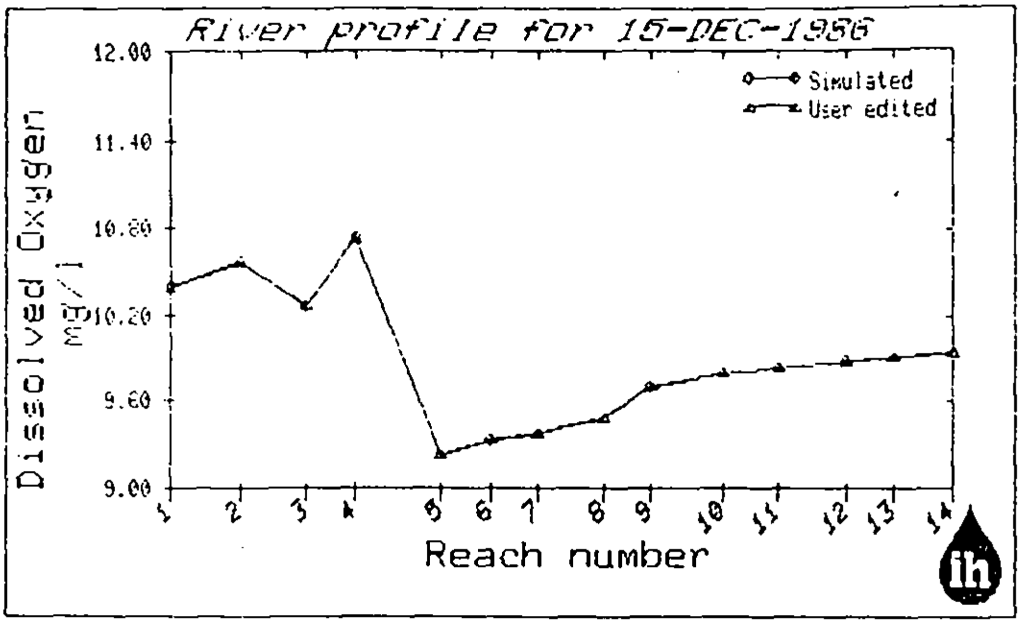
Ammonia = 0.2 mg/L

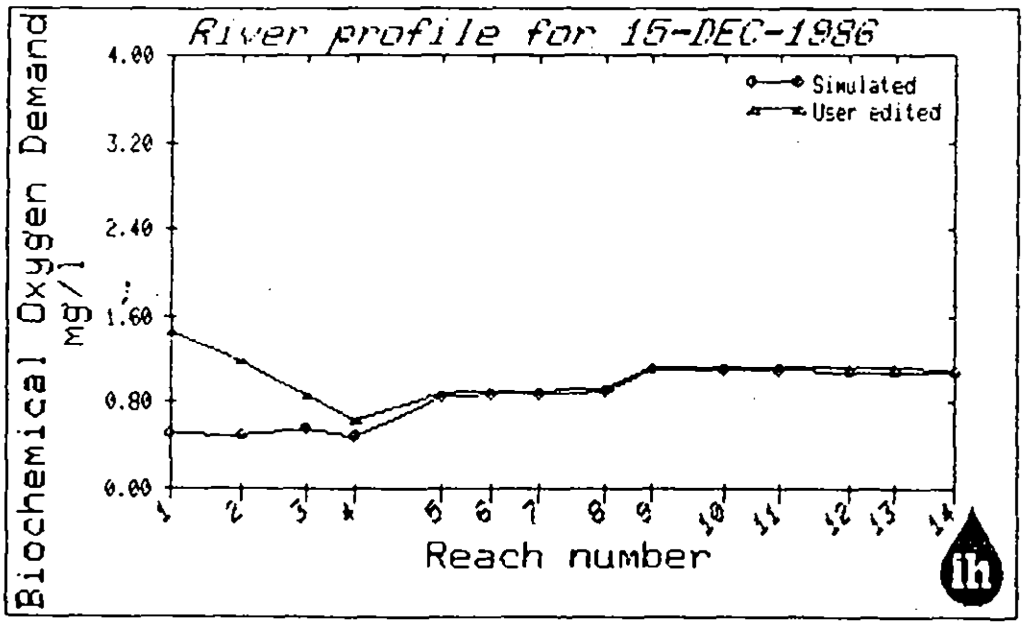




Flow = 1 cumec

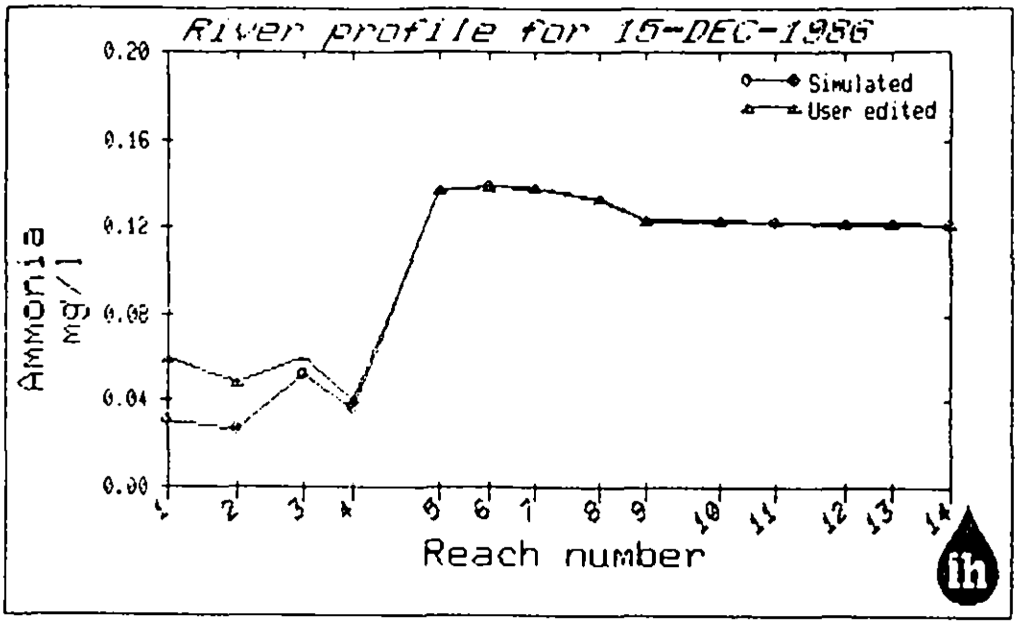
Temperature = 3°C

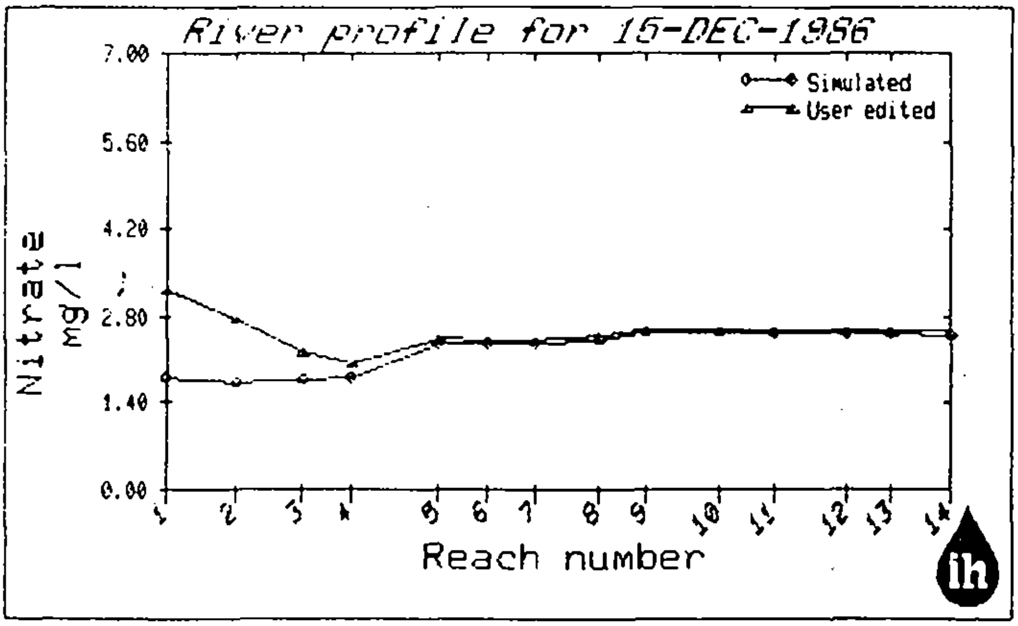




Flow = 1 cumec

BOD = 6 mg/L

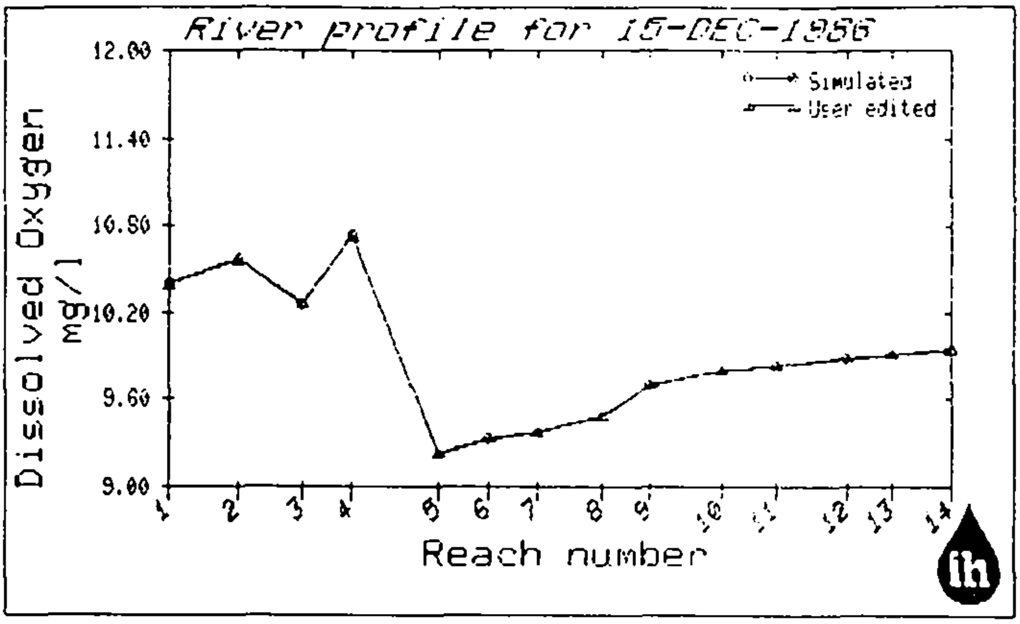


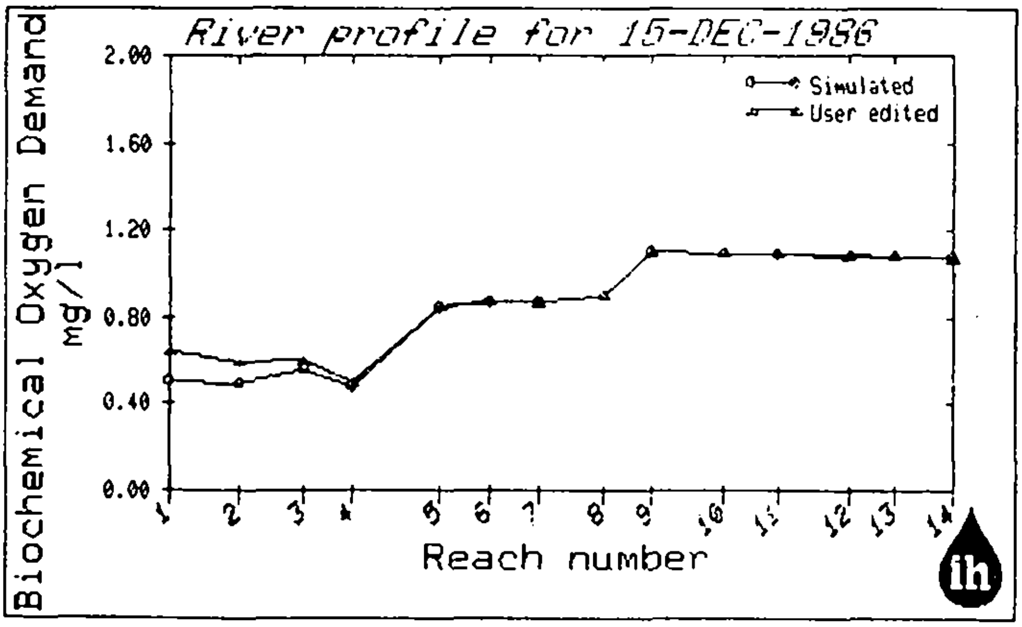


Flow = 1 cumec

Nitrate = 10 mg/L

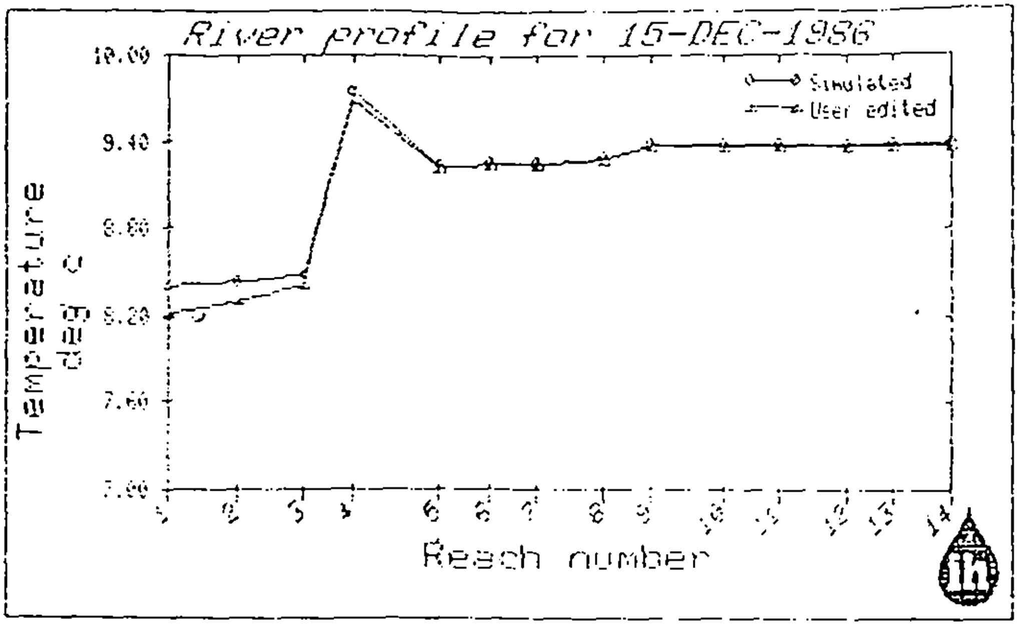
Ammonia = 0.2 mg/L

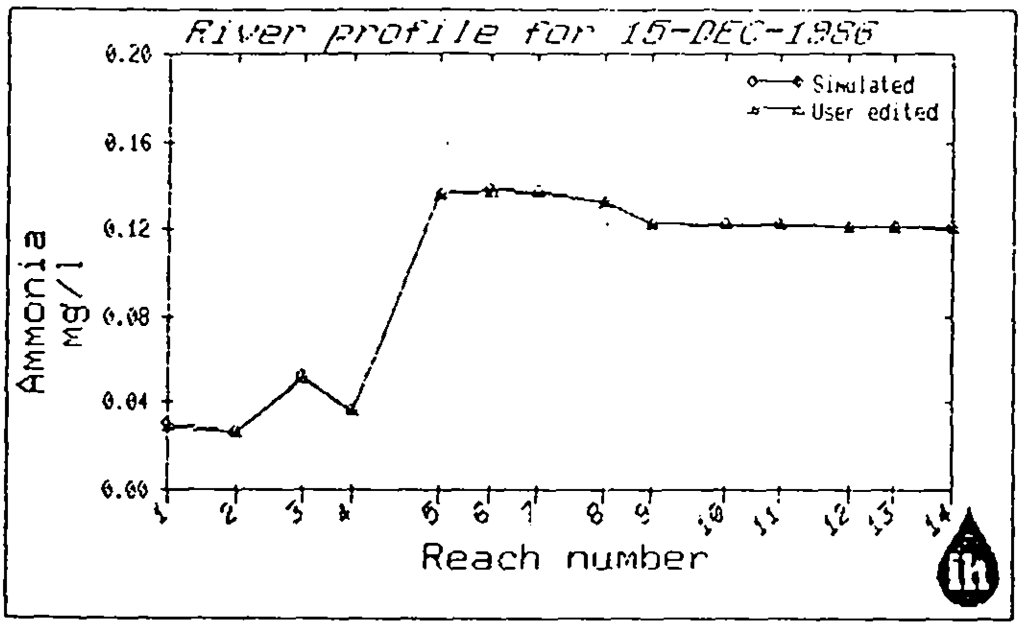


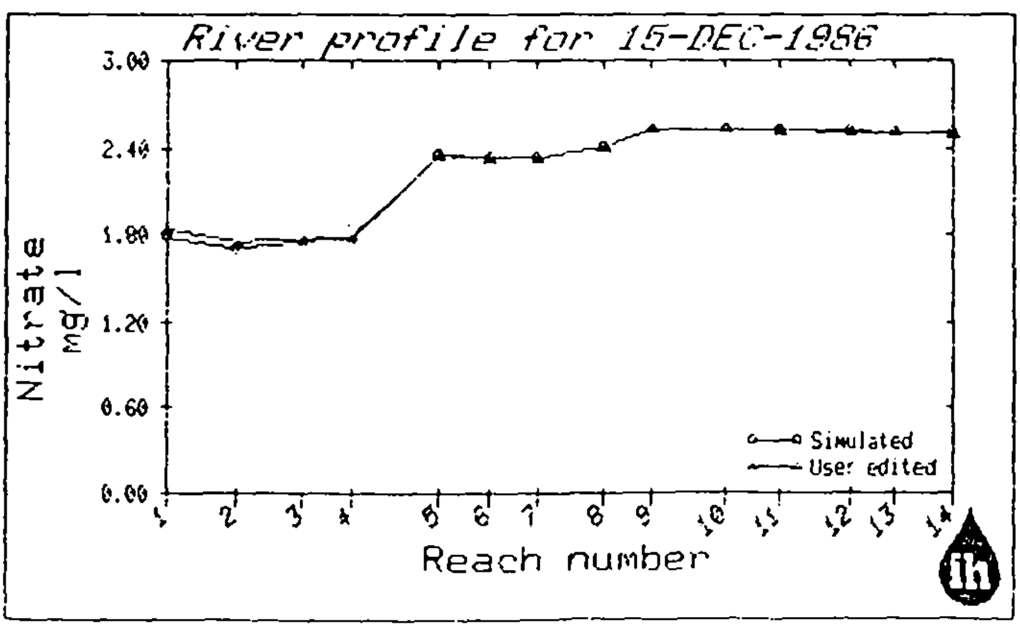


Flow = 1 cumec

BOD = 1.3 mg/L

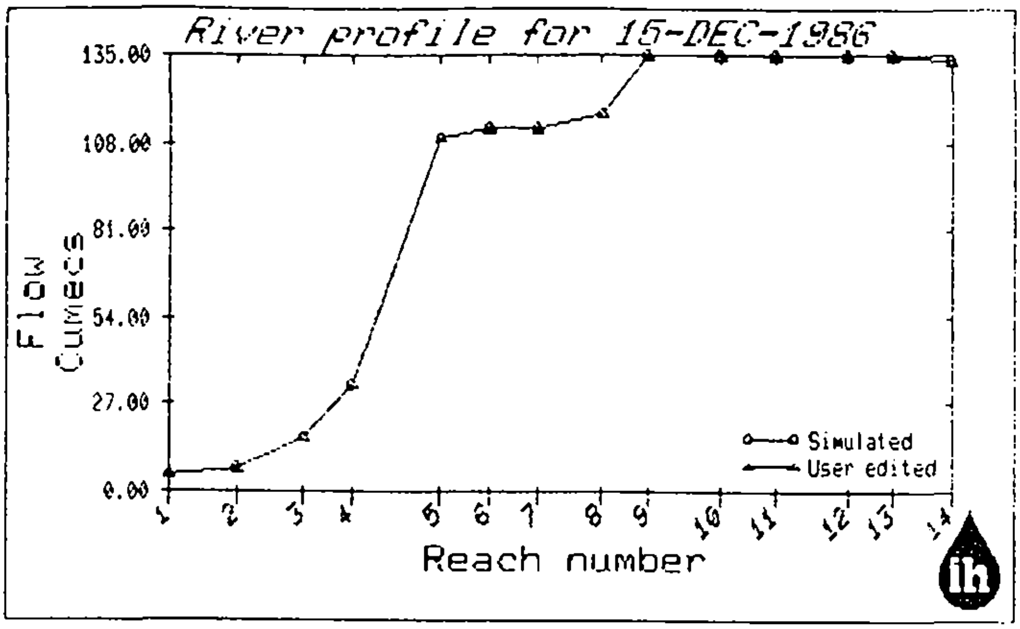


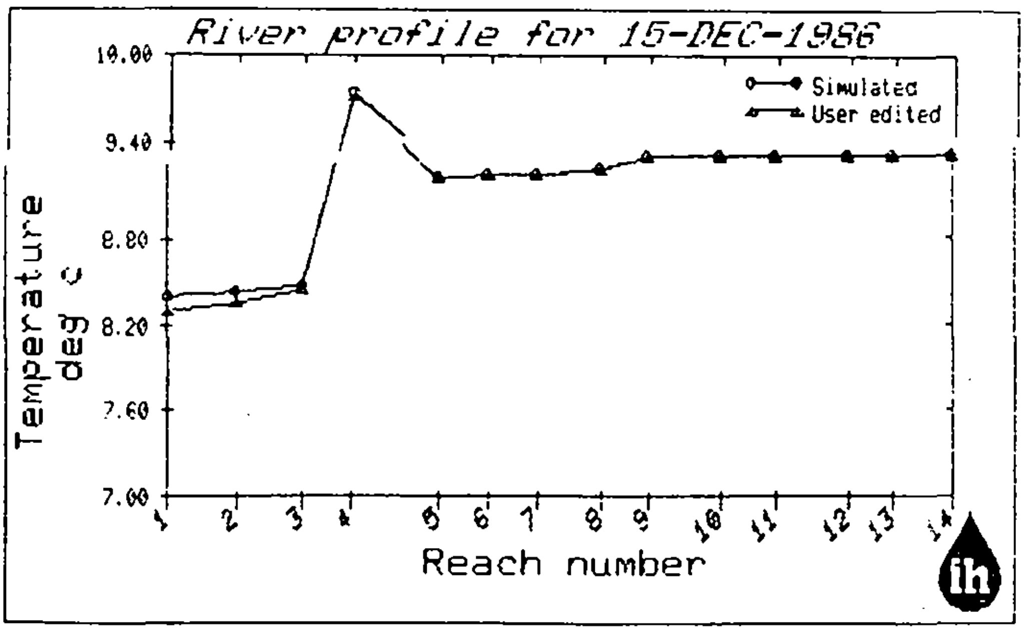




Flow = 1 cumec Temperature = 7.3°C

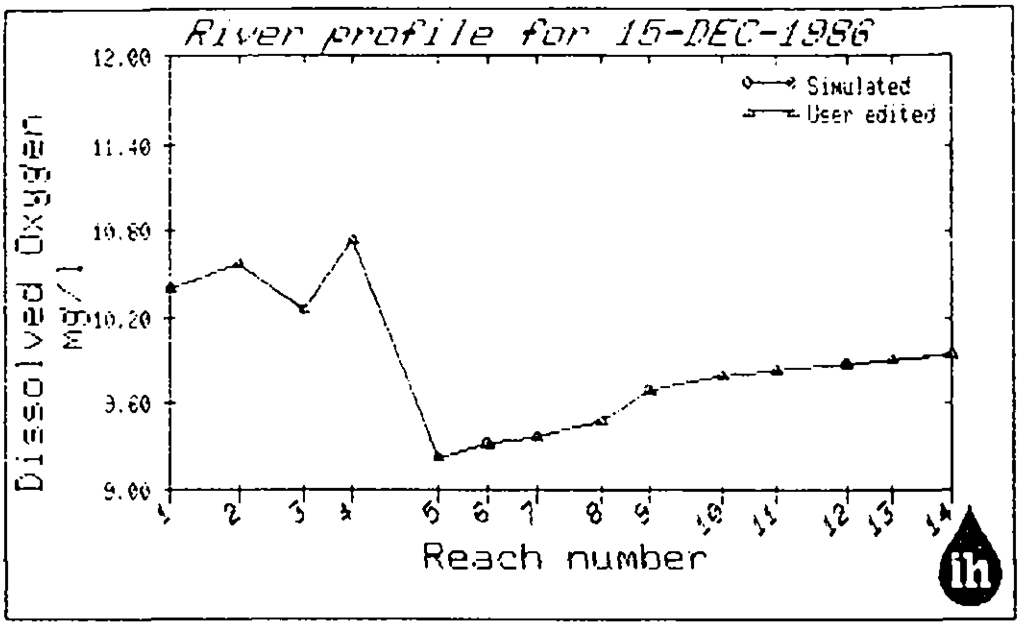
Nitrate = 2.1 mg/L Ammonia = 0.02 mg/L

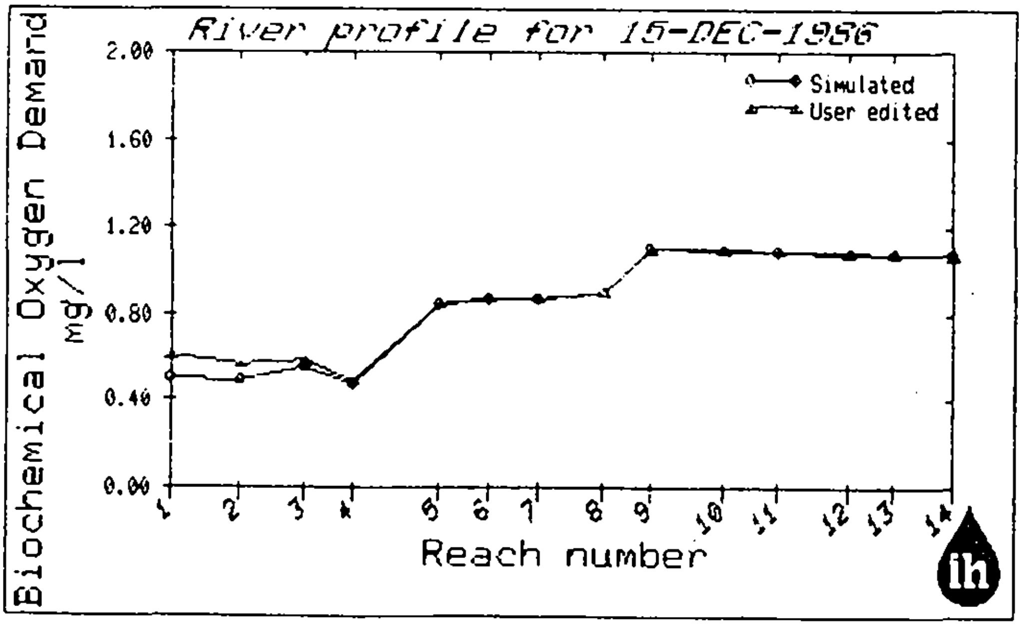




Flow = 0.1 cumec

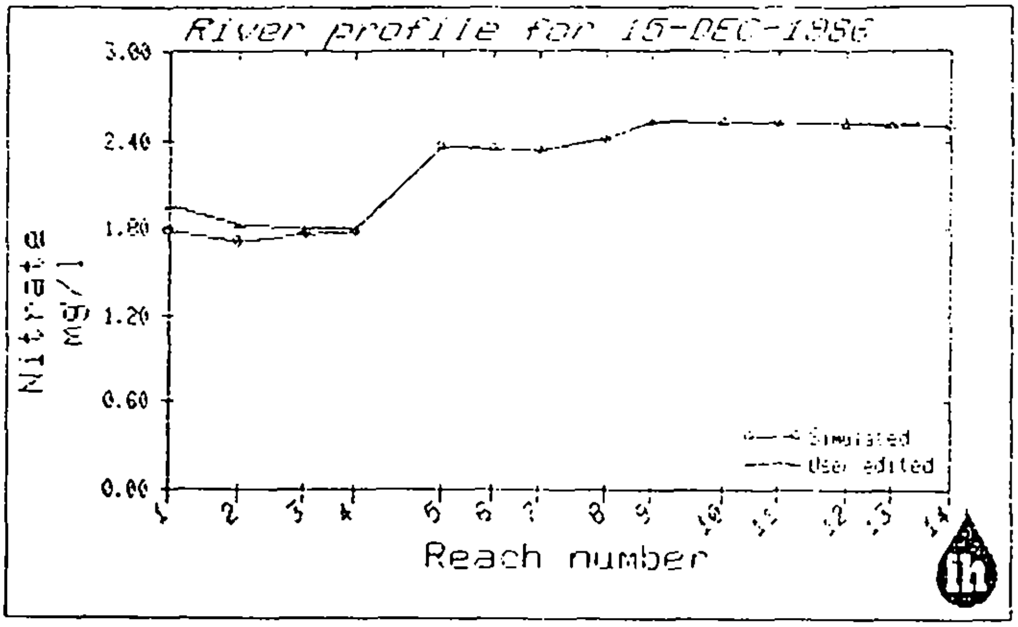
Temperature = 3°C

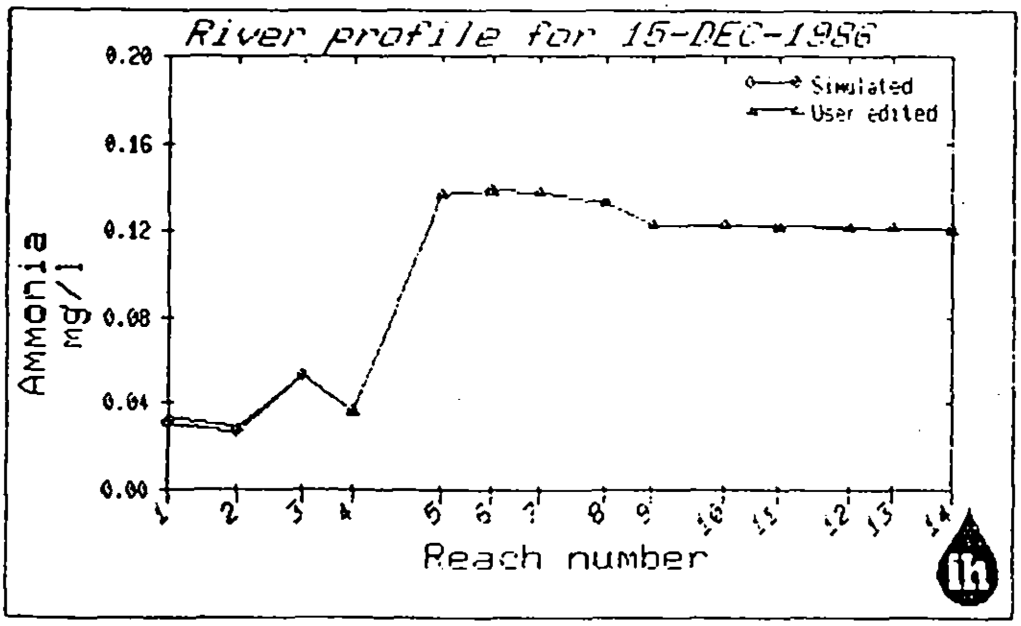




Flow = 0.1 cumecs

BOD = 6 mg/L





Flow = 0.1 cumec

Nitrate = 10 mg/L

Ammonia = 0.2 mg/L

Appendix 3

The Institute of Hydrology River Quality Model (IHQM) Modelling Flow

In order to model water quality it is necessary to first simulate streamflow in all the reaches of the river. In the Tamar streamflow model each reach is characterised by a number of cells and the model for flow variations in each cell is based on an analogy with the lumped parameter equations for the variations in concentration of a conservative pollutant under the assumption of uniform mixing over the cell (Whitehead et al., 1979). The model may be viewed in hydrological flow routing terms as one in which the relationship between inflow I, outflow, Q, and storage, S, in each cell is represented by the continuity equation:

$$\frac{dS}{dt} = I - Q \tag{1}$$

with

$$S = \tau Q$$

where τ is a travel time parameter. In order to represent the variation in travel time with flow; τ is expressed as

$$\tau(Q) = \frac{L}{UN} \tag{2}$$

where N is the number of compartments in the reach, L is the reach length and U, the mean flow velocity in the reach, is related to discharge through

$$U = a\, Q_m^b \tag{3}$$

where Q_m is the mean flow in the reach and where a and b are coefficients to be estimated.

The value of N affects the relative importance of floodwave advection and dispersion in a reach; values of N, a and b can be determined by calibration on an observed record of downstream flow or from tracer experiments (see Whitehead et al., 1984).

Given information on upstream and tributary inputs, the flow routing model can be used to derive simulations of downstream flow by solving the differential equation (1). The equation is solved using a numerical integration technique which contains an automatic adjustment to the integration step length. This is particularly useful since under periods of low flow and high residence times, the integration step length can be increased thereby saving computer time. Under high flow conditions, however, residence times are reduced and in order to solve the equation to the same accuracy, it is necessary to reduce the integration step length. Since this is achieved automatically, there are relatively few numerical integration problems.

Modelling Water Quality

The water quality models for the River Tamar are based on a mass balance principle but include factors to allow for the non-conservative nature of water quality variables. For example dissolved oxygen in the river is a balance between the various sources and sinks of oxygen. On the one hand there is oxygen supplied by the reaeration from the atmosphere and photosynthetic oxygen produced by plants and algae and, on the other hand, oxygen is being consumed by respiration processes and the removal of oxygen during nitrification of ammonia or breakdown of organic material and effluents. The basic mass balance equations required to simulate water quality behaviour are as follows:

Chloride or any conservative determinand

$$\frac{dx_1(t)}{dt} = \frac{u_1(t)}{\tau(t)} - \frac{x_1(t)}{\tau(t)} \tag{4}$$

Nitrate

$$\frac{dx_2(t)}{dt} = \frac{u_2(t)}{\tau(t)} - \frac{x_2(t)}{\tau(t)} - k_1 \; x_2(t) \tag{5}$$

Ammonia

$$\frac{dx_3(t)}{dt} = \frac{u_3(t)}{\tau(t)} - \frac{x_3(t)}{\tau(t)} - k_2 \; \left(\frac{1}{Q(t)}\right) x_3(t) \tag{6}$$

Dissolved Oxygen (DO)

$$\frac{dx_4(t)}{dt} = \frac{u_4(t)}{\tau(t)} - \frac{x_4(t)}{\tau(t)} - 4.33 \; k_2\left(\frac{1}{Q_o(t)}\right) x_3(t) - k_3 \; x_5(t)$$

$$+ k_4 \; (C_s(t) - x_4(t)) + P(t) + R(t) + M(t) \tag{7}$$

Biochemical Oxygen Demand (BOD)

$$\frac{dx_5(t)}{dt} = \frac{u_5(t)}{\tau(t)} - \frac{x_5(t)}{\tau(t)} - (k_3 + k_5) \; x_5(t) + A(t) \tag{8}$$

where x refers to the downstream (reach output) concentration mg ℓ^{-1};
u refers to the upstream (reach input) concentration mg ℓ^{-1}
Q is the flow rate (determined from the flow model $m^3 sec^{-1}$);
τ is the reach residence time (varying as a function of flow) days;
P,R,M refer to the additional sources and sinks affecting dissolved oxygen such as photosynthesis, respiration and uptake by mud or the benthos.
Cs is the saturation concentration of dissolved oxygen, and k_1, k_2, k_3, k_4 and k_5 are the rate coefficients of the various reactions.
A refers to the addition BOD created by the death of algae in river systems.
t is time.

The rate coefficients are not constants but generally vary as a function of temperature or other variables such as depth. For example, the denitrification rate k_1 is

$$k_1 = \frac{0.05}{d} \; 10^{0.0293\theta} \tag{9}$$

where d is river depth, m, and θ is water temperature in $^{\circ}$C. This nitrate relationship has been shown to provide a good representation of denitrification processes in rivers (see Whitehead and Williams, 1982).

The saturation concentraiton for DO is determined as,

$$C_S = 14.652 - 0.41022T + 0.0079910\ T^2 - 0.000077774\ T^3$$

where T is the stream temperature $^{\circ}$C.

A common problem with water quality models is to determine parameter values such as the BOD decay coefficient and reaeration rate coefficients. The standard approach is to select parameter values from the literature or from experimental measurements. Knowles and Wakeford (1978) describe a number of relationships and parameter values which can be used in situations where little information is available and this approach has been applied by Casapieri et al (1978) in a study of the Blackwater Catchment of the Thames.

A more sophisticated approach was developed by Beck and Young (1976) in which the parameters of a dynamic water quality model were estimated directly from field data using the extended Kalman filter (EKF). The EKF is essentially a statistical technique which accounts for measurement errors and system noise, both of which are highly significant in water quality studies. Whitehead (1978, 80, 81) applied the EKF technique and the instrumental variable (IV) technique to estimate water quality parameters in the dynamic models developed for the Bedford Ouse. However, a requirement of these techniques is that an extensive record of daily or continuous data is available. Since such a data set does not exist for the Tamar a set of standard relationships have been used to provide estimates of the various processes in the model. For example in the case of photosynthetic oxygen production in river systems, Owens et al (1969) developed a simplified model in which oxygen production is related to light intensity and plant biomass or algal levels. Whitehead et al (1981) used a modified version of the Owens model and estimated the relevant parameters for the Bedford Ouse. A similar approach was adopted for the Thames and the following relationship developed.

$$P = \frac{8.6}{10^5} \; Cl_a I^{0.79} \; 1.08^{(T-20)}$$

Here Cl_a is the chlorophyll-A concentration mg m^{-3}
I is the solar radiation level watt hours m^{-2} per day. The coefficient 8.6 was determined from a linear regression analysis using as variates the observed oxygen production, obtained from continuous data recorded by TWA. This relationship has been employed for the Tamar although continuous DO data and Cl_a information in summer 1987 will be used to update this relationship.

R in the DO equation refers to the loss of oxygen via algal respiration.

Kowalczewski and Lack (1971) developed a relationship between algal concentration measured as chlorophyll A and respiration rate for the River Thames, where

$$R = (0.14 + 0.013\ Cl_a)\ 1.08^{(T-20)}$$

and this relationship has been incorporated into the model. Again this can be updated for the Tamar given suitable records.

M in the DO equation refers to the respiration of the river bed or mud. There has been considerable research into this process (Edwards and Rolley, 1965) and the following equation has been used,

$$M = \frac{k_6}{d}\ x_4^{\ 0.45}\ 1.08^{(T-20)}$$

where x_4 is the DO concentration mg l^{-1}, d is depth, m, and k_6 is a parameter to be determined. The original work of Edward and Rolley was conducted on the highly polluted muds of the River Ivel and later studies by Rolley and Edwards (1967) showed that the parameter k_6 varied considerably from river to river. In the Tamar study a value for k_6 of 0.15 days was found to provide the best fit to the observed DO data.

Finally A in the BOD equation refers to the conversion of algae to decaying organic matter. In previous algal modelling studies on the Thames (see Whitehead 1984) the concentration of dead algae is assumed proportional to the concentration of live algae. Thus A can be expressed

$$A = k_7\ Cl_a\ .1.047^{(T-20)}$$

Where Cl_a is the chlorophyll a concentration mg m^{-3} and k_7 is a parameter. From simulation studies on the Thames k_7 was found to be 0.01.. This parameter has been included in the Tamar model.

The remaining rate coefficients in the model refer to the ammonia decay, k_2, which is flow dependent (see Whitehead 1984), k_3 is the BOD decay coefficient, k_4 is the reaeration coefficient and k_5 is a BOD sedimentation coefficient. All the rate coefficients can be altered using an interactive feature in the model program.