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Modelling the Influence of Eutrophication on the Coldwater Fishery Habitat of Lake McConaughy, a "Two-Story" Reservoir

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ABSTRACT

The lifespan of the existing coldwater habitat in Lake McConaughy is unknown. To promulgate effective management and regulatory strategies, a method of predicting this lifespan was needed. Ideally, this procedure should also provide potential management philosophies that would retard eutrophication. The LAKSCI computerized simulation model of Systems Control, Inc. was modified to assist in solving this problem. Data for model input were collected from August 1976 to August 1978. When calibrated the model proved satisfactory for predicting water level and temperatures, but unsatisfactory in prediction of water chemistry without additional data and refinement.

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INTRODUCTION

To maximize productivity and recreational use state and federal agencies have attempted to establish "two-story" fisheries in many man-made reservoirs (Axon, 1974; Baker and Hulsey, 1967; Keith and Hulsey, 1967; Kirkland and Bowling, 1966; Wilkens, et al., 1968; McCarraher, et al., 1971; Nichols, 1959; Schumacker, 1964). A "two-story" fishery is defined as one supporting both warm and coldwater species. Lake McConaughy is one reservoir where this strategy has been successful (McCarraher, et al., 1971). In fact, Lake McConaughy has become the most important fishery resource in Nebraska, particularly for coldwater species. The lake provides 85% of the state's "two-story" fishery and 75% of the total coldwater fishery of the state.

The estimated use of Lake McConaughy in 1975 was 532,000 visitor days, of which 343,000 were for the purpose of fishing (Morris, 1976). Based on the "Economic Survey of Wildlife Recreation" conducted in 1974, the 1975 fishery at Lake McConaughy was worth $11 to $14 million. Another estimate based on Supplement No. 1 to Senate Document Number 97, "Evaluation Standards for Primary Recreation Benefits" (1964) placed the value of the fishery in 1975 at $1 to $3 million. Regardless of which estimate is more correct, it is obvious that Lake McConaughy supports a fishery worthy of conservation. A portion of this fishery is dependent upon the lake's continued ability to support coldwater species, particularly rainbow trout (*Salmo gairdneri*).

Most trout fisheries in "two-story" lakes are maintained by stocking. However, some reservoirs have self-sustaining populations that migrate into tributaries to spawn. Lake McConaughy has a self-sustaining rainbow trout population (Van Velson, 1974) as does Watauga Lake in Tennessee (Wilkens, 1965) and Lake Kabekona in Minnesota (Schwmacker, 1964). In an effort to enhance the McConaughy trout fishery, considerable research funds have been spent developing methods for managing spawning and nursery streams in the watershed (Van Velson, 1978). To protect this investment, it is imperative that the coldwater habitat of Lake McConaughy be maintained if possible.

Reservoirs with "two-story" fisheries range from almost completely coldwater reservoirs in the north to almost completely warmwater reservoirs in the south-eastern U.S. (Wilkens, et al., 1968). To maintain the coldwater portion of the fishery, reservoirs must contain some water with suitable dissolved oxygen and temperature conditions to support trout throughout the year (Wilkens, et al., 1968). Kirkland and Bowling (1966) reported that 70°F or less and 3 ppm dissolved oxygen or more are necessary for trout habitat.

In Lake McConaughy and many other reservoirs (Lake Lanier in Georgia; Dale Hollow, Center Hill, South Holston, Watauga and Old Hickory Lakes in Tennessee; Lake Cumberland in Kentucky; Lake Havasu in California; and Lakes Norfolk, Bull Shoals and Ouachita in Arkansas), the volume of trout habitat, based on the 70°F and 3 ppm dissolved oxygen criteria, becomes substantially reduced during summer stratification. This reduction is the result of depletion of oxygen in the hypolimnion and of warming of the epilimnion above 70°F.

Van Velson (1978) documented the summer depletion of trout habitat in Lake McConaughy and also showed that depletion has become more severe in recent years. At the peak of stratification in August, 1969, a 10 m thick stratum of trout habitat was available. By 1973, only a 1 m thick layer of acceptable trout habitat which extended only 6 miles (9.6 km) up the reservoir was found. Thus in 4 years the oxygen depletion floor appeared to move nearly 9 m closer to the surface. Although the actual trend may be somewhat exaggerated over this 4-year period, it is an indication that eutrophication may be progressing rather rapidly in Lake McConaughy.

Myers (1973) reported that chlorophyll concentrations in Lake McConaughy ranged from 6-32 mg/m^3. Based on Vollenweider's (1970) criteria of lake condition, chlorophyll concentrations of this magnitude indicate that Lake McConaughy is already eutrophic. Furthermore, by plotting annual loading of nitrogen and phosphorus per unit area versus mean depth, Myers (1973) also found that Lake McConaughy should be classified as eutrophic.

It has taken Lake McConaughy less than 40 years since its impoundment in 1941 to become eutrophic. Continued nutrient loading will result in more severe eutrophication. According to Myers (1973) the net nutrient loading is approximately 1400 tons of nitrate nitrogen and 65 tons of phosphates per year which results in an annual increase in concentration of 0.8 mg/l of nitrate nitrogren and 0.028 mg/l of phosphate. Since 80% of the flow entering Lake McConaughy is return flow from upstream irrigation, which varies little from year to year, it seems safe to predict that nutrient enrichment and subsequent eutrophication of the lake will continue. Eventually, trout habitat will be eliminated from the reservoir, but at what point in the future this will occur is uncertain. Precise predictions are needed for promulgation of management and regulatory policies and to provide guidelines for possible retardation of the process. These predictions should demonstrate the relationship between nutrient loading and the physical and chemical dynamics of the lake and help pinpoint the critical factors upon which to concentrate efforts for improvement and protection of the water resource.

To provide precise predictions, a more sophisticated approach must be taken in the future than has been utilized in the past. Development of computerized, mathematical models of aquatic ecosystems has recently become a powerful tool for assisting in the solution of similar problems (Chen, 1970; Dale, 1969; Shepherd and Finnemore, 1974). However, none of the existing models have been applied to "two-story" lakes with the expressed purpose of predicting the future of the coldwater fishery of the lake. The objectives of this research were:

(1) To modify, calibrate, and verify a mathematical model to predict physical/chemical changes in Lake McConaughy as a consequence of continuing eutrophication; and

(2) To utilize the model to identify critical factors in the physical/chemical management of the lake as they would affect coldwater fish habitat.

DESCRIPTION OF STUDY AREA

Kingsley Dam impounds the North Platte River near Keystone, Nebraska to form McConaughy Reservoir. The dam was constructed by the Central Nebraska Public Power and Irrigation District in 1941 for storage of irrigation water. Electricity is also produced at the dam (Table 1).

The reservoir is long and narrow with few embayments (Figure 1 and Table 2). The substrate is muck and silt in the deeper areas with sand predominating near shore. The shoreline is largely sand with occasional patches of rock and gravel. Water level fluctuates 6 to 8 m seasonally with highest levels from October to May. Strong westerly winds are common.

The fishery of the lake is a combination warm and coldwater population. Major species include striped bass (*Morone saxatilis*), walleye (*Stizostedion vitreum*), white bass (*Morone chrysops*), channel catfish (*Ictalurus punctatus*), rainbow trout (*Salmo gairdneri*), and smallmouth bass (*Micropterus dolomieui*). Gizzard shad (*Dorosoma cepedianum*) is the primary forage species. A complete discussion of the fishery can be found in (McCarraher, et al., 1971). Van Velson (1978) described in detail the life history of the self-sustaining rainbow trout population.

Various aspects of the reservoir's limnology have been described by (EPA, 1976; McCarraher, et al., 1971; Morris, 1976; Myers, 1973; Rosowski, et al., 1976 and 1977; Van Velson, 1978). No comprehensive analysis of the lake's limnology has been reported.

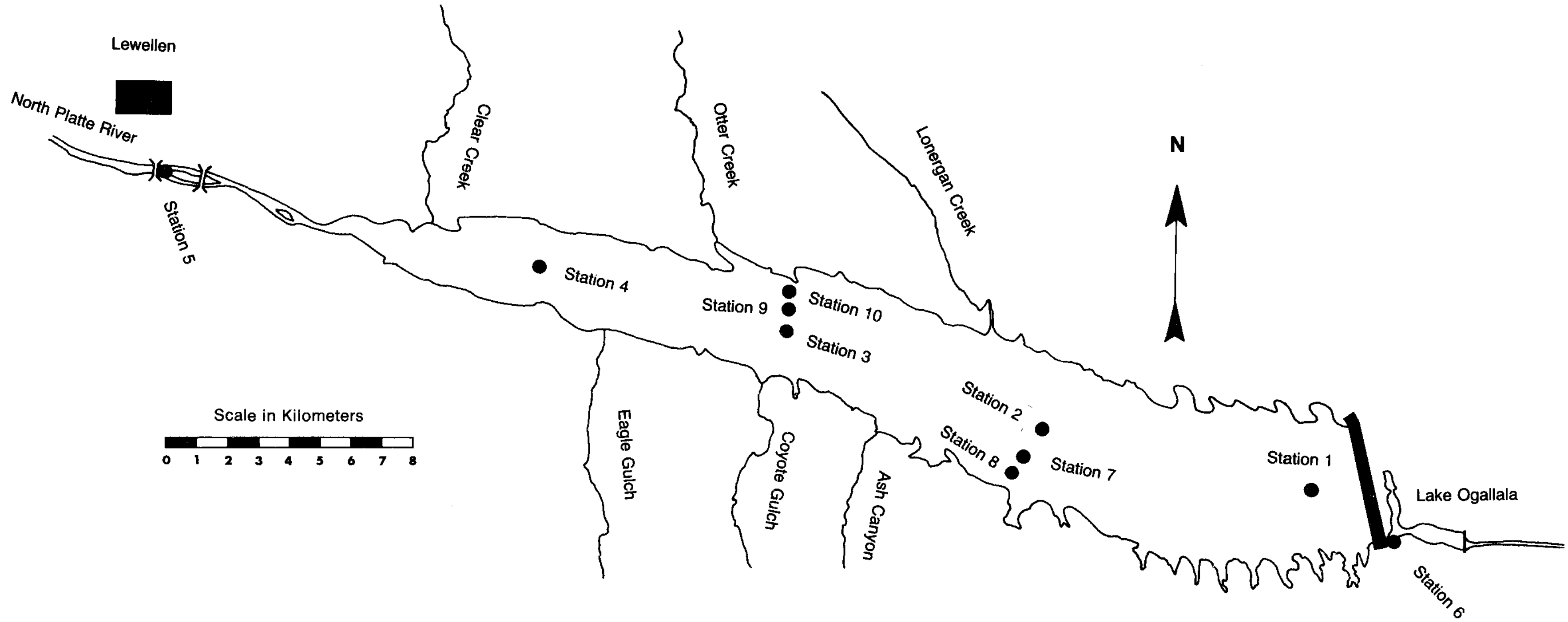

Figure 1. *Lake McConaughy and the location of sampling stations.*

The lake exhibits thermal stratification but not as distinctly as in many smaller or more protected lakes. In the open, wind-swept environment, the thermal stratification is somewhat diffuse but definitely present.

Table 1. Characteristics of Kingsley Dam

Length, km	5.6
Height above stream bed, m	49.4
Base thickness, m	335.4
Surface outlet elevation, m msl	992.1
Surface outlet capacity, m^3/sec	1529.0
Bottom outlet elevation, m msl	953.8
Bottom outlet capacity, m^3/sec	510.0

Table 2. Physical characteristics of Lake McConaughy.

Surface Area, hectares	14,164
Reservoir length, km	35.2
Reservoir width, km	6.4
Maximum depth, m	53
Mean depth, m	22
Volume at maximum pool, m^3	2.4×10^9
Surface elevation, maximum pool, m msl	996.9
Shoreline length, km	169
Shoreline development	4.8
Flushing time, years	2.4

A graphical representation of a typical stratification pattern in Lake McConaughy is shown in Appendix I.

During most of the year dissolved oxygen levels between 5 and 12 mg/l are present at all depths in the reservoir. However, under conditions of thermal stratification in summer, near 100 percent hypolimnetic oxygen depletion occurs (Van Velson, 1978). The depletion is attributable to decomposition of excessive amounts of organic material originating as phytoplankton in the epilimnion as a consequence of increased inflow of nutrients.

Table 3 shows typical values for various other chemical characteristics (EPA, 1976; McCarraher, et al., 1971; Morris, 1976; Myers, 1973; Rosowski, et al., 1976; Van Velson, 1978).

Secchi disc transparency ranges from a few cm near the inlet in the summer to 10 m or more in winter and early spring near the dam. Most of the turbidity in the lower reservoir is attributable to plankton populations, not suspended inorganic material.

The zooplankton populations include at least 14 species of cladocerans and copepodes. Their typical seasonal distribution is shown in Figure 2 (McCarraher, et al., 1971). Phytoplankton assemblages include _Spirogyra_, _Diatoma_, _Synedra_, _Navicula_, _Fragilaria_, _Cymbella_ and _Pedisastrum_ (Keiner, 1952; McCarraher, et al., 1971). An intensive study of the diatoms has been reported by Rosowski, et al. (1976, 1977).

Table 3. Ranges in values of various chemical and physical characteristics of Lake McConaughy.

	DEPTH		
	0-10 m composite	15m	45m
Ammonia nitrogen, mg/l	0.01 - 0.75	0.01 - 0.64	0.01 - 0.95
Nitrate nitrogen, mg/l	0.00 - 8.70	0.00 - 5.40	0.00 - 5.40
Kjeldahl nitrogen, mg/l	0.10 - 9.30	0.40 - 2.30	0.40 - 1.60
Total phosphate, mg/l	0.02 - 1.90	0.01 - 2.30	0.01 - 0.90
Orthophosphate, mg/l	0.01 - 0.90	0.01 - 0.58	0.02 - 0.72
Turbidity, NTU	1.00 - 108.00	1.00 - 26.00	1.80 - 11.00
Total alkalinity, mg/l	150.00 - 250.00	145.00 - 210.00	160.00 - 210.00
Conductivity, (μmhos)	680.00 - 790.00	700.00 - 780.00	710.00 - 750.00
pH	7.70 - 8.70	7.70 - 8.40	7.50 - 8.40
Total dissolved solids, mg/l	243.00 - 575.00	325.00 - 522.00	336.00 - 538.00
Total solids, mg/l	418.00 - 739.00	436.00 - 542.00	476.00 - 595.00
Chemical oxygen demand, mg/l	0.10 - 108.60	0.10 - 45.30	0.10 - 82.50
Chlorophyll A, μg/l	0.10 - 29.30	0.10 - 21.00	0.20 - 19.60
Chlorides, mg/l	18.00 - 19.50	17.00 - 20.00	18.00 - 20.00
Total hardness, mg/l	180.00 - 435.00	180.00 - 427.00	170.00 - 440.00
Calcium hardness, mg/l	88.00 - 265.00	100.00 - 258.00	96.00 - 280.00

Myers (1973) has estimated annual nutrient loadings to be approximately 1400 tons of nitrate nitrogen and 65 tons of phosphate.

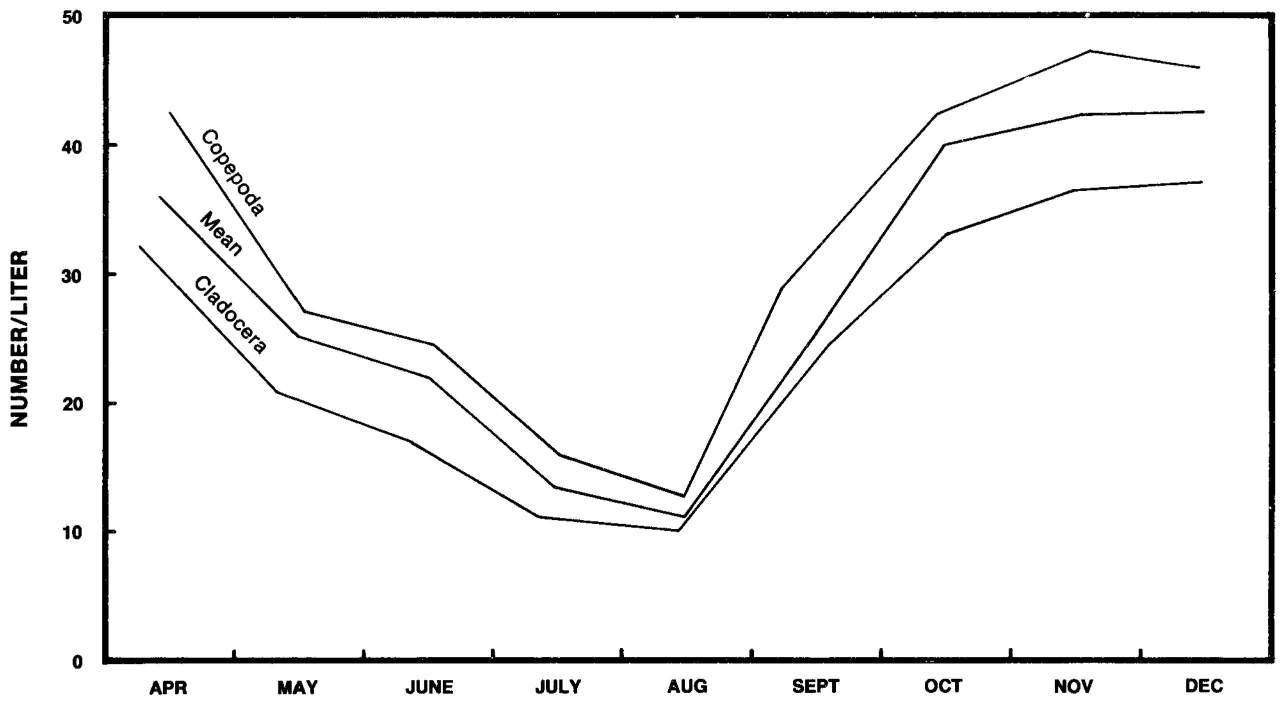

Figure 2. *The typical seasonal abundance of* ***cladocera*** *and* ***copepoda*** *in Lake McConaughy (McCarraher, et al., 1971).*

MATERIALS AND METHODS

Field Sampling

Field samples were collected from August 1976 to August 1978. A bi-weekly schedule was followed during reservoir stratification (April to November) in 1976 and 1977. Monthly samples were collected only at the inlet and outlet during the winter. In 1978 reservoir samples were collected less frequently except during the height of stratification in July and August. Samples were collected from 10 locations (Figure 1). At each reservoir station (Stations 1, 2, 3, 4, 7, 8, 9, 10), temperature (°C) and dissolved oxygen (mg/l) were measured at 1 m depth intervals with a YSI Model 57 Dissolved Oxygen Meter. Water samples for laboratory analysis were collected from five depths including a composite from the upper 10 m, mid-thermocline, upper hypolimnion, mid-hypolimnion and near the bottom. At the shallower stations (3 and 4) fewer than five samples were collected because of the lack of a thermocline or a significant hypolimnion. Two 2-liter bottles were filled from each sample depth. One was fixed with 5 ml of concentrated sulfuric acid to stop biological activity. This sample was used for the determination of ammonia nitrogen, Kjeldahl nitrogen, nitrate nitrogen, chemical oxygen demand, and orthophosphate. The other sample was used for the analysis of total alkalinity, chlorides, chlorophylls, specific conductance, calcium hardness, total hardness, total phosphates, total dissolved solids, total solids and turbidity. Hydrogen ion concentration (pH) was determined in the field with an Horizon Ecology Model 5985-40 pH meter. Water transparency was measured with a secchi disc. At the inlet and outlet (Stations 5 and 6) only one depth was sampled. With the exception of secchi disc transparency which was not measured, determinations were the same as those for the lake samples. All samples were iced immediately and returned to the laboratory for analysis.

Laboratory Analysis

Total and calcium hardness (mg/l) were determined using the EDTA titrimetric method described in Standard Methods (1971).

Total alkalinity (mg/l) was determined by procedures outlined in Standard Methods (1971).

Chloride concentration (mg/l) was found using the mercuric nitrate method of Standard Methods (1971).

Chlorophyll a, b, and c (µg/l) was determined using the trichromatic method described in Standard Methods.

Specific conductance (µmhos) was found using a Model 31, YSI conductivity bridge.

Turbidity (NTU) was measured with a Hach 2100A turbidimeter.

Total solids (mg/l) was determined by evaporating 75 ml of water in a weighed dish in a Thelco Model 26 drying oven. The increase in weight over the empty dish was considered to be the concentration of total solids. Dissolved solids was determined in a similar manner except the sample was first filtered through a No. 3 Whatman, 11 cm diameter filter to remove particulate solids. The filtrate was evaporated and the dish weighed to obtain the concentration of dissolved solids.

Total phosphate (mg/l) was measured using the ascorbic acid procedure from Standard Methods (1971).

Orthophosphate (mg/l) was measured with a Technicon Auto-analyzer using an automated ascorbic acid method.

Nitrate nitrogen (mg/l) and ammonia nitrogen (mg/l) were also determined on the auto-analyzer.

Chemical oxygen demand (mg/l) was determined using the potassium dichromate method of Standard Methods (1971).

Kieldahl nitrogen (mg/l) was determined by the procedure described in Methods for Chemical Analysis of Water and Wastes (1976).

Data for all variables were transferred to computer media for processing and analysis.

Model Development

A number of aquatic simulation models were reviewed in an effort to locate a model or combination of models that could be modified for use on Lake McConaughy (Abernathy and Bungay, 1972; Bella, 1970a; Bella, 1970b; Chen, 1970; Chen and Orlob, 1972; Dale, 1969; Delay and Seaders, 1966; DiGiano, 1971; DiToro, et al., 1971; Gearheart, 1973; Goodling and Arnold, 1972; Green, 1972; Grenney, et al., 1973; Imboden, 1974; Johnson and Straub, 1971; Jones and Bachmann, 1976; Markofsky and Harleman, 1973; Newbold and Liggett, 1974; O'Melia, 1972; Orlob and Selna, 1970; Park, et al., 1974; Prober, et al., 1971; Raphael, 1962; Scavia, 1974; Shepherd and Finnemore, 1974; Slotta, et al., 1969; Symons, et al., 1967; Varga, et al., 1972; Varga and Falls, 1972). Based on our evaluation and a later independent evaluation by Grimsrud, Finnemore and Owen (1976), the LAKSCI model developed by Systems Control, Inc. was judged to have the most potential for meeting the project objectives.[1] Copies of the FORTRAN coding and user's manuals for the LAKSCI model were obtained. The model was implemented on an IBM 370/158 computer system utilizing the IBM product Conversational Monitor System (CMS) for access to the central processor. This system proved to be quite efficient for modeling as it provided easy file editing and rapid execution time.

Several modifications to the original program were made to make it more useful and realistic for modeling Lake McConaughy. The model was divided into two segments, PREPMAC and LAKEMAC. The initial program (PREPMAC) computes daily lake level from inflow, outflow and meteorologic data and also prepares the meteorological data for use in calculating the thermal dynamics of the lake. The results of this analysis are

[1]Mention of trade names or commercial products does not constitute their endorsement or recommendation for use by the U.S. Government.

recorded on a file to be used by the second portion (LAKEMAC). PREPMAC has to be run only when changes in hydrologic or weather parameters are desired. Otherwise, information from the created file can be used to make successive runs of LAKEMAC. Input for each program was simplified for convenience but still remains basically consistent with the LAKSCI format. The output format was radically changed to show only required information in a more readable form. For each selected day of output this included lake volume, lake depth, depth of thermocline, surface air temperature, downstream (outflow) temperature and depth profiles for temperature, dissolved oxygen, ammonia nitrogen, nitrate nitrogen and total phosphate. A graphic display of the temperature profile was also included.

Subroutine BAL, which calculates the hydrologic parameters for the model, was modified to accomodate the effects of a large excavated hole in front of the dam. This hole is essentially a stagnant parcel of water during stratification since the outlet does not draw from that depth. The outlet is located on the old riverbed, and the hole is approximately 7-15 m deeper and to the side of the old channel. Due to its inactivity this portion of the lake was essentially ignored during stratification except for its role as a sink for nutrients and other materials.

Subroutine SUBL, which models the thermal stratification of the reservoir, was modified to more realistically model the physics of thermal diffusion. These changes had the effect of adding calibration capabilities to the thermal portion of the model. Changes were necessary in order to properly model the thermal dynamics of Lake McConaughy.

Lake McConaughy, due to its open, wind-swept nature, has unique reaeration coefficients. The method of calculating these coefficients in the program was altered to account for the uniqueness of the McConaughy system.

The program was modified in two places to insure that negative arguements did not appear in the calculation of square roots. Prior to the implementation of this change, LAKSCI was incapable of accomodating a negative net inflow for a given day. Negative net inflows occasionally arise at Lake McConaughy due to low inflow, seepage and evaporation.

Biological oxygen demand (BOD) was not measured in field experiments, hence modeling of this important variable was not attempted. BOD does, however, significantly affect the other constituents which were to be modeled. A procedure was developed to try and accomodate the affects of BOD on the constituents which were modeled. In a sense, the effects of BOD were "black boxed". This procedure has definite drawbacks but was the only alternative available considering the lack of sufficient data.

After modifications were completed, parameters were selected for Lake McConaughy and the model calibrated using data collected in 1977. Verification of the calibrated model was attempted using data from 1978.

RESULTS AND DISCUSSION

The results of all physical and chemical analyses and determinations are shown graphically in Appendix I. The objectives of this research do not provide for a lengthy description of physical-chemical parameters. This will be provided, however, in a secondary publication, "The Limnology of Lake McConaughy" to be printed in the Nebraska Technical Series in 1981. A short summary is included here to provide background information relative to model input.

Mean values for each variable measured for the entire sampling period over all stations are shown in Table 4.

The LAKSCI model chosen for use in this research is not capable of simulating horizontal variations in a lake. The model assumes horizontal homogeneity and simulates only one station and the outlet given certain inflow characteristics. Therefore, the primary data that could be used in the model was from Stations 1, 5 (inlet) and 6 (outlet). To test the potential for errors in assuming Station 1 similar to other lake stations a one-way analysis of variance was run on each variable using Stations 1, 2, 3, and 4 as treatments. The only significant differences found showed Station 4 different from 1, 2 and 3. This was not surprising since Station 4 is nearly riverine rather than lacustrine. All of the coldwater fishery habitat lies in the vicinity of Stations 1 and 2. Consequently, it was concluded that the differences found for Station 4 would not seriously affect the results of simulated phenomenon relative to available coldwater habitat.

To test for horizontal differences perpendicular to the long axis of the reservoir, t-tests were employed using each of the measured variables. These were used to test Station 2 vs Station 7, Station 2 vs Station 8, Station 3 vs Station 9 and Station 3 vs Station 10. No significant differences were found with these tests, hence it was concluded that there was little if any horizontal variation in the measured variables perpendicular to the long axis of the lake.

Table 4. Mean, range, and standard deviation of measured variables over the entire period for all reservoir stations.

SAMPLE	SIZE	RANGE	MEAN	STANDARD DEVIATION
Ammonia nitrogen, mg/l	390	0.00 - 1.20	0.110	0.159
Nitrate nitrogen, mg/l	382	0.10 - 2.80	0.694	0.459
Kjeldahl nitrogen, mg/l	288	0.00 - 7.92	0.902	1.161
Total phosphate, mg/l	339	0.10 - 2.55	0.194	0.239
Orthophosphate, mg/l	386	0.00 - 0.66	0.070	0.074
Turbidity, NTU	372	1.00 - 315.00	14.645	30.234
Total alkalinity, mg/l	389	153.00 - 279.00	187.784	21.365
Conductivity, μmhos	336	460.00 - 920.00	676.854	73.843
pH	354	7.50 - 9.05	8.451	0.307
Dissolved oxygen, mg/l	388	0.00 - 16.10	7.392	3.758
Temperature, °C	390	0.00 - 30.20	14.985	6.522
Total dissolved solids, mg/l	355	354.70 - 842.70	512.275	49.307
Total solids, mg/l	369	356.00 - 999.80	567.649	90.885
Chemical oxygen demand, mg/l	352	1.20 - 93.00	12.974	8.650
Chlorophyll A, μg/l	362	0.00 - 151.50	15.717	18.255
Chlorophyll B, μg/l	363	0.00 - 42.10	4.542	5.695
Chlorophyll C, μg/l	362	0.00 - 103.80	17.153	18.249
Chlorides, mg/l	339	8.39 - 23.20	18.531	1.410
Total hardness, mg/l	390	164.00 - 315.00	216.562	22.900
Calcium hardness, mg/l	386	96.00 - 293.00	170.617	38.431
Secchi disc, m	171	0.10 - 6.00	1.339	0.987

As a result of these tests it was concluded that the reservoir is fairly homogenous in the region of Stations 1, 2, 3, 7, 8, 9 and 10. Since this area encompasses nearly all of the volume of the reservoir and 100% of the coldwater habitat, it was concluded that errors encountered in simulating this region as a single station would be small to non-existent. Because it was located in the deepest portion of the lake, Station 1 was used as a representative station for input to the model. Mean values of variables collected at Stations 1, 5 and 6 are shown in Tables 5, 6, and 7, respectively.

The modified model was calibrated using data collected in 1977. Where data was lacking, default coefficients supplied in the model were used. A special calibration procedure was used to determine coefficients in subroutine BAL (Dauer, 1978). After a series of runs and considerable adjustment of coefficients, reasonably good correspondence to actual data was achieved for temperature profiles (Figure 3), hydrologic variables (Figure 4), and dissolved oxygen. The fit obtained for ammonia nitrogen, nitrate nitrogen and total phosphate was less than adequate due to lack of proper data. The procedure developed to "black box" BOD simply did not perform realistically. Considerable adjustment of coefficients did not improve realism. To test model validity, a simulation was made for 1978 and compared to actual data collected. The fit for temperature (Figure 5) and hydrologic data (Figure 6) was again reasonably good. Had it not been for a very strong wind the day prior to sampling in August 1978, the fit of the temperature profile would have been even better. The remaining variables, however, showed a poor response.

The model as modified does not mechanistically model chemical constituents due to the lack of BOD data. Therefore, a realistic simulation with good fit could not be expected, particularly over a period of more than one year.

Table 5. Mean, range, and standard deviation of all variables measured at Station 1 for the entire period.

	SAMPLE SIZE	RANGE	MEAN	STANDARD DEVIATION
Ammonia nitrogen, mg/l	99	0.00 - 1.20	0.205	0.256
Nitrate nitrogen, mg/l	94	0.00 - 1.70	0.545	0.294
Kjeldahl nitrogen, mg/l	71	0.03 - 6.70	0.988	1.123
Total phosphate, mg/l	82	0.01 - 1.75	0.181	0.224
Orthophosphate, mg/l	96	0.00 - 0.34	0.083	0.067
Turbidity, NTU	94	1.00 - 26.00	4.298	4.137
Total alkalinity, mg/l	98	156.00 - 213.00	184.837	11.378
Conductivity, µmhos	84	485.00 - 785.00	677.595	65.536
pH	88	7.65 - 8.95	8.278	0.316
Dissolved oxygen, mg/l	99	0.00 - 12.50	4.357	4.234
Temperature, °C	99	1.50 - 22.50	13.687	4.859
Total dissolved solids, mg/l	88	354.70 - 581.30	503.956	38.392
Total solids, mg/l	93	461.00 - 706.70	544.276	39.019
Chemical oxygen demand, mg/l	87	1.20 - 27.10	10.526	39.019
Chlorophyll A, µg/l	92	0.00 - 27.30	8.808	5.744
Chlorophyll B, µg/l	92	0.00 - 10.00	2.766	2.428
Chlorophyll C, µg/l	92	0.00 - 32.70	10.727	7.539
Chlorides, mg/l	84	15.70 - 22.50	18.462	1.093
Total hardness, mg/l	99	164.00 - 242.00	214.737	15.770
Calcium hardness, mg/l	98	106.00 - 220.00	166.061	33.853
Secchi disc, m	24	1.00 - 6.00	2.354	1.140

Table 6. Mean, range, and standard deviation of all variables measured at Station 5 over the entire sampling period.

	SAMPLE SIZE	RANGE	MEAN	STANDARD DEVIATION
Ammonia nitrogen, mg/l	36	0.00 - 0.18	0.043	0.054
Nitrate nitrogen, mg/l	37	0.00 - 2.80	1.632	0.683
Kjeldahl nitrogen, mg/l	31	0.00 - 6.06	1.354	1.469
Total phosphate, mg/l	34	0.04 - 2.55	0.464	0.485
Orthophosphate, mg/l	36	0.02 - 0.55	0.120	0.112
Turbidity, NTU	36	2.00 - 315.00	65.861	68.871
Total alkalinity, mg/l	37	166.00 - 279.00	233.243	24.049
Conductivity, μmhos	34	520.00 - 920.00	732.765	100.415
pH	35	7.60 - 8.85	8.484	0.292
Dissolved oxygen, mg/l	36	4.20 - 13.80	8.831	1.788
Temperature, °C	37	0.00 - 30.20	15.276	9.922
Total dissolved solids, mg/l	34	397.30 - 842.70	584.335	76.062
Total solids, mg/l	36	396.00 - 999.80	765.336	145.641
Chemical oxygen demand, mg/l	32	5.90 - 45.70	20.041	11.678
Chlorophyll A, μg/l	33	0.00 - 114.90	26.382	28.765
Chlorophyll B, μg/l	34	0.00 - 21.00	6.247	5.901
Chlorophyll C, μg/l	34	0.00 - 77.80	27.306	22.885
Chlorides, mg/l	34	8.39 - 23.20	19.136	2.651
Total hardness, mg/l	37	186.00 - 315.00	255.297	35.266
Calcium hardness, mg/l	37	96.00 - 293.00	203.378	53.454

Table 7. Mean, range, and standard deviation of all variables measured at Station 6 over the entire sampling period.

	SAMPLE SIZE	RANGE	MEAN	STANDARD DEVIATION
Ammonia nitrogen, mg/l	35	0.00 - 1.00	0.028	0.167
Nitrate nitrogen, mg/l	35	0.10 - 1.20	0.677	0.239
Kieldahl nitrogen, mg/l	29	0.00 - 7.92	1.561	2.012
Total phosphate, mg/l	33	0.01 - 0.65	0.142	0.110
Orthophosphate, mg/l	36	0.01 - 0.35	0.081	0.061
Turbidity, NTU	35	1.00 - 9.00	4.086	1.805
Total alkalinity, mg/l	36	157.00 - 223.00	185.889	12.879
Conductivity, μmhos	33	525.00 - 758.00	676.606	61.196
pH	34	7.50 - 8.95	8.347	0.384
Dissolved oxygen, mg/l	35	6.80 - 16.00	11.143	2.050
Temperature, °C	36	0.00 - 19.80	10.028	6.258
Total dissolved solids, mg/l	34	84.00 - 614.70	504.432	41.216
Total solids, mg/l	33	470.70 - 677.30	545.373	38.753
Chemical oxygen demand, mg/l	34	2.10 - 17.60	10.165	3.592
Chlorophyll A, μg/l	33	0.00 - 28.10	7.618	6.604
Chlorophyll B, μg/l	33	0.00 - 24.40	3.103	4.727
Chlorophyll C, μg/l	33	0.00 - 85.80	11.394	15.792
Chlorides, mg/l	33	13.40 - 21.67	18.028	1.834
Total hardness, mg/l	36	168.00 - 260.00	216.056	18.801
Calcium hardness, mg/l	36	117.00 - 247.00	172.278	37.257

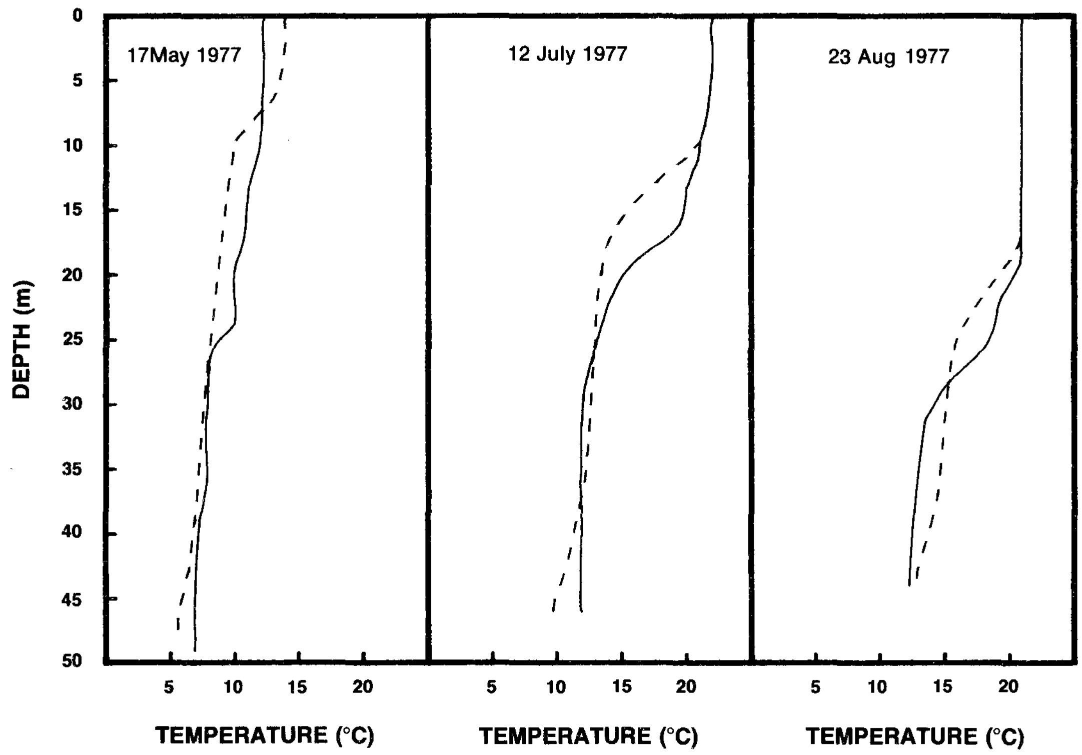

Figure 3. *A comparison of simulated temperature profiles (broken lines) with measured profiles (solid lines) for 1977 showing the calibration capability of the model.*

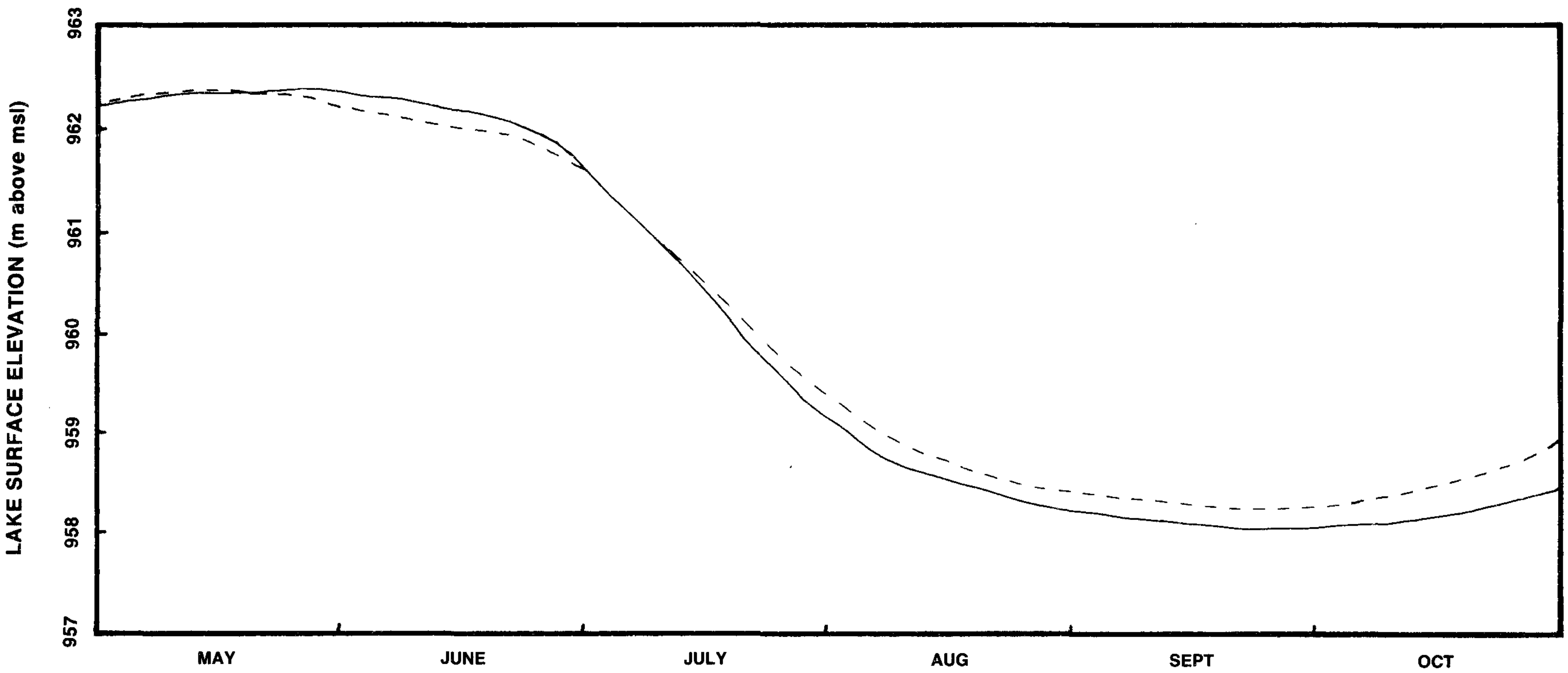

Figure 4. *A comparison of the simulated water level (broken line) with measured water level (solid line) in 1977 showing the calibration capability of the model.*

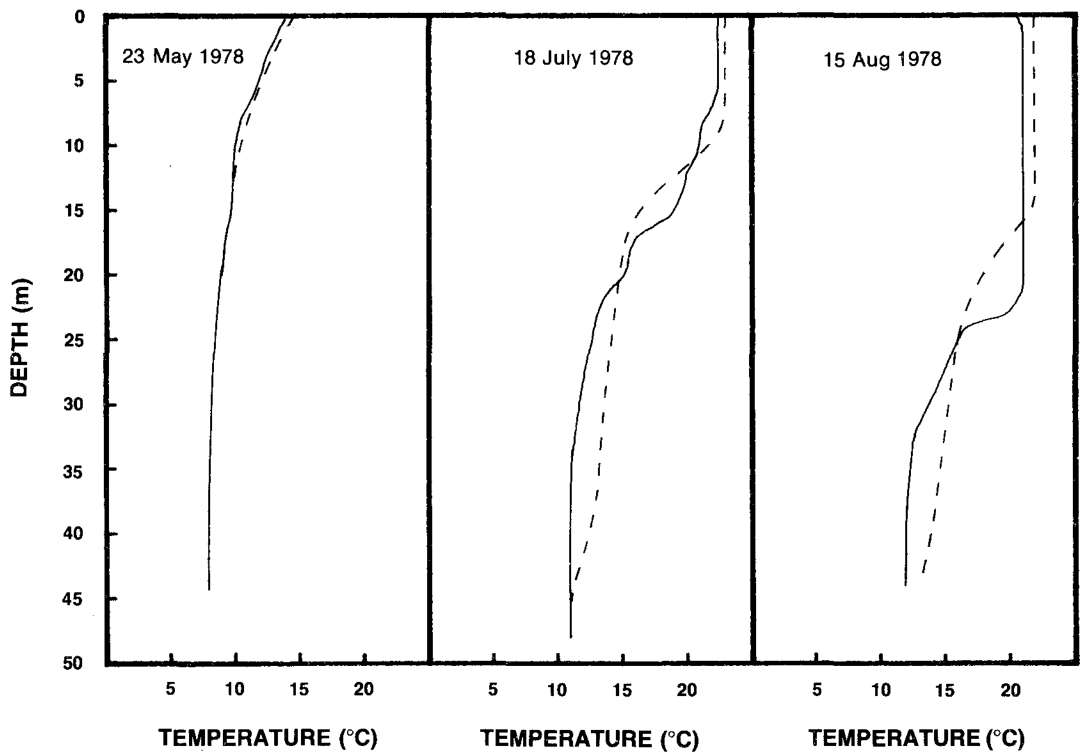

Figure 5. *A comparison of simulated temperature profiles (broken lines) with measured profiles (solid lines) for 1978 used to verify the precision of the model.*

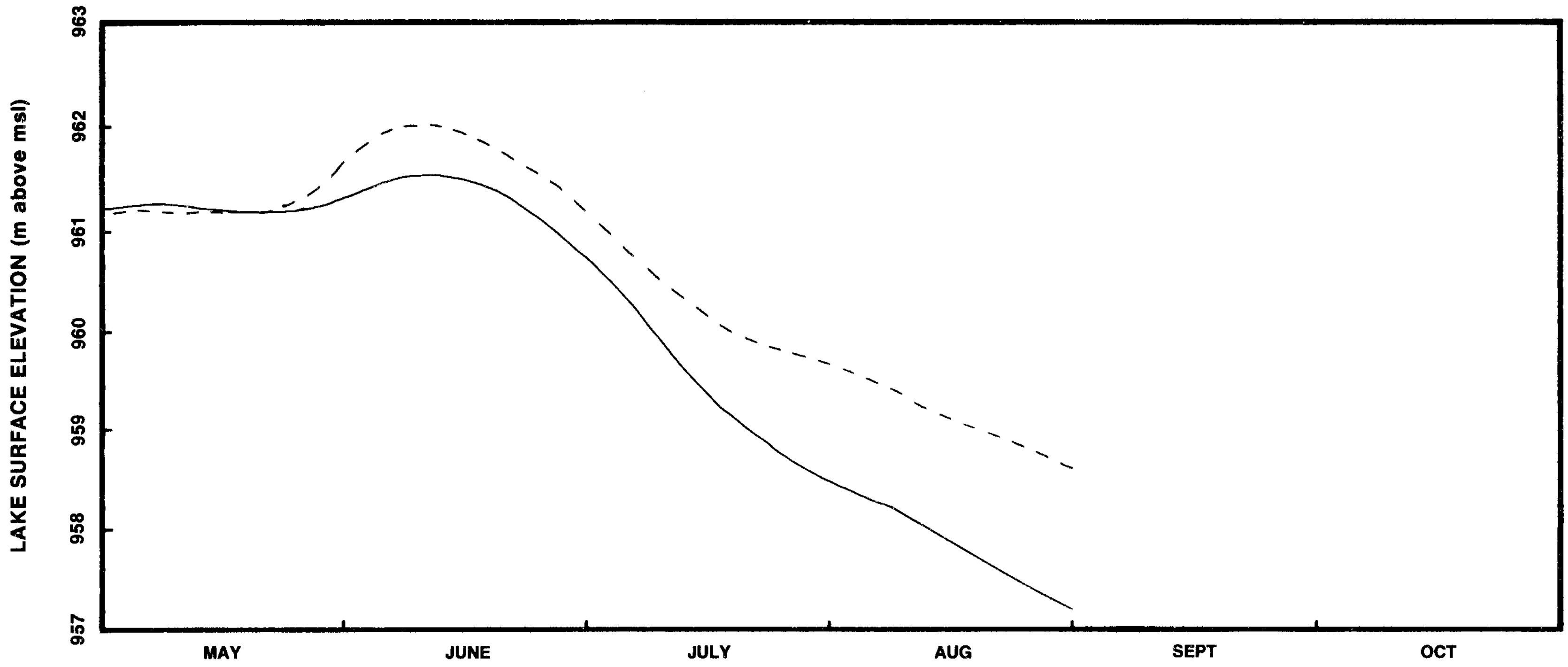

Figure 6. *A comparison of the simulated water level (broken line) with measured water level (solid line) in 1978 used to verify the precision of the model.*

From these modeling runs it was concluded that the model was quite precise in predicting hydrologic characteristics and temperature profiles given basic inflow-outflow data and meteorological information. Use of the model for predicting the concentration of chemical constituents, however, appeared to be quite limited.

To further substantiate these conclusions a number of runs were made to ascertain the model's usefulness in predicting the future availability of coldwater fish habitat in Lake McConaughy given certain conditions. These runs were made in an attempt to isolate practices which could aid in maximizing the life of the coldwater fish habitat.

The first run consisted of lowering the lake inflow by 15%. This is a realistic possibility due to potential upstream water demands. The results of this inflow reduction are shown in Figures 7 and 8 as compared to the 1977 simulation. The water level dropped about 0.6 m with a resultant movement of the thermocline 1.6 m closer to the surface. The effects on water level seemed rather small, but if one considers the cumulative effects over a period of years, the drop in water level could be rather large. The significance of this to the coldwater fishery was difficult to ascertain since the simulated epilimnetic temperature never exceeded 21.1° C, a tolerable temperature for coldwater species. During warm periods however, this epilimnetic temperature may climb to 25°C or higher. The question left unanswered is, "How much dissolved oxygen remains in waters cool enough for trout?" As the water level drops, it would seem reasonable to assume that the volume of the hypolimnion would

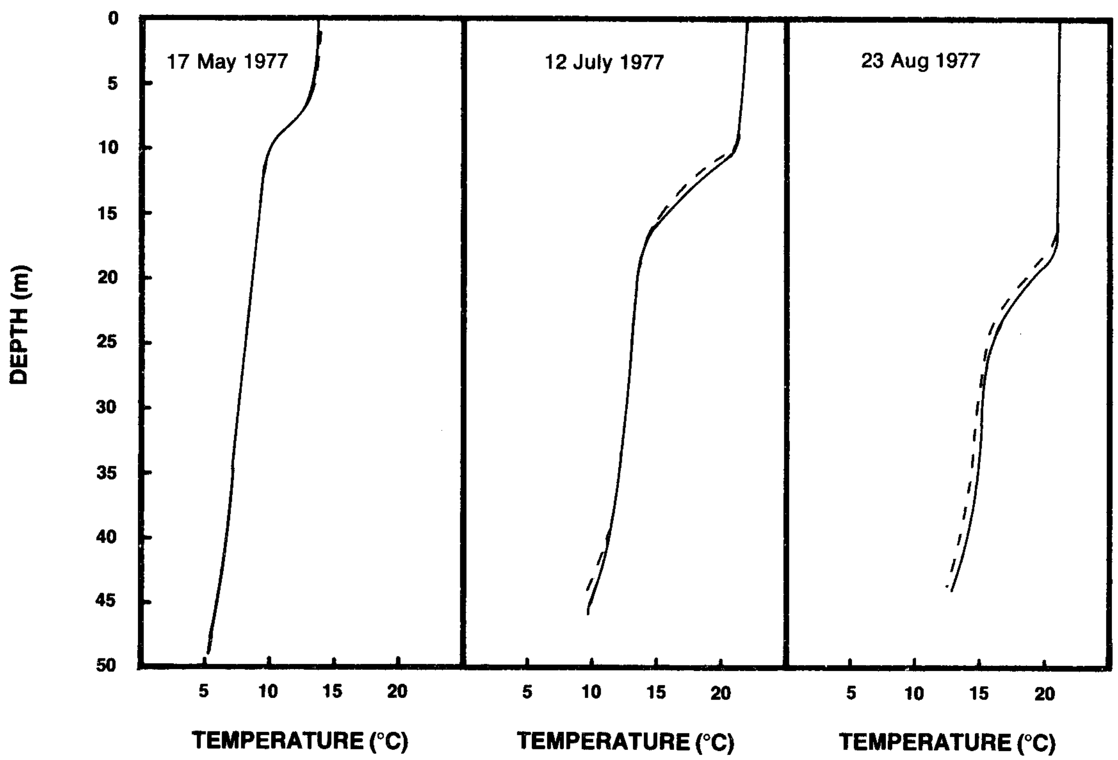

Figure 7. A comparison of simulated temperature profiles (solid lines) for 1977 under normal inflows with profiles (broken lines) simulating a 15% reduction in reservoir inflow.

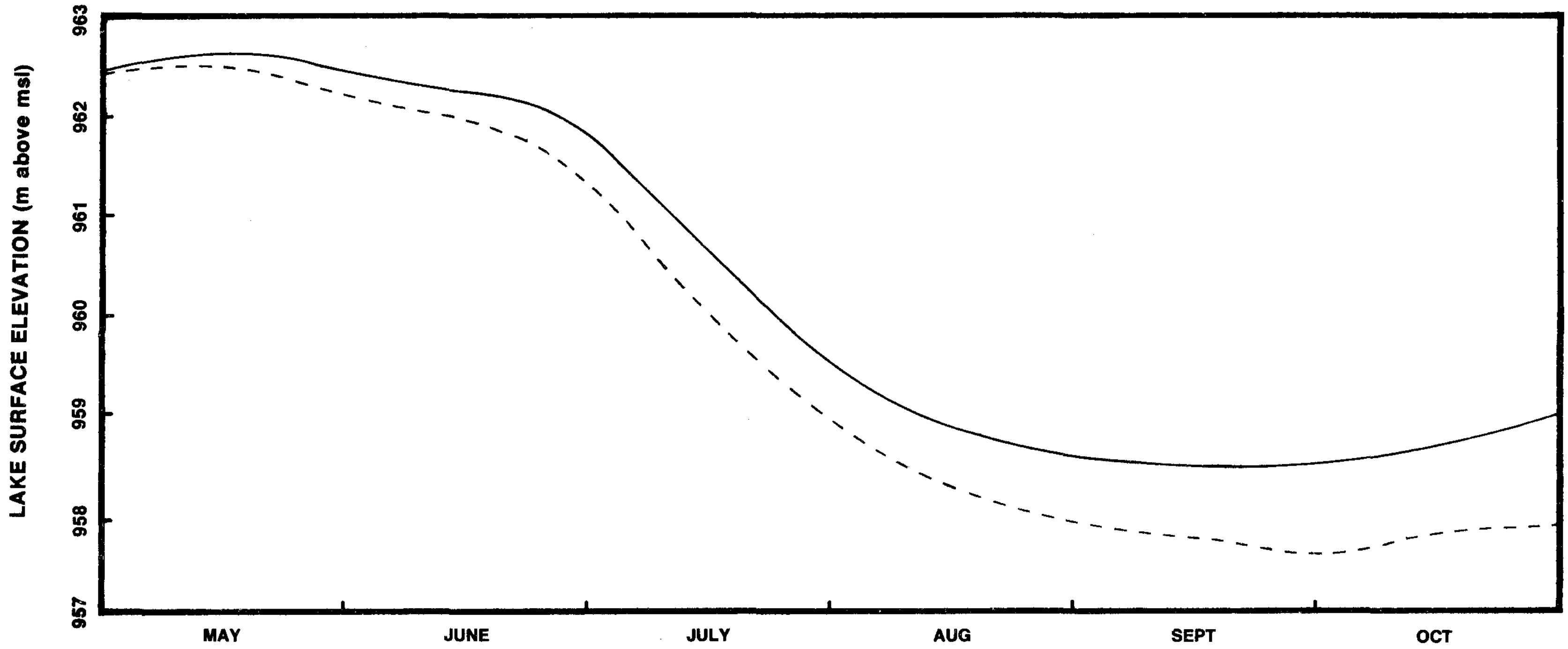

Figure 8. *A comparison of the simulated water level (solid line) in 1977 under normal inflows with the simulated water level (broken line) under a 15% reduction in reservoir inflow.*

decrease, therefore, reducing its capacity to assimilate organic materials. This would at first appear to most certainly increase the depletion of oxygen in the hypolimnion. However, production of organic matter would be smaller with a reduced surface area. Also, the depth of the thermocline evidently moves closer to the surface with less warm inflows. This would expand the volume of the hypolimnion. All of these factors and more are impossible to evaluate simultaneously without the use of a comprehensive model. Since the model developed proved to be in error in predicting dissolved oxygen levels, its usefulness for solving this problem is limited.

A second experimental run was made to determine the effect of using only the surface discharge instead of the bottom discharge which was used in the 1977 simulation (Figure 9). Theoretically, such a management practice would affect both the depth to the thermocline and the nutrient loading of the reservoir. Nutrients, particularly phosphates, are present in higher concentrations in anoxic hypolimnetic waters than in oxygenated water (Monkmeyer, et al., 1974). A bottom discharge should contain a higher concentration of phosphate than the surface discharge. Hence, phosphate loading and therefore overall concentration should be reduced with a bottom rather than a surface discharge, particularly during summer stratification. The simulated response to such a management practice does show that the thermocline moved considerably closer to the surface with a surface discharge (Figure 9). No change was evident in the nitrate or phosphate concentrations due to the inability of this portion of the model to simulate this information. From a coldwater

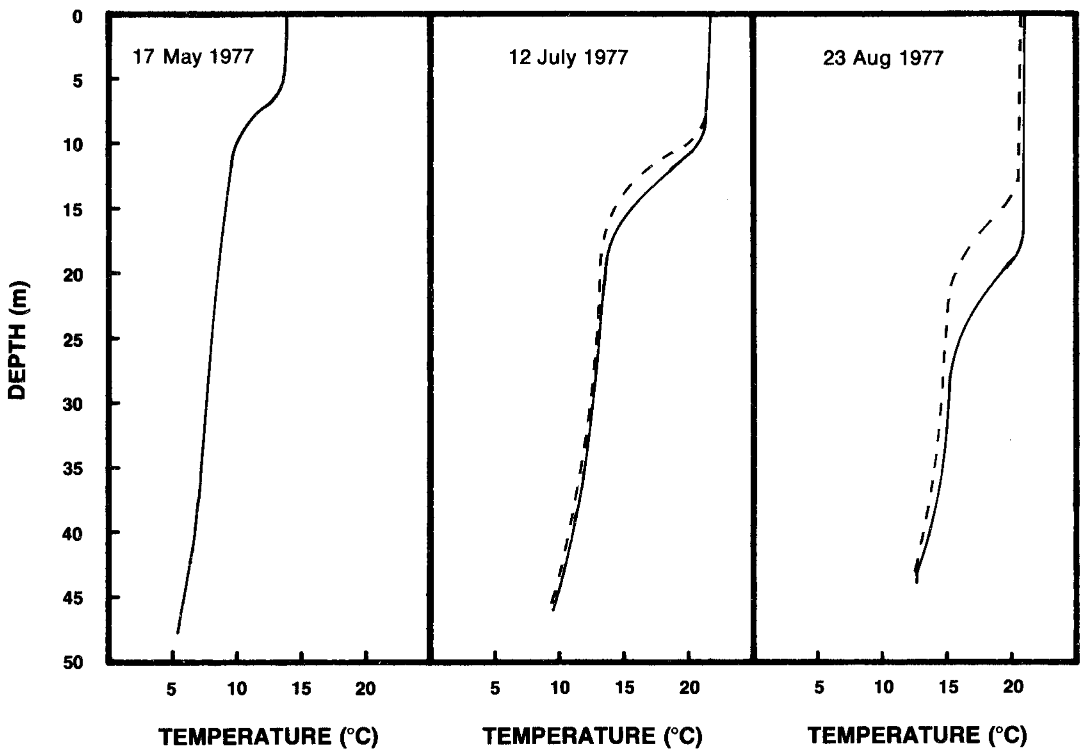

Figure 9. *A comparison of simulated temperature profiles (solid lines) for 1977 when a bottom only discharge was used with simulated profiles (broken lines) assuming a surface only discharge.*

fishery standpoint, based on the thermal characteristics alone, it would seem more appropriate to release water from the hypolimnion rather than the epilimnion. Bottom releases have also been suggested as a eutrophication control procedure as it should reduce the overall concentration of nutrients in the lake water. From a practical standpoint, this management practice will almost certainly be followed because the water level is always below the surface outlet structure in Lake McConaughy during summer stratification.

Additional runs were made simulating the effects of increased levels of nitrates and phosphates in the lake. These runs simply substantiated the earlier conclusion that additional data must be obtained to properly calibrate the chemical constituent portion of the model.

The model as it is presently calibrated will provide a valuable tool for simulating changes in hydrologic conditions given changes in inflow, outflow or some unusual weather factor. The thermal dynamics of the reservoir can also be predicted with good precision. This portion of the model alone will be extremely valuable in evaluating the effect of reduced inflows as a result of upstream diversion of water or increased outflows as a result of downstream requests for more irrigation water.

RECOMMENDATIONS AND CONCLUSIONS

1. The hydrologic and thermal dynamics portions of the model appear to be quite precise. They should be utilized to model the effects of any perturbations which could affect this portion of the reservoir's dynamics. For example, it could be used to model the effect on water level and the thermal dynamics of a reduced inflow due to upstream diversion. Effects of drought, extremely hot weather and various outflow regimes are other potential changes that can be modeled.

2. The chemical constituent portion of the model is presently inaccurate and should not be used without modification. In order to make this model more useful, a considerable amount of work on the model would be needed followed by collection of needed field data. Some highly skilled and specialized personnel would be required for this approach to be successful. At this point in time, such a project would not seem cost justified for the Nebraska Game and Parks Commission.

3. The field data collected plus previously collected data provide an excellent basis for preparing a description of the physical and chemical limnology of Lake McConaughy. This analysis could be used as a planning guide instead of the model. A technical paper to accomplish this task is being planned. It will include an in depth analysis of each varible which has been measured plus recommended management procedures for protecting and enhancing water quality, water quantity and fishery values.

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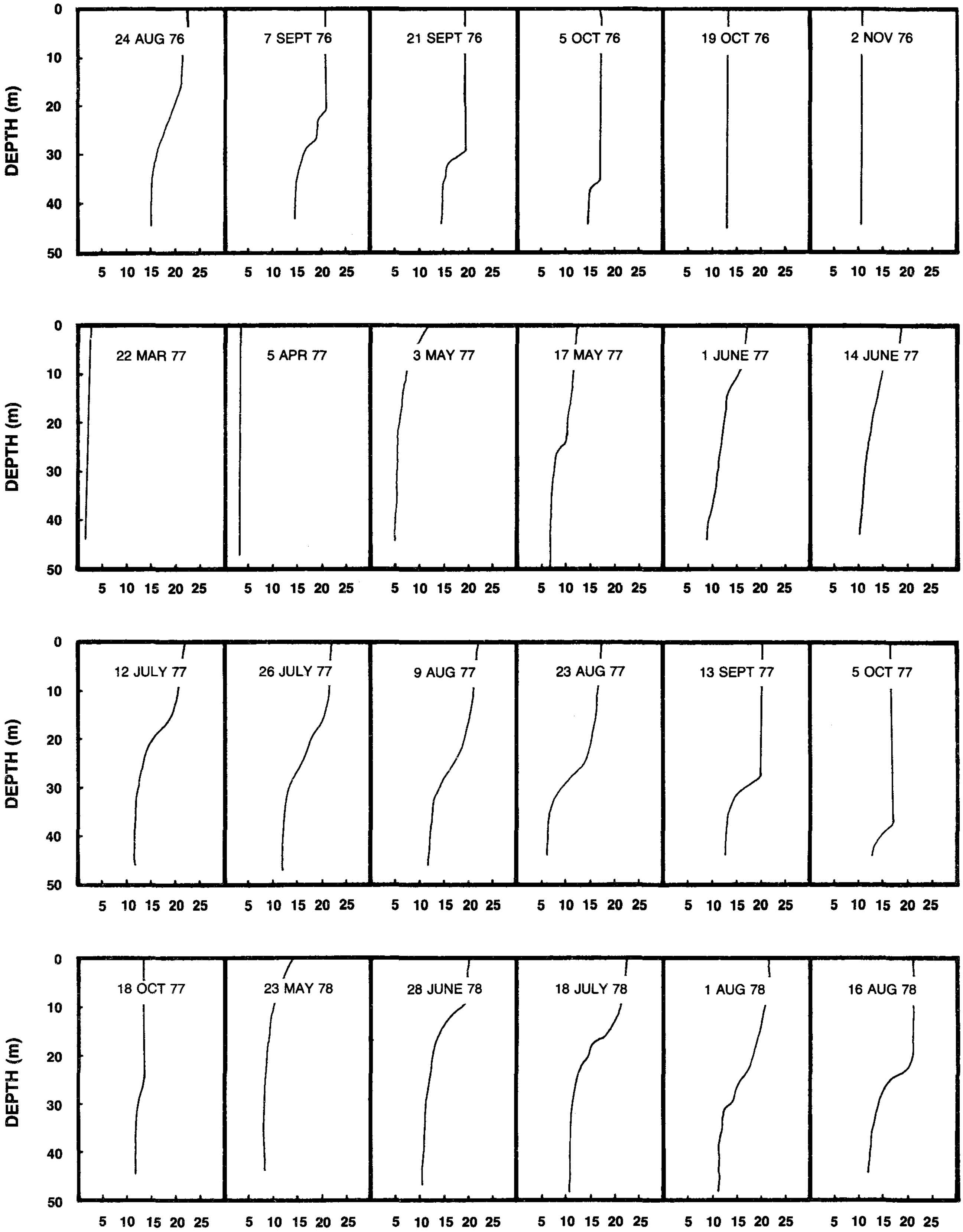
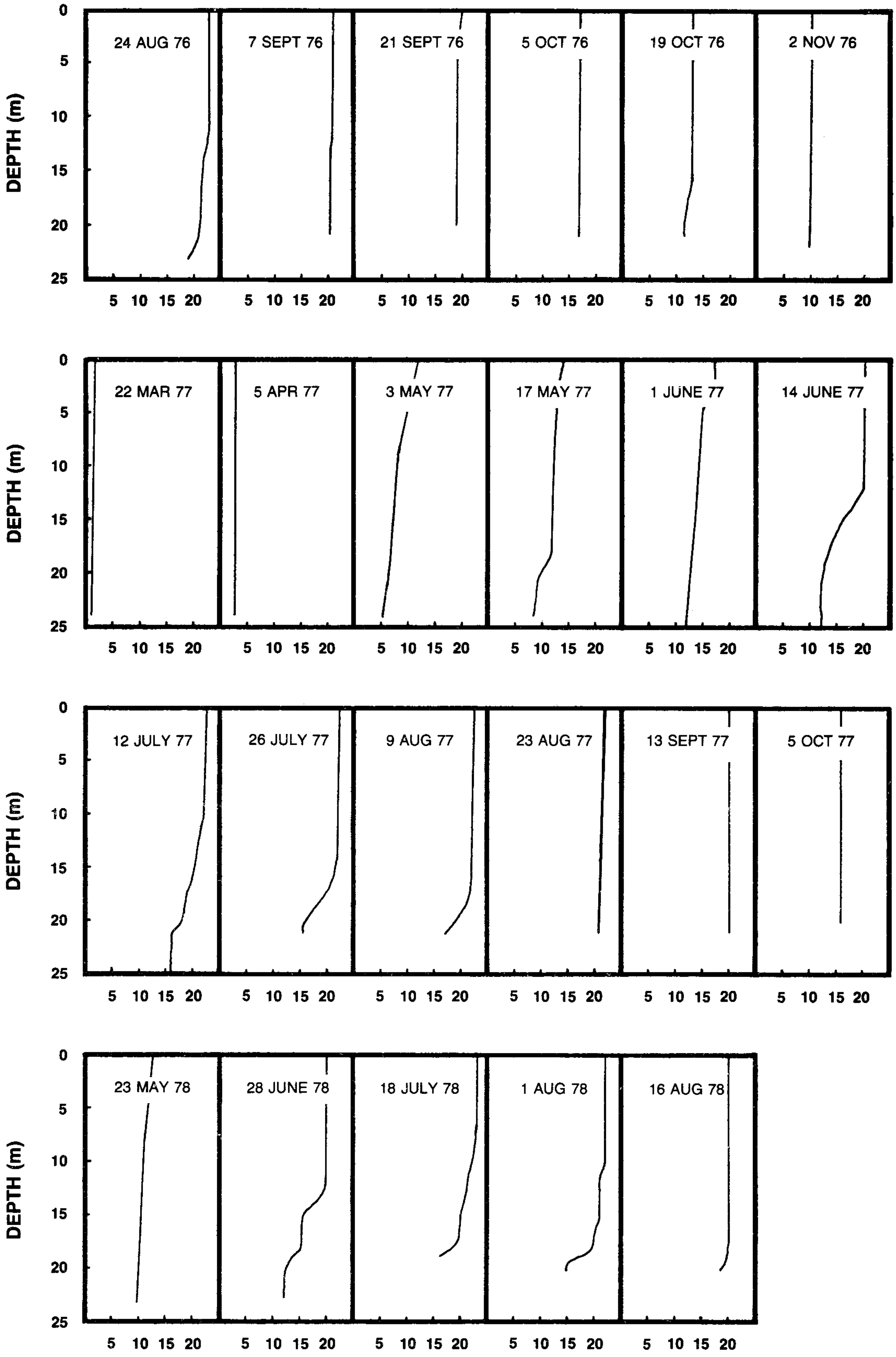
APPENDIX I

STATION 1



TEMPERATURE (°C)

STATION 2



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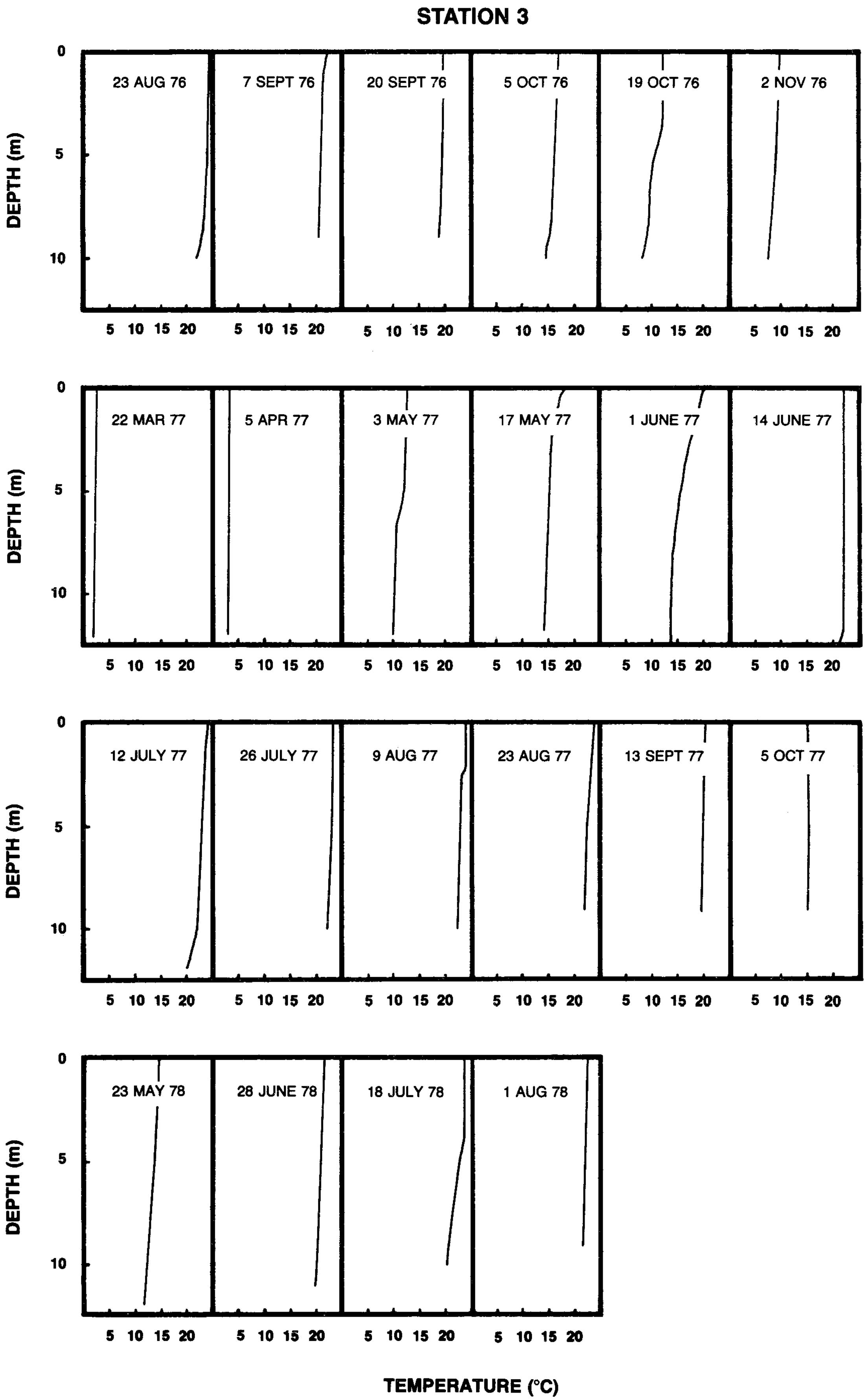
STATION 3
DEPTH (m)
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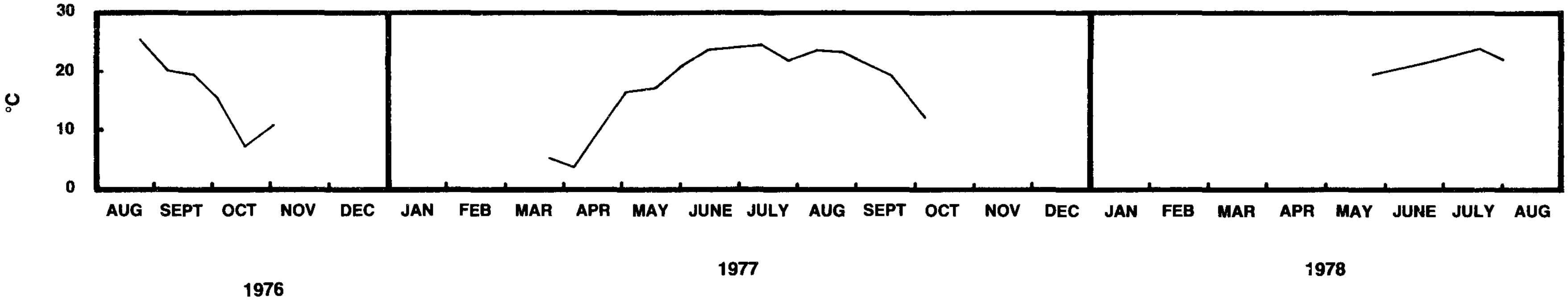
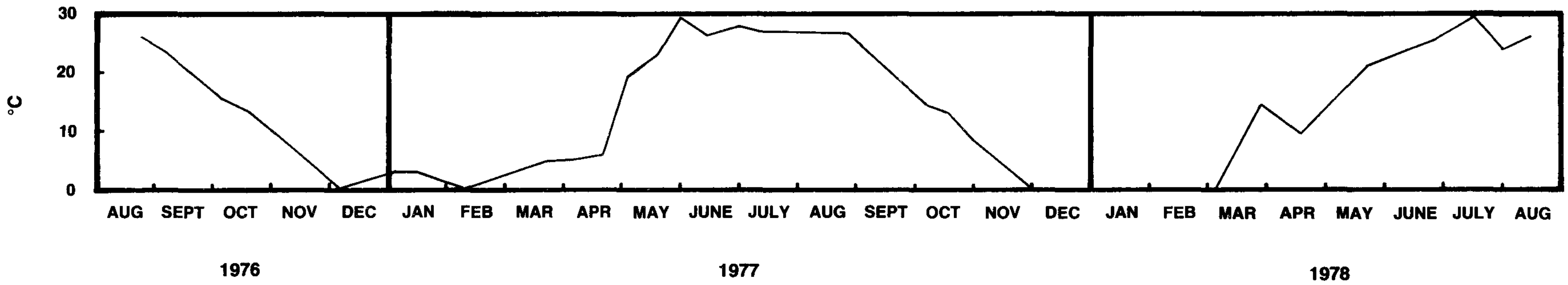
20 SEPT 76
5 OCT 76
19 OCT 76
2 NOV 76
22 MAR 77
5 APR 77
3 MAY 77
17 MAY 77
1 JUNE 77
14 JUNE 77
12 JULY 77
26 JULY 77
9 AUG 77
23 AUG 77
13 SEPT 77
5 OCT 77
23 MAY 78
28 JUNE 78
18 JULY 78
1 AUG 78
0
5
10
5 10 15 20
TEMPERATURE (°C)

STATION 4



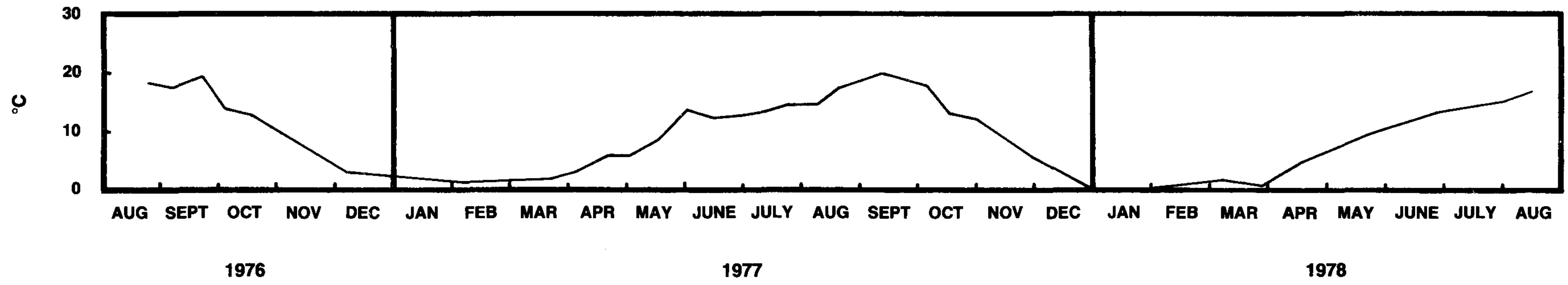
TEMPERATURE (°C)

STATION 5



TEMPERATURE (°C)

STATION 6



TEMPERATURE (°C)

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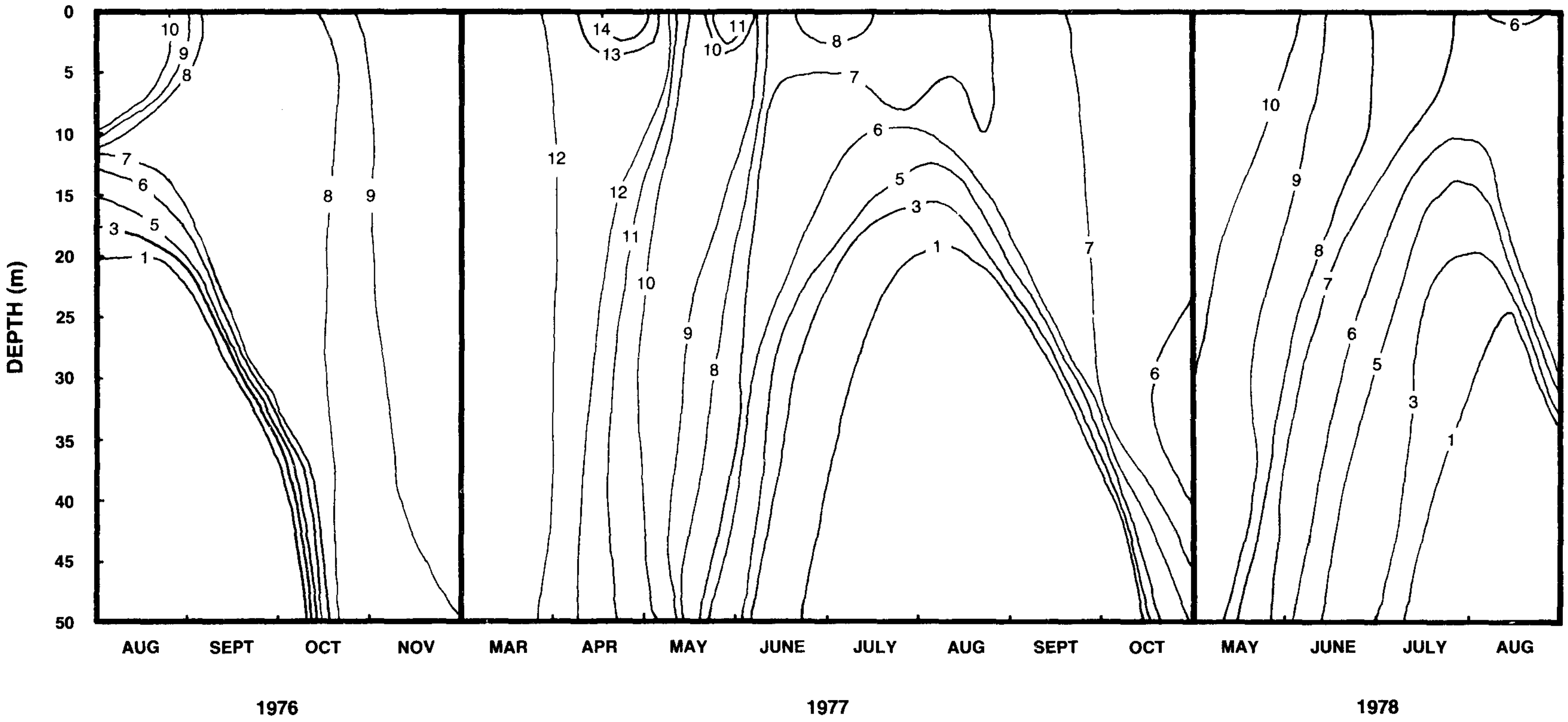
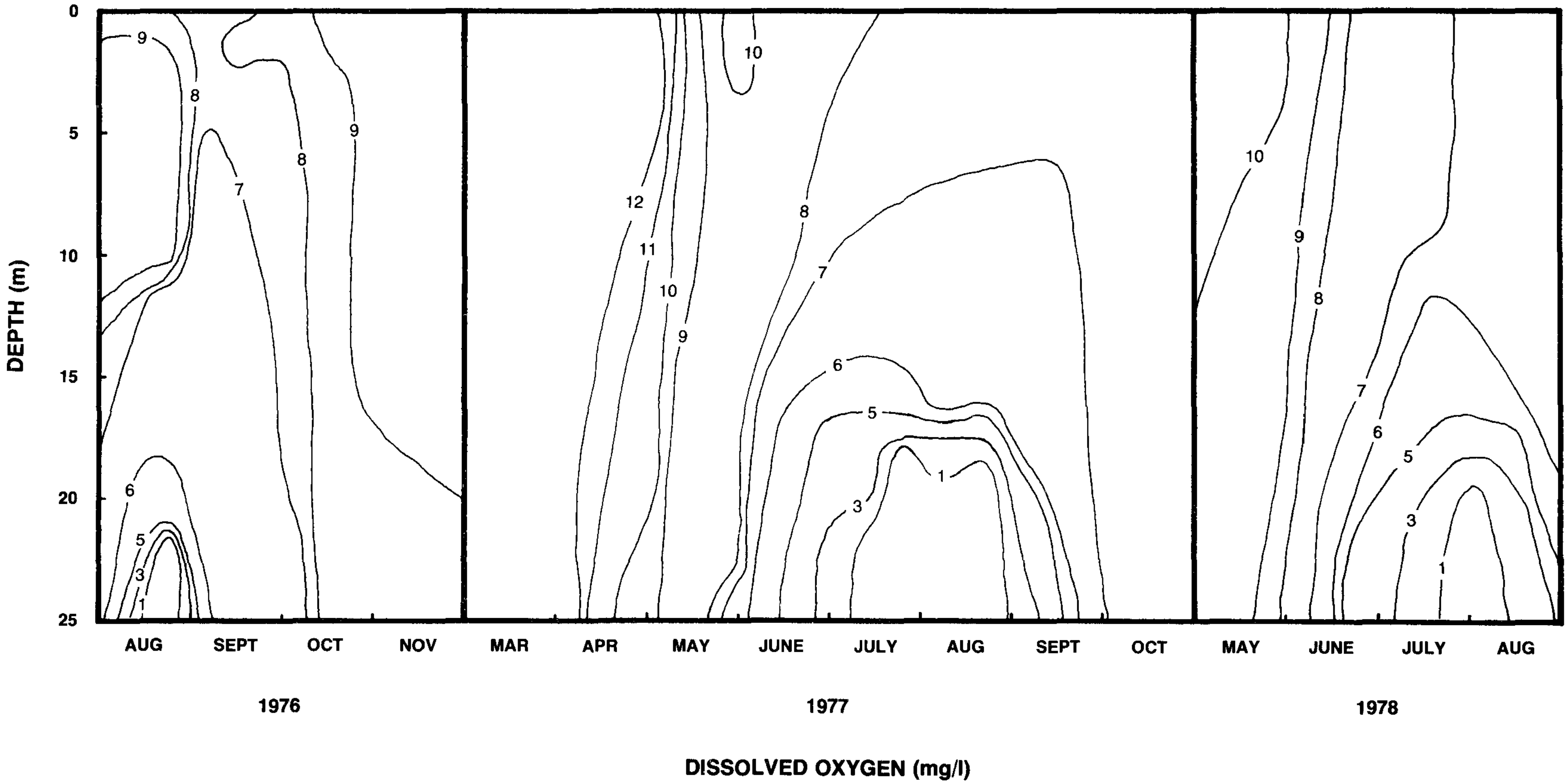


DISSOLVED OXYGEN (mg/l)

STATION 2



DEPTH (m)
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JULY
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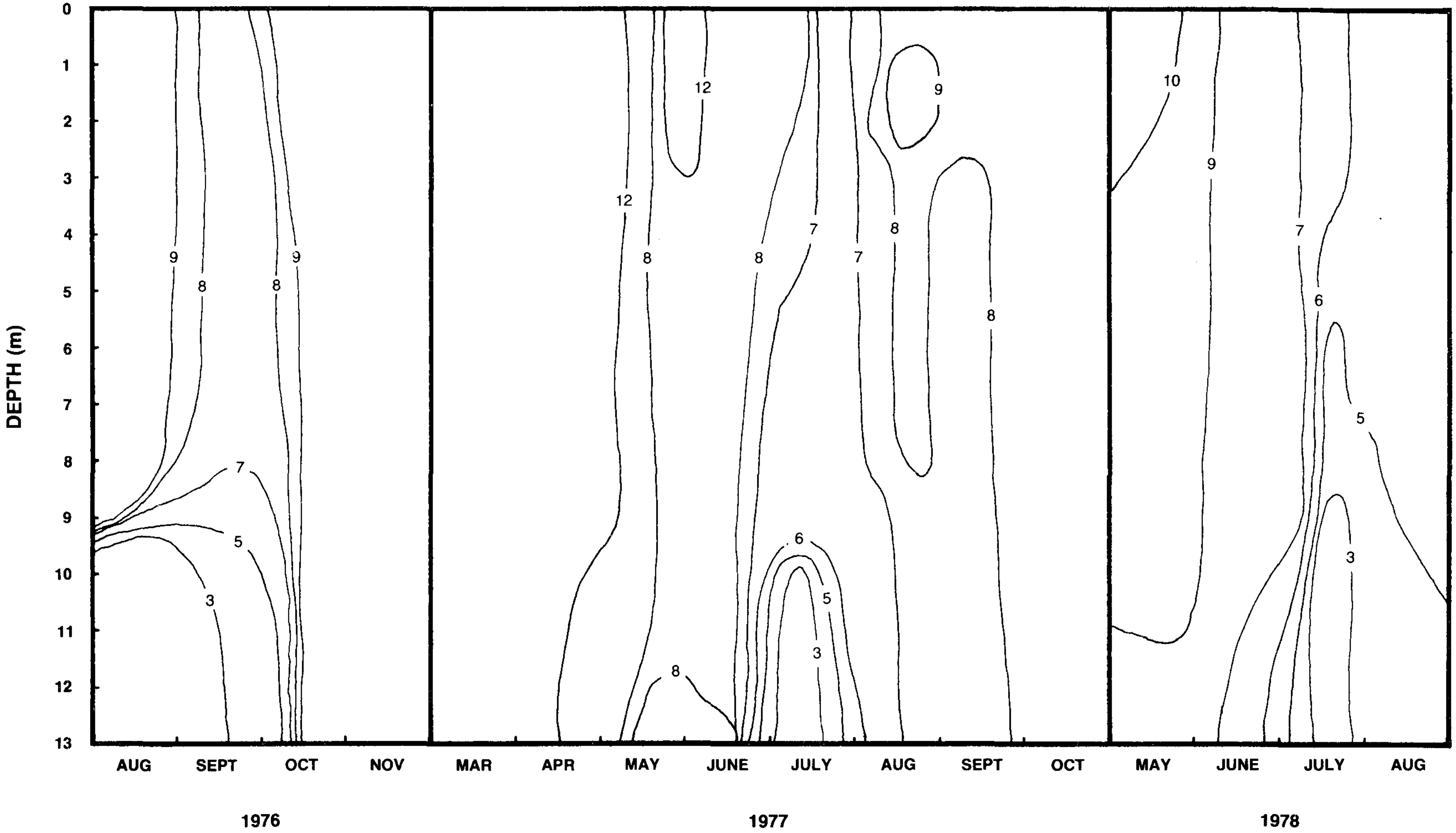
1976
1977
1978
DISSOLVED OXYGEN (mg/l)

STATION 3



DISSOLVED OXYGEN (mg/l)

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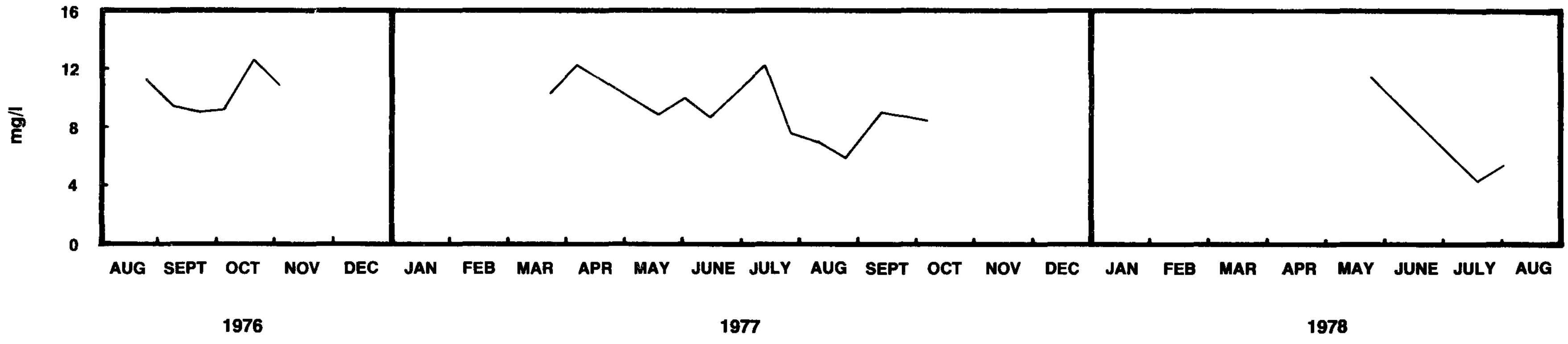

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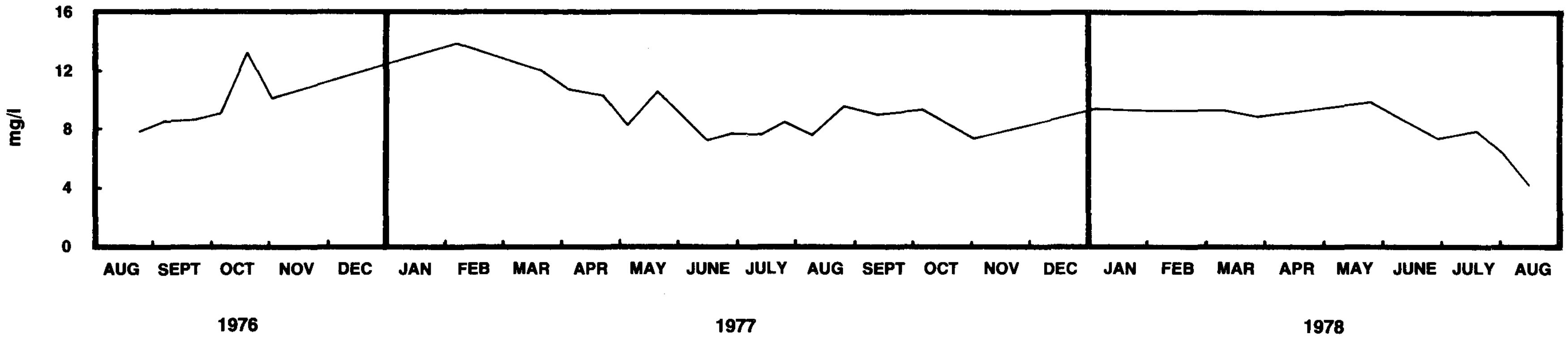
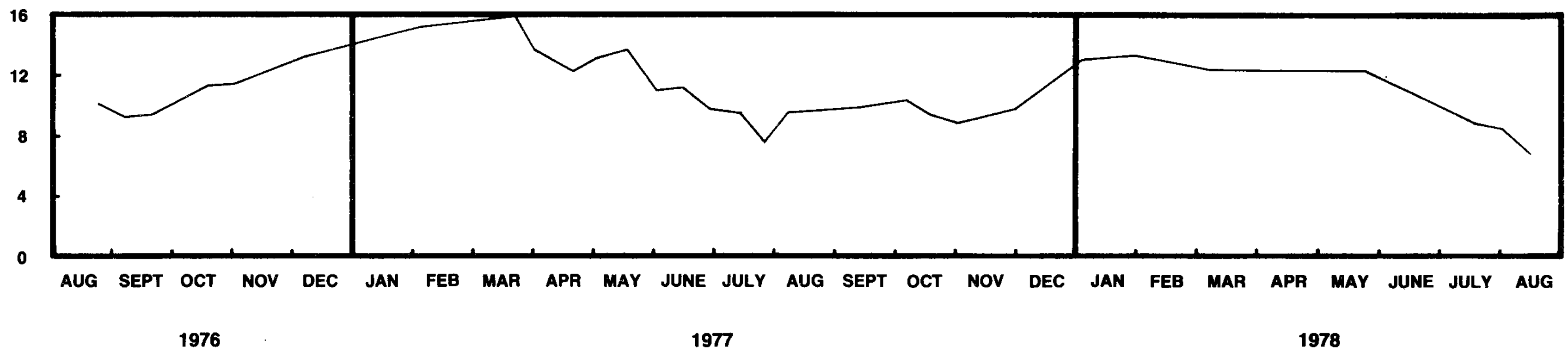
STATION 5



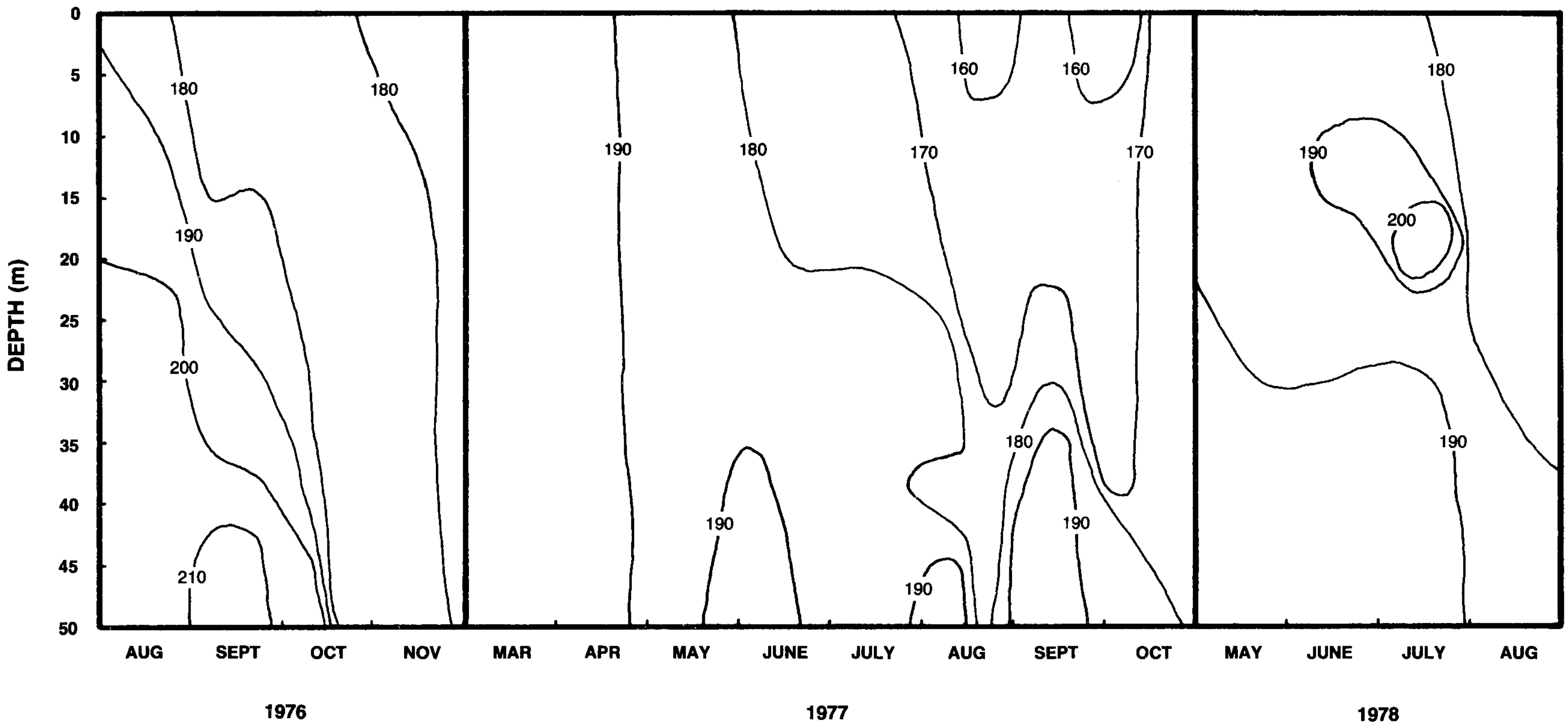
DISSOLVED OXYGEN (mg/l)

STATION 6



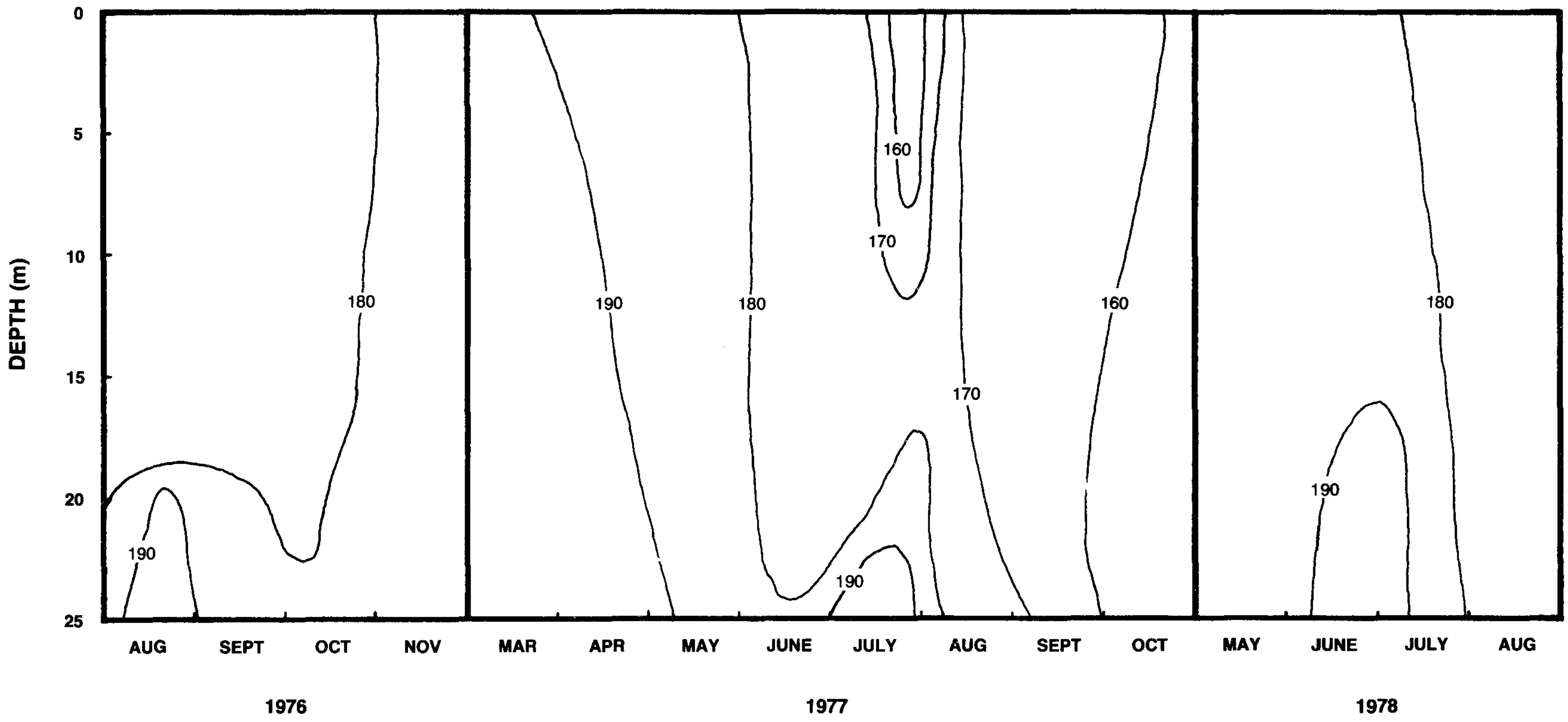
DISSOLVED OXYGEN (mg/l)

STATION 1



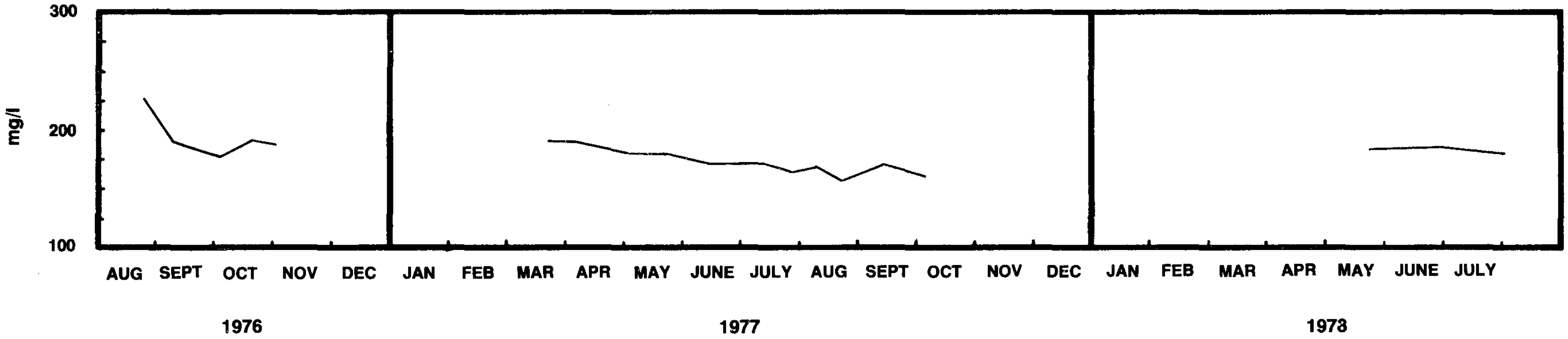
TOTAL ALKALINITY (mg/l)

STATION 2



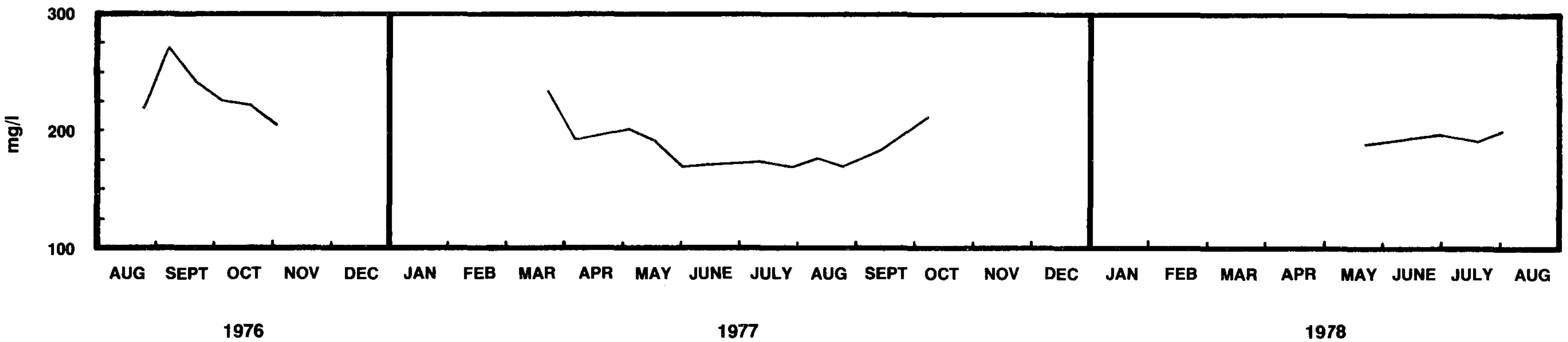
TOTAL ALKALINITY (mg/l)

STATION 3



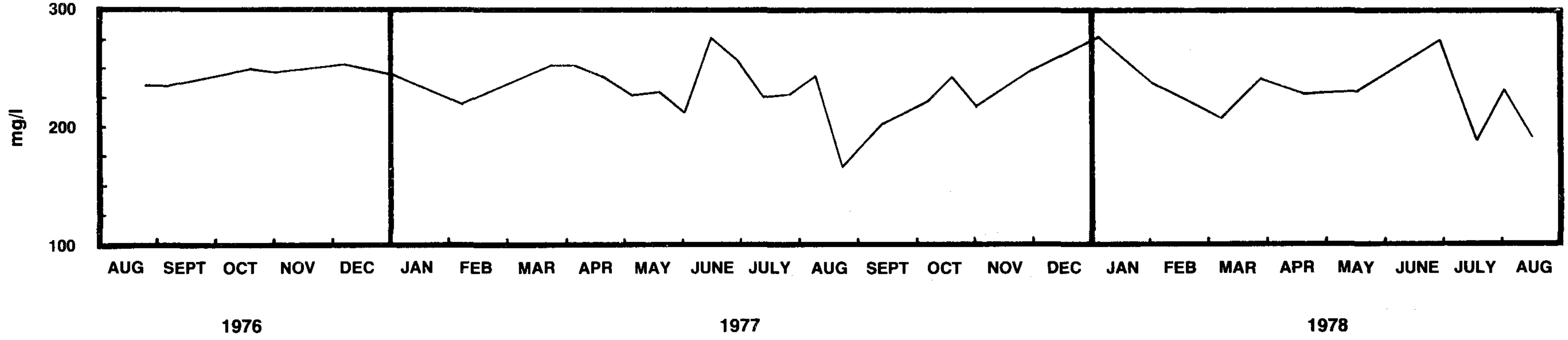
TOTAL ALKALINITY (mg/l)

STATION 4



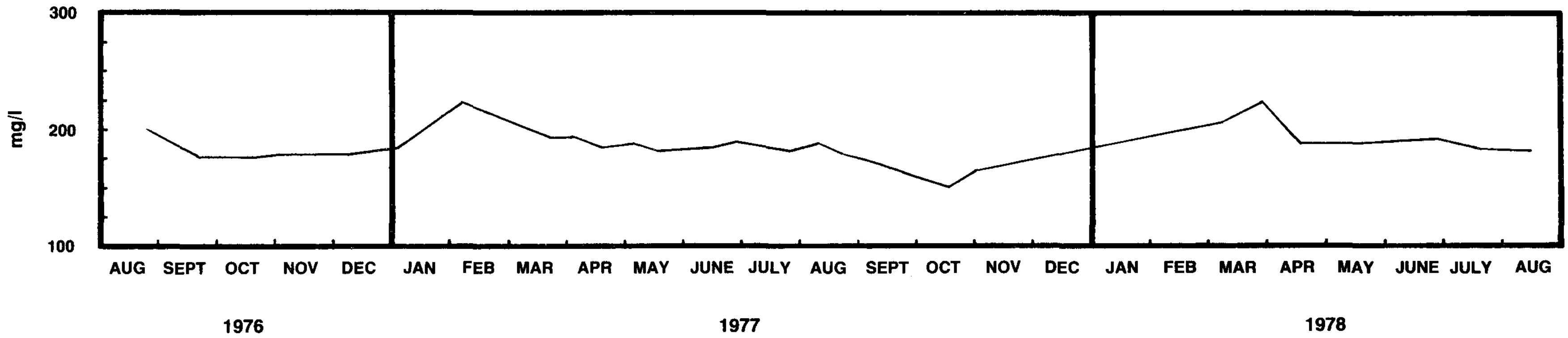
TOTAL ALKALINITY (mg/l)

STATION 5



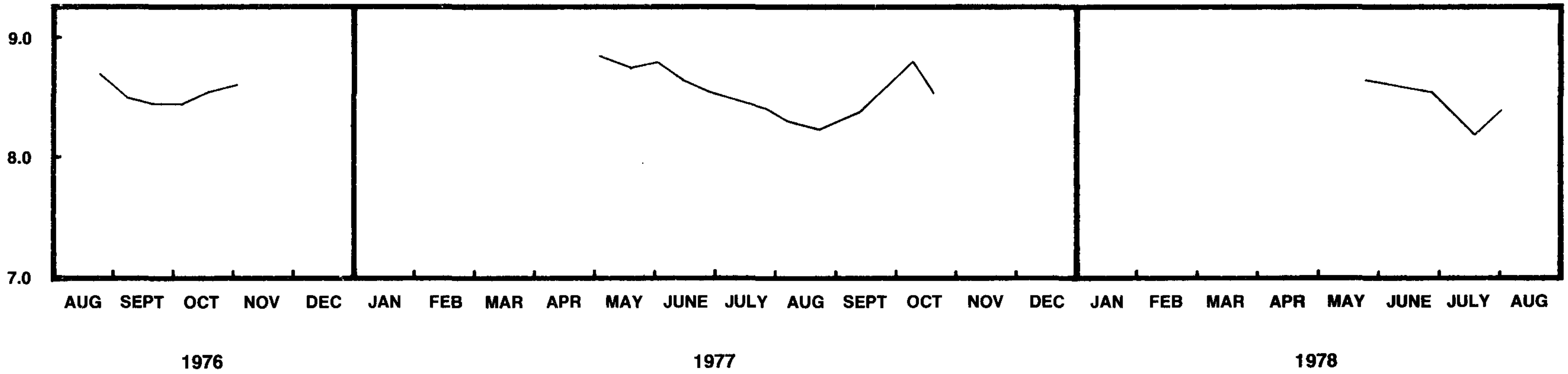
TOTAL ALKALINITY (mg/l)

STATION 6



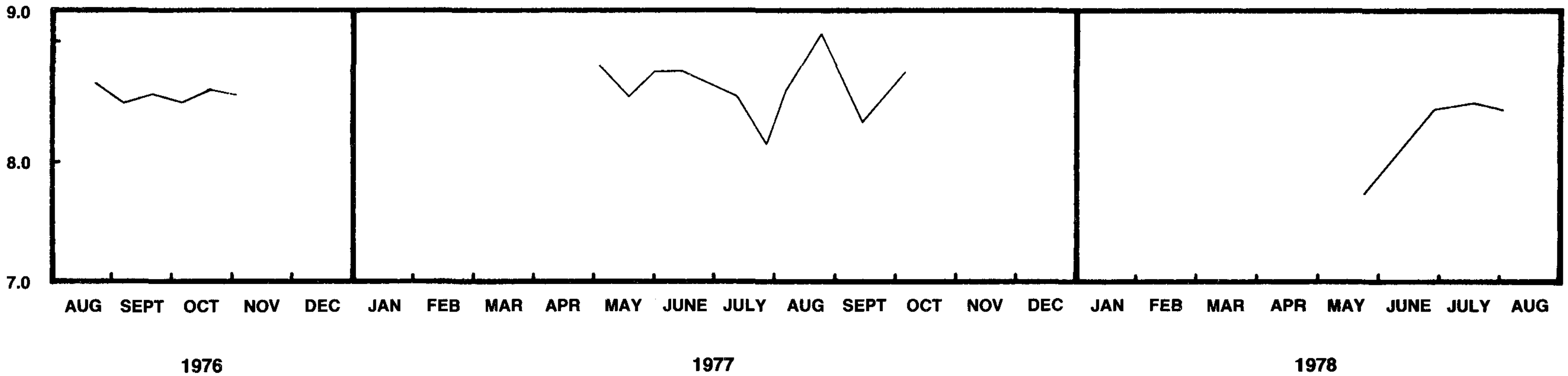
TOTAL ALKALINITY (mg/l)

STATION 1



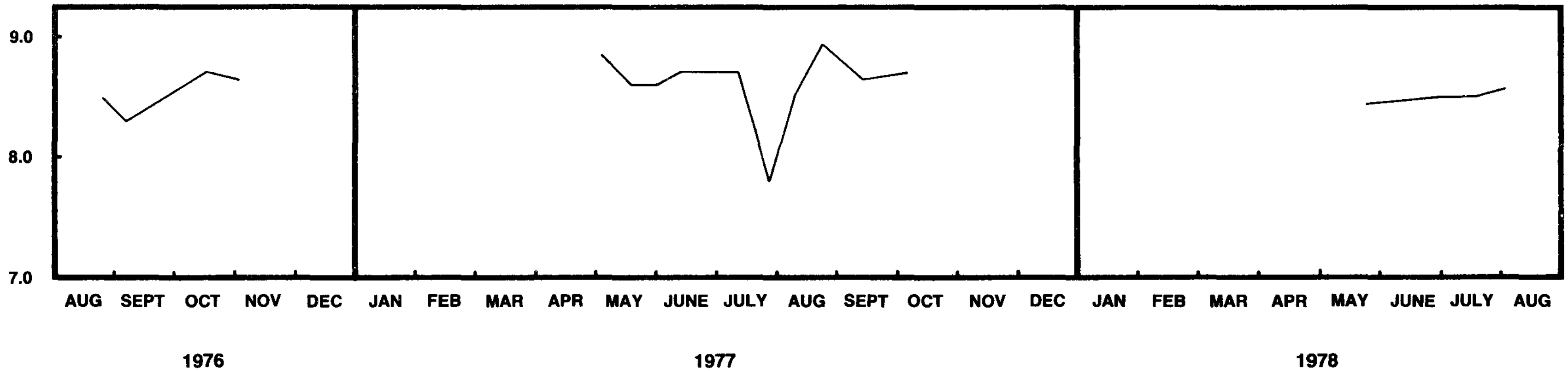
HYDROGEN ION CONCENTRATION (pH)

STATION 2



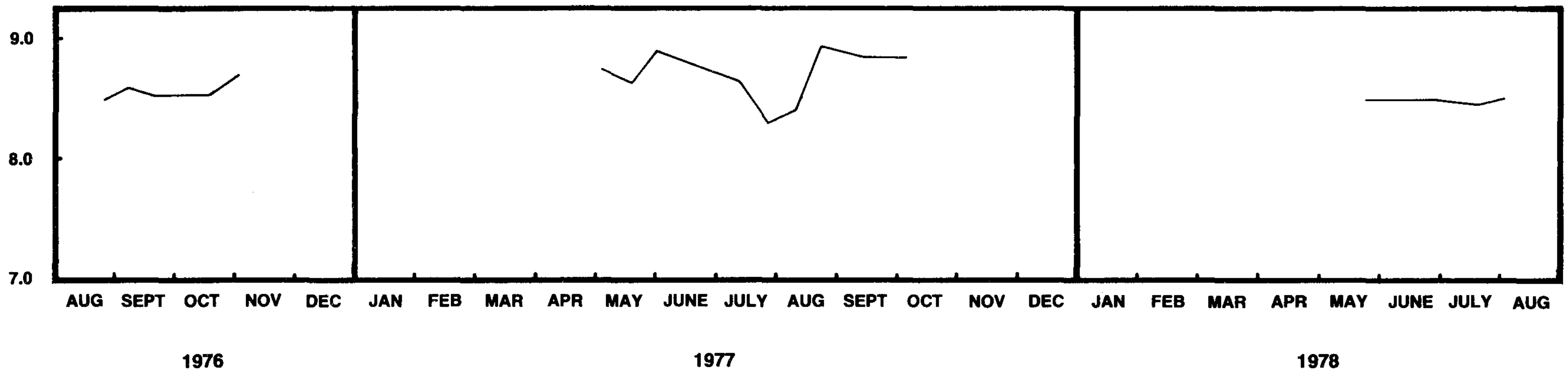
HYDROGEN ION CONCENTRATION (pH)

STATION 3



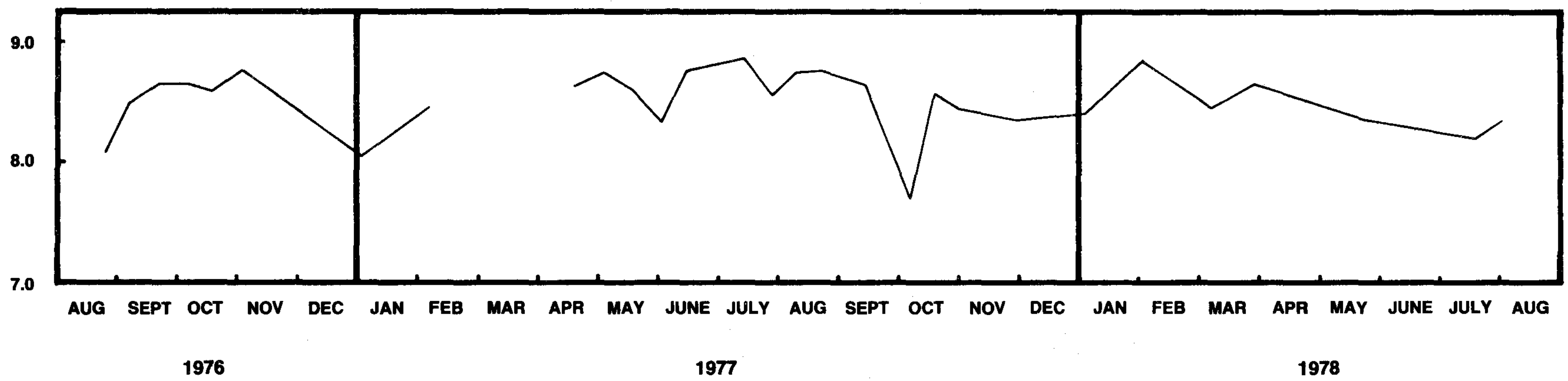
HYDROGEN ION CONCENTRATION (pH)

STATION 4



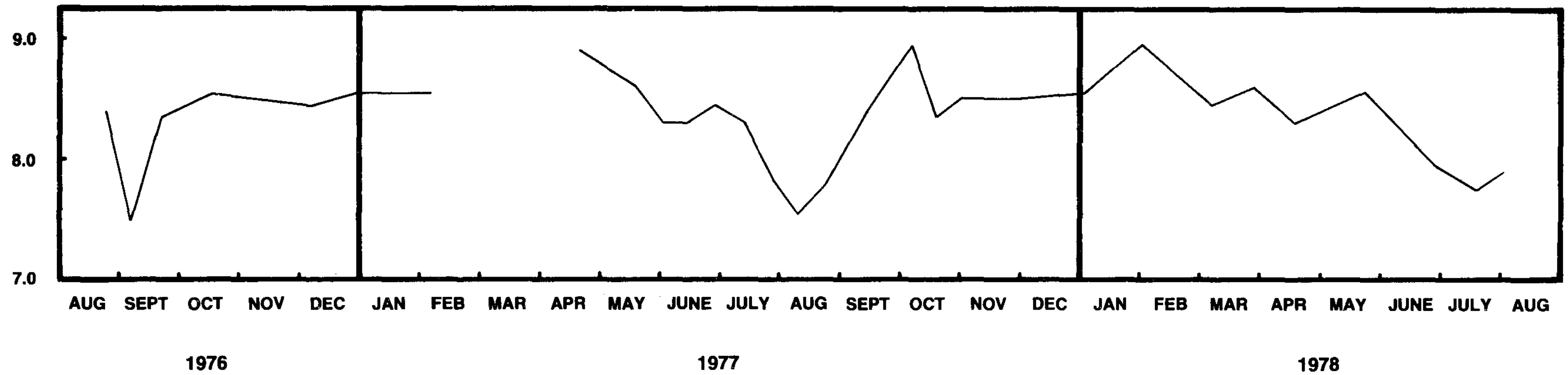
HYDROGEN ION CONCENTRATION (pH)

STATION 5



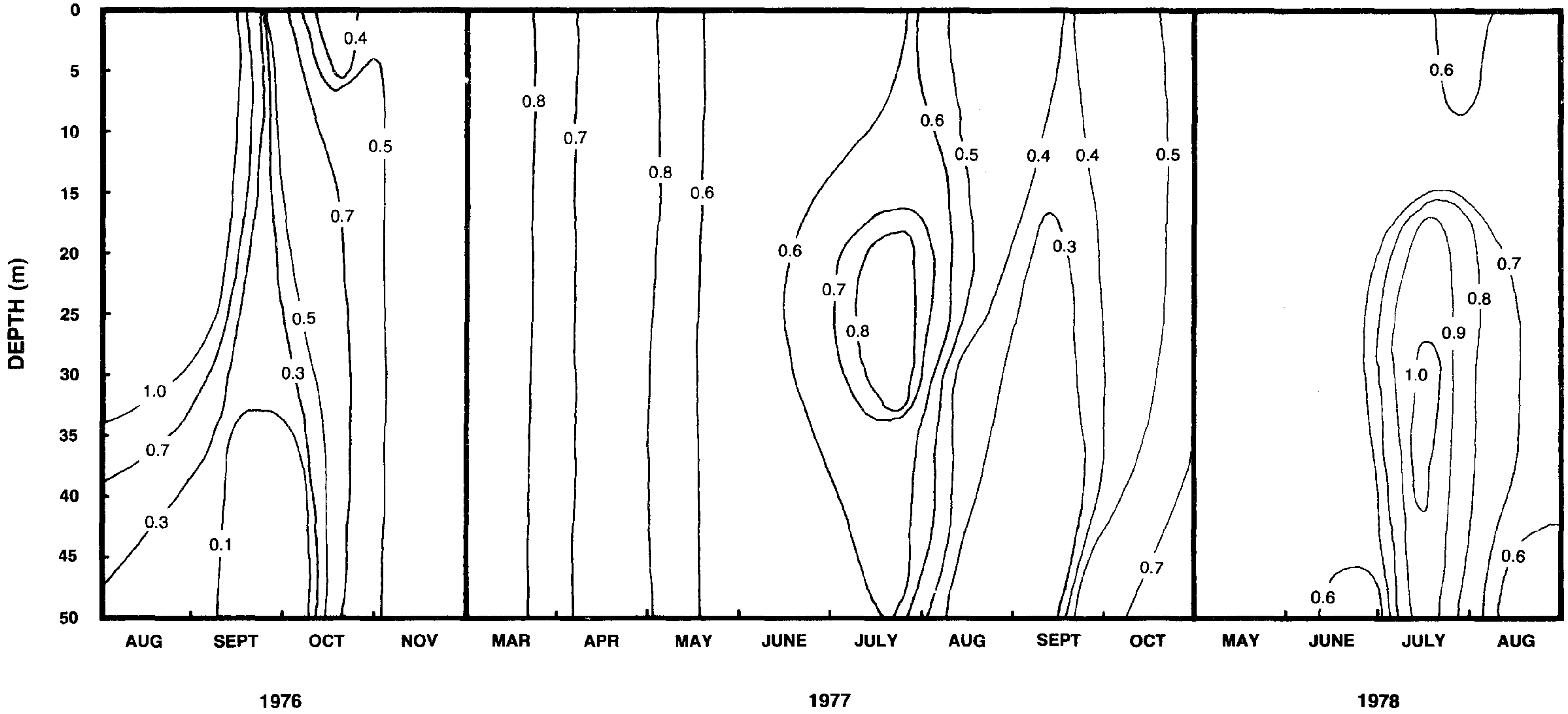
HYDROGEN ION CONCENTRATION (pH)

STATION 6



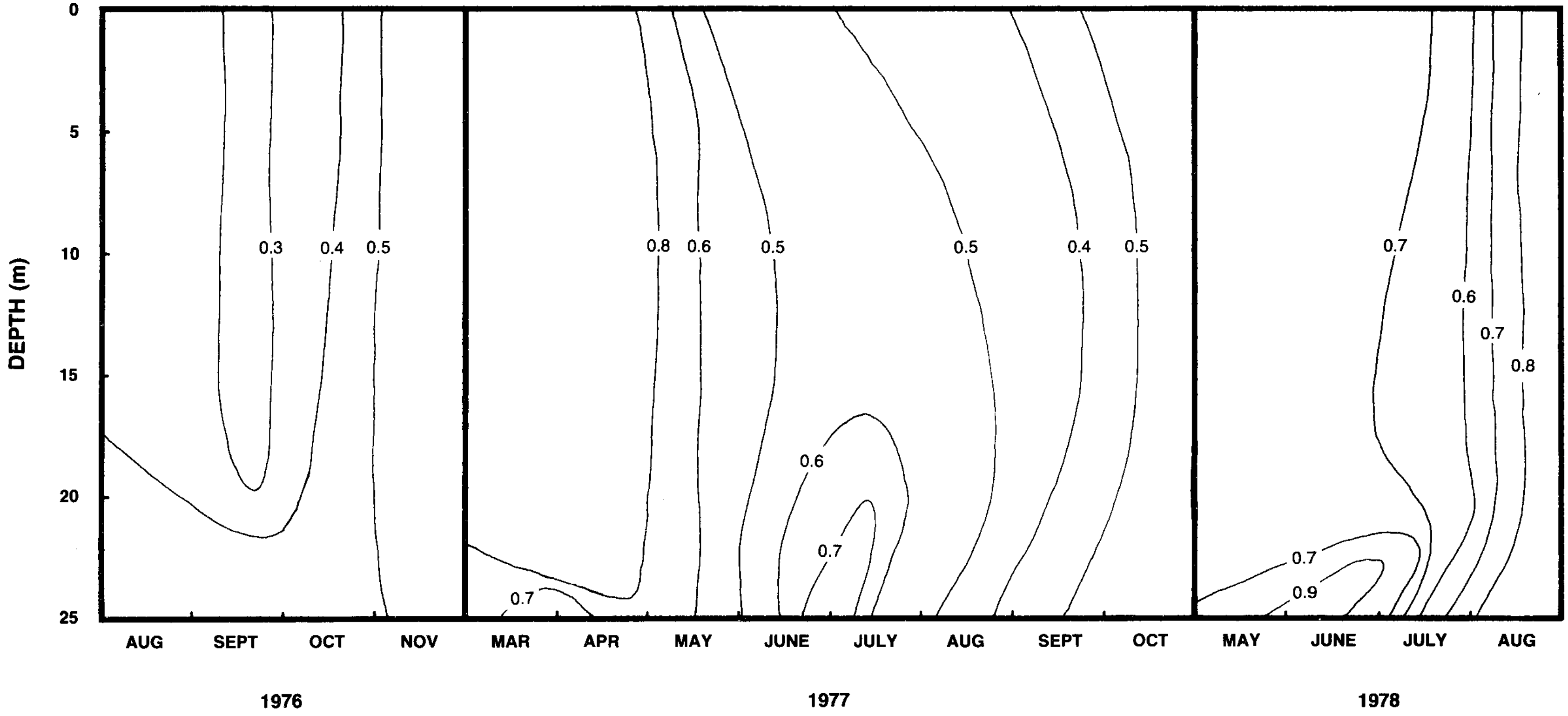
HYDROGEN ION CONCENTRATION (pH)

STATION 1



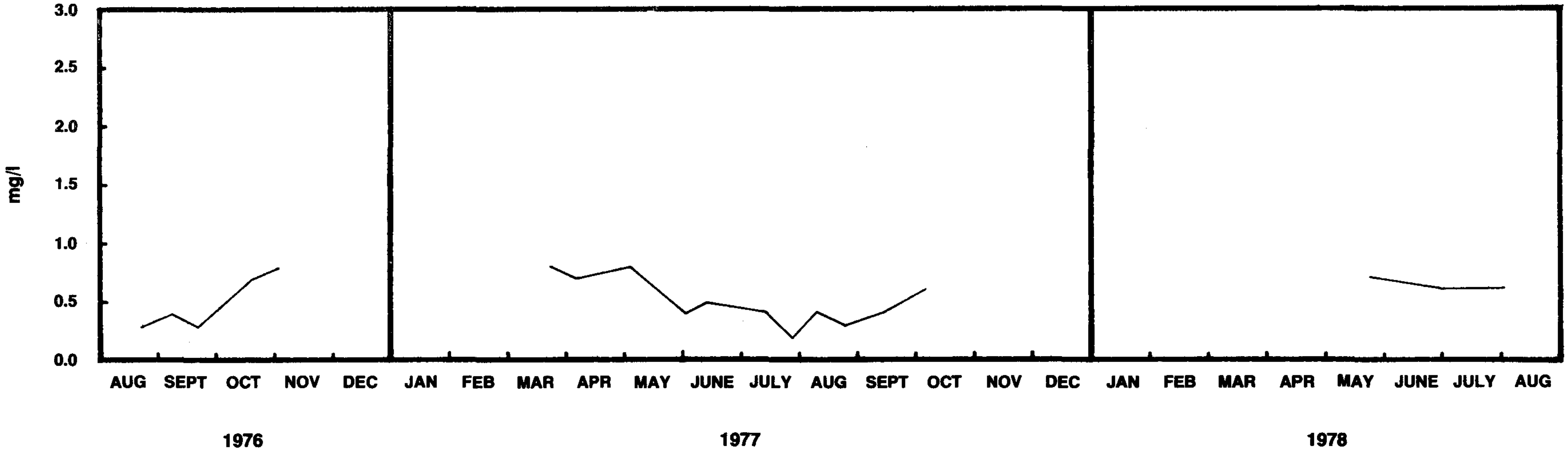
NITRATE NITROGEN (mg/1)

STATION 2



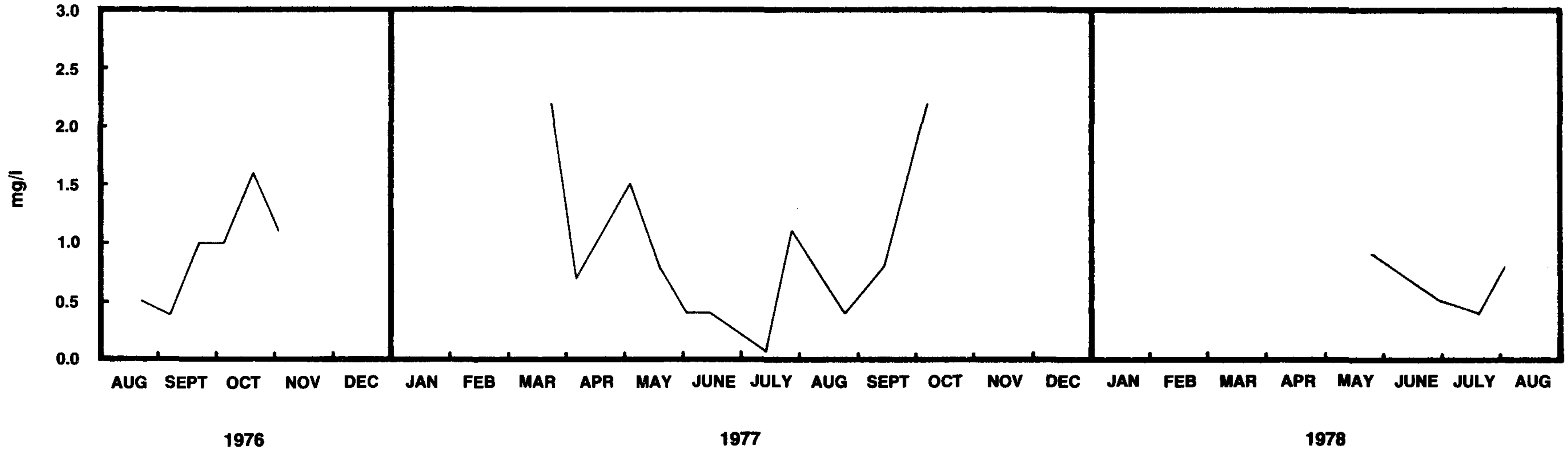
NITRATE NITROGEN (mg/1)

STATION 3



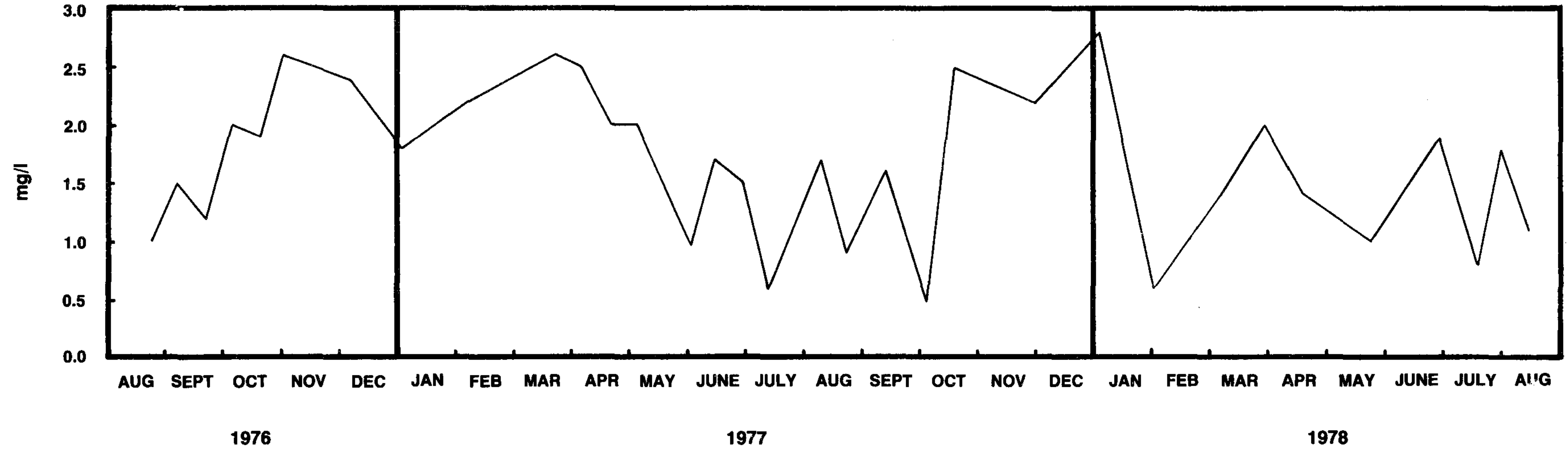
NITRATE NITROGEN (mg/1)

STATION 4



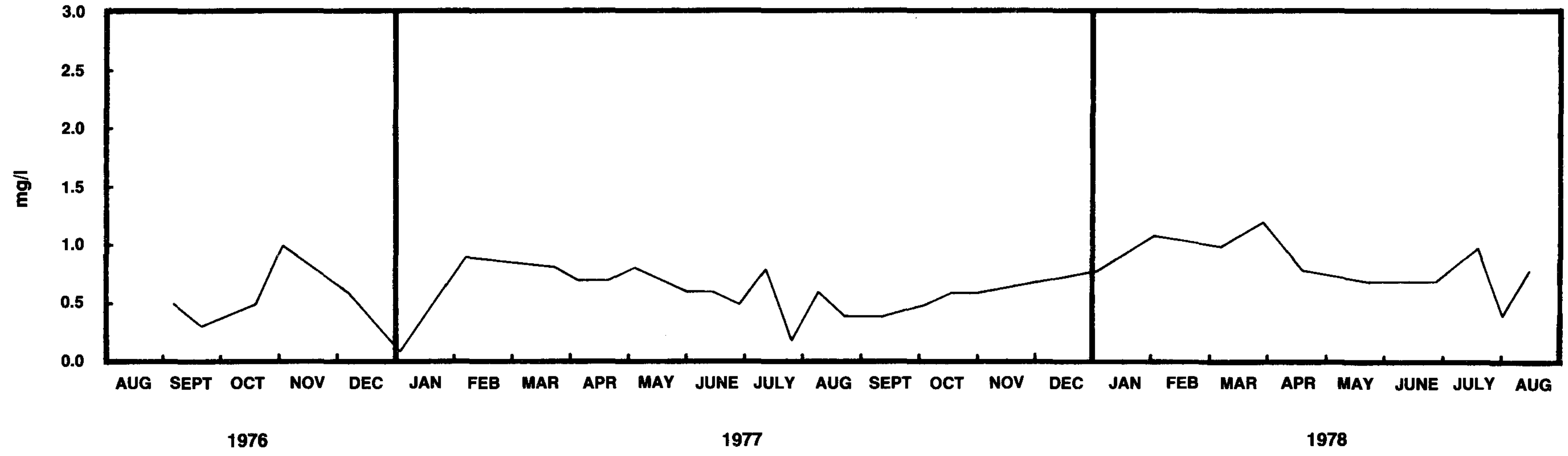
NITRATE NITROGEN (mg/1)

STATION 5

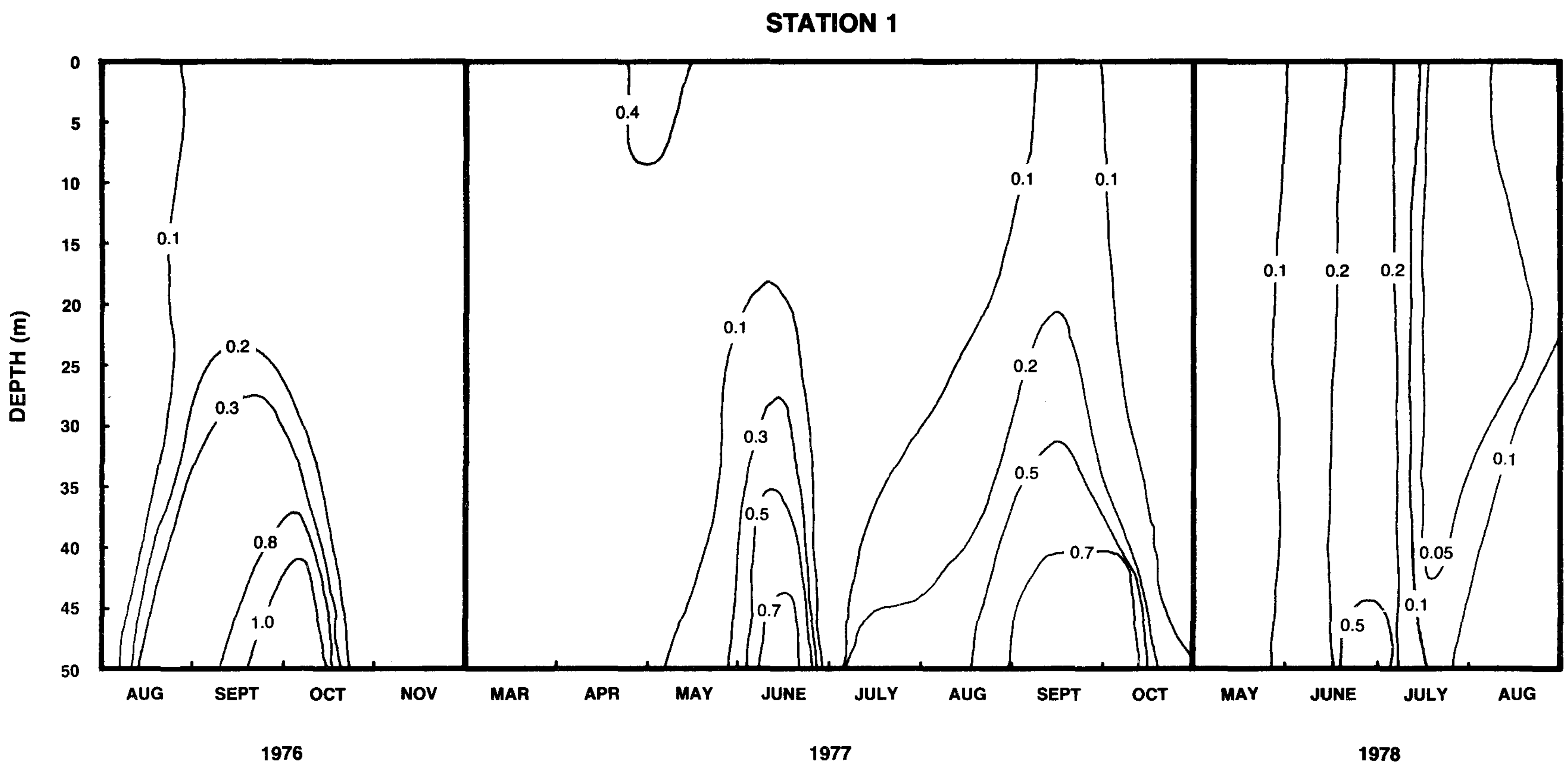


NITRATE NITROGEN (mg/1)

STATION 6

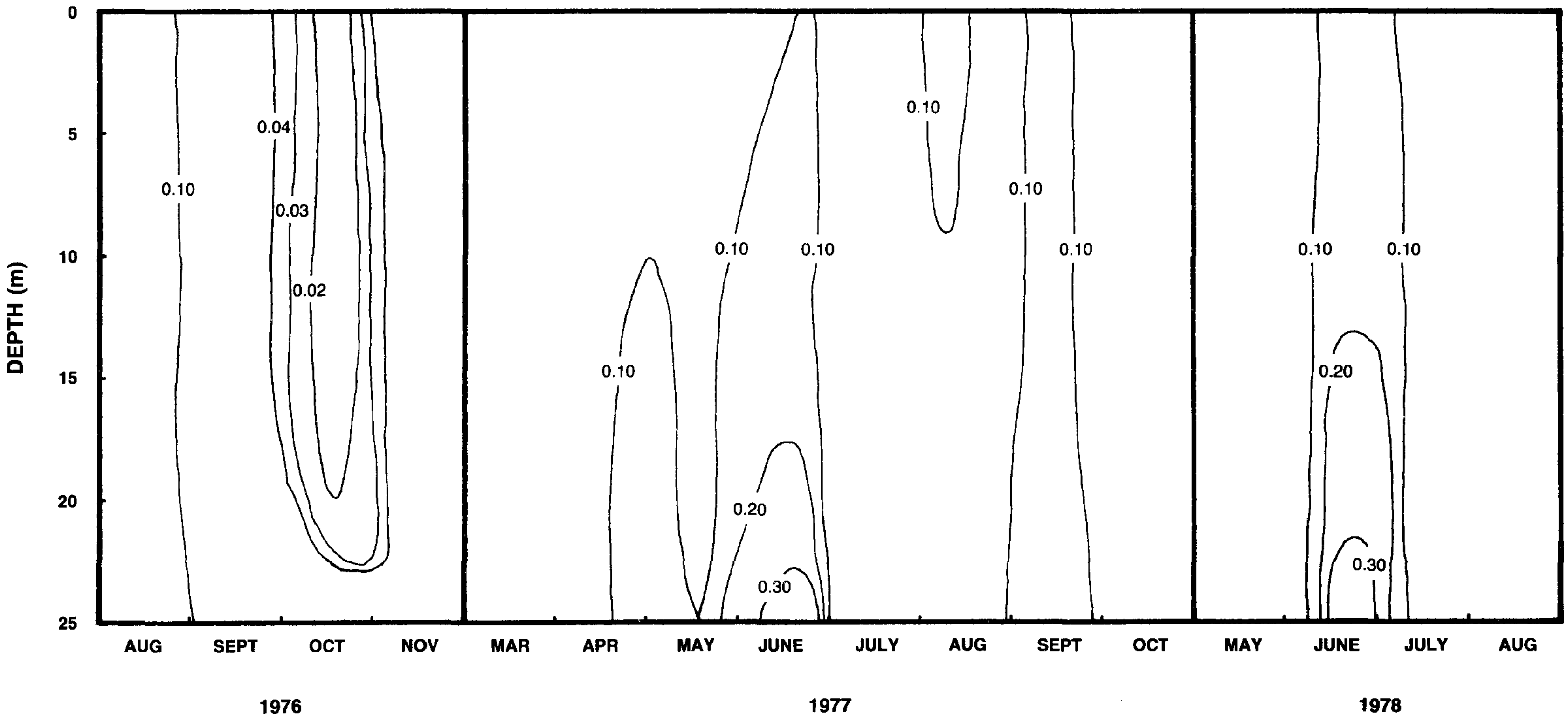


NITRATE NITROGEN (mg/1)



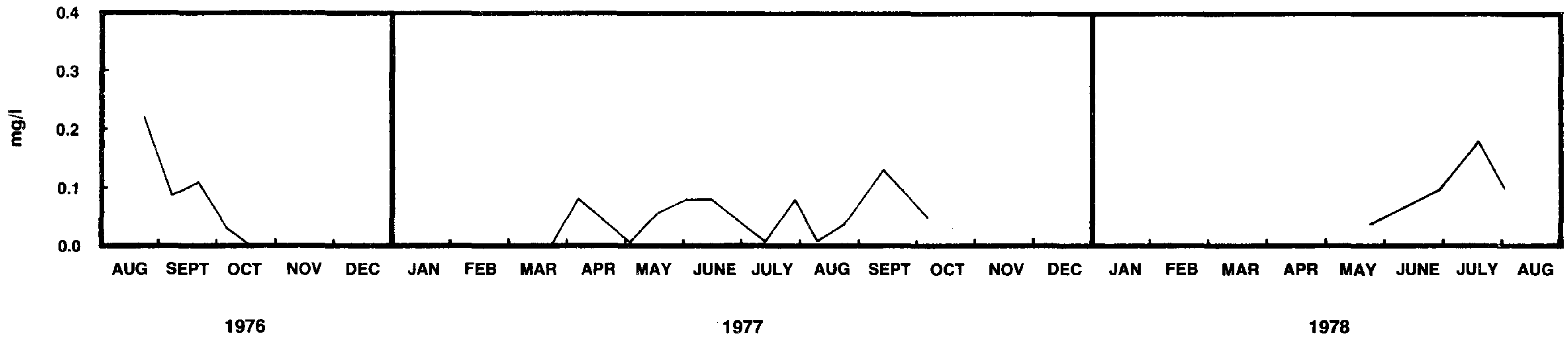
AMMONIA NITROGEN (mg/1)

STATION 2



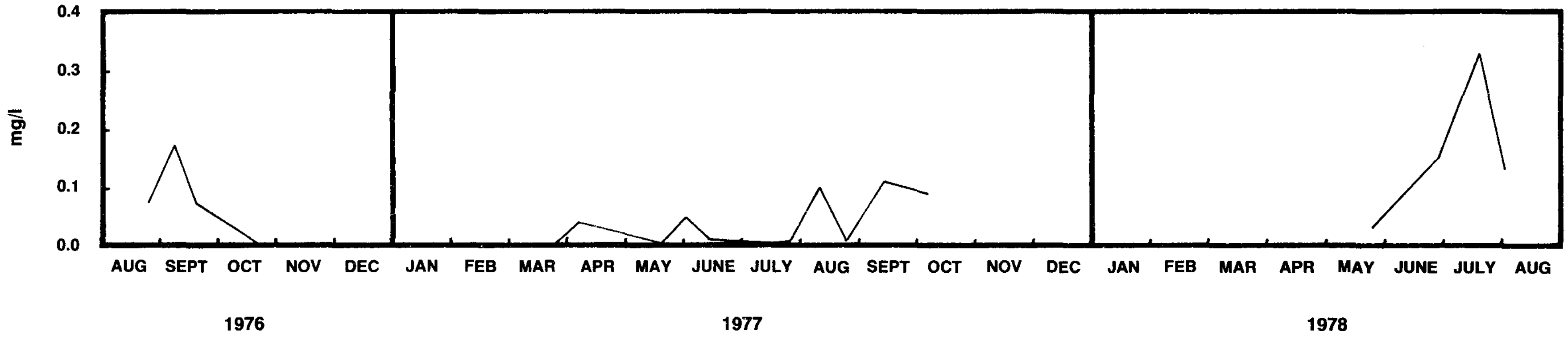
AMMONIA NITROGEN (mg/1)

STATION 3



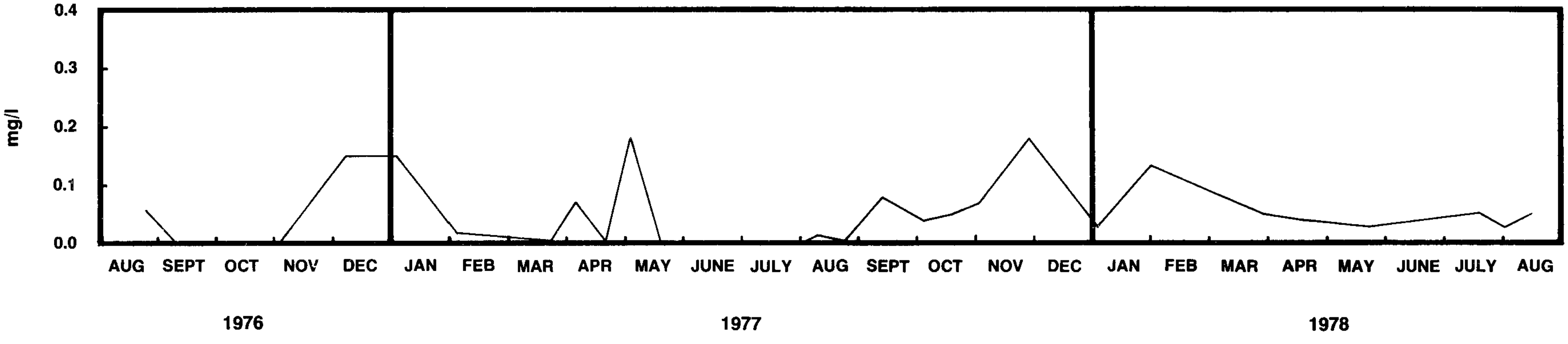
AMMONIA NITROGEN (mg/1)

STATION 4



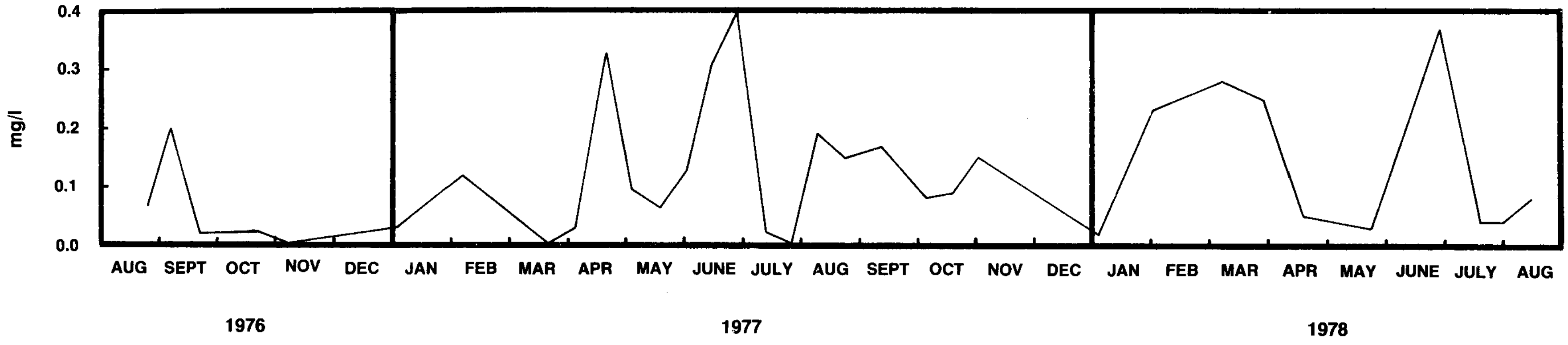
AMMONIA NITROGEN (mg/1)

STATION 5



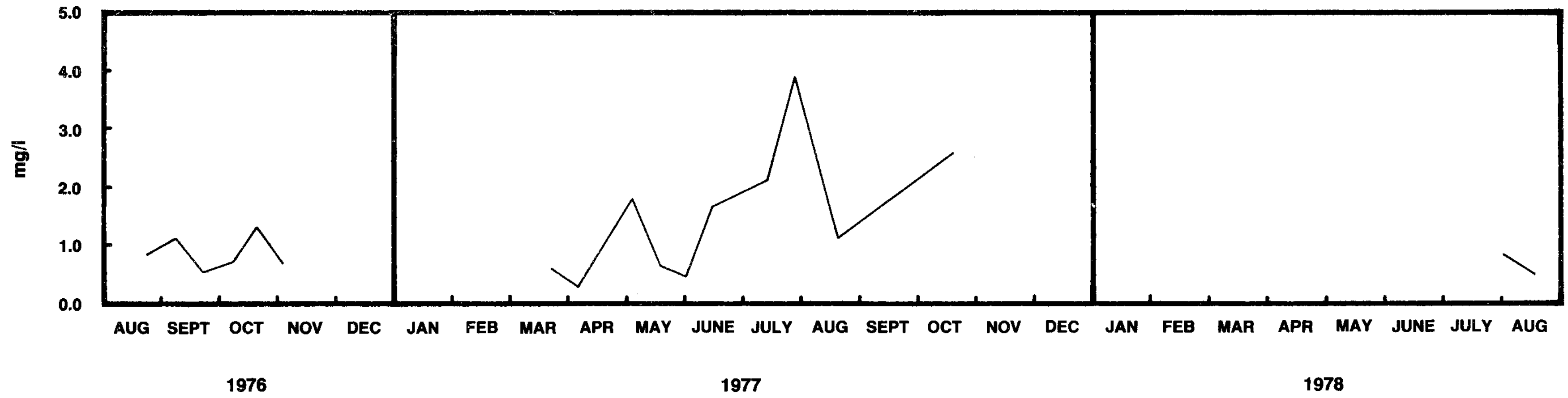
AMMONIA NITROGEN (mg/1)

STATION 6



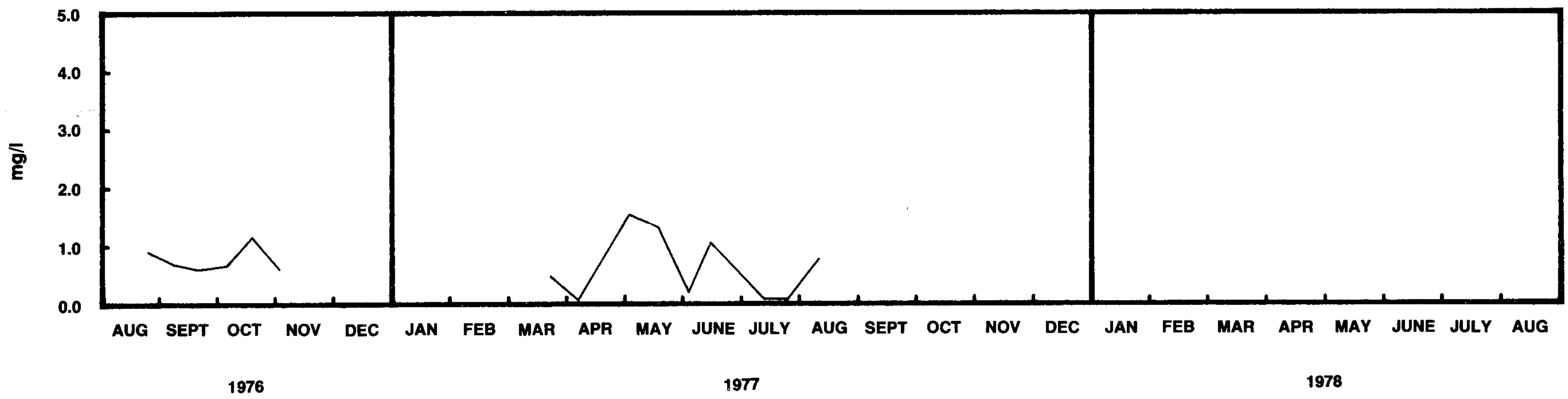
AMMONIA NITROGEN (mg/1)

STATION 1



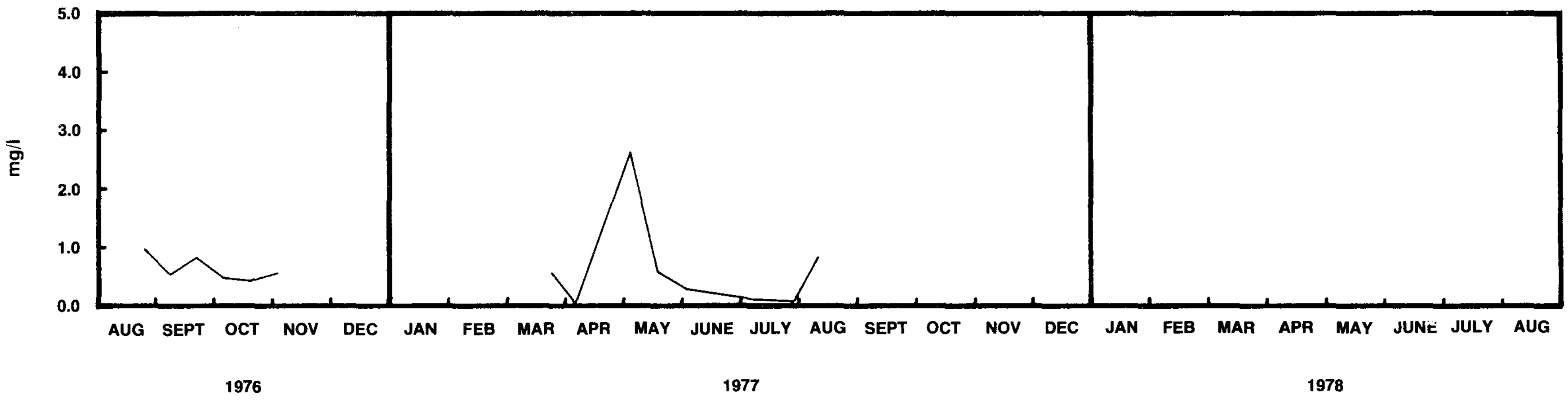
KJELDAHL NITROGEN (mg/l)

STATION 2



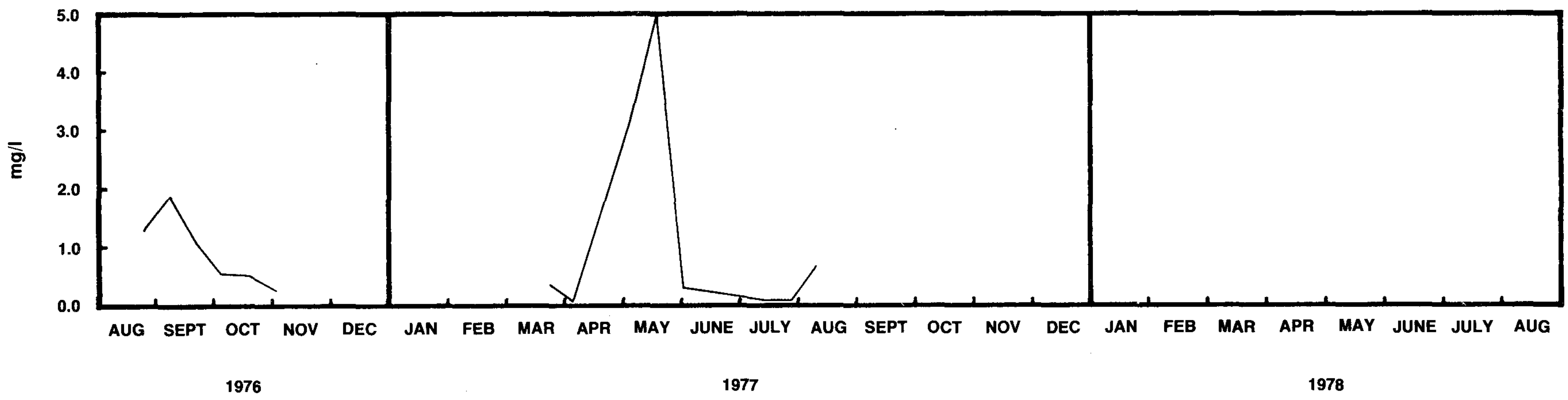
KJELDAHL NITROGEN (mg/l)

STATION 3



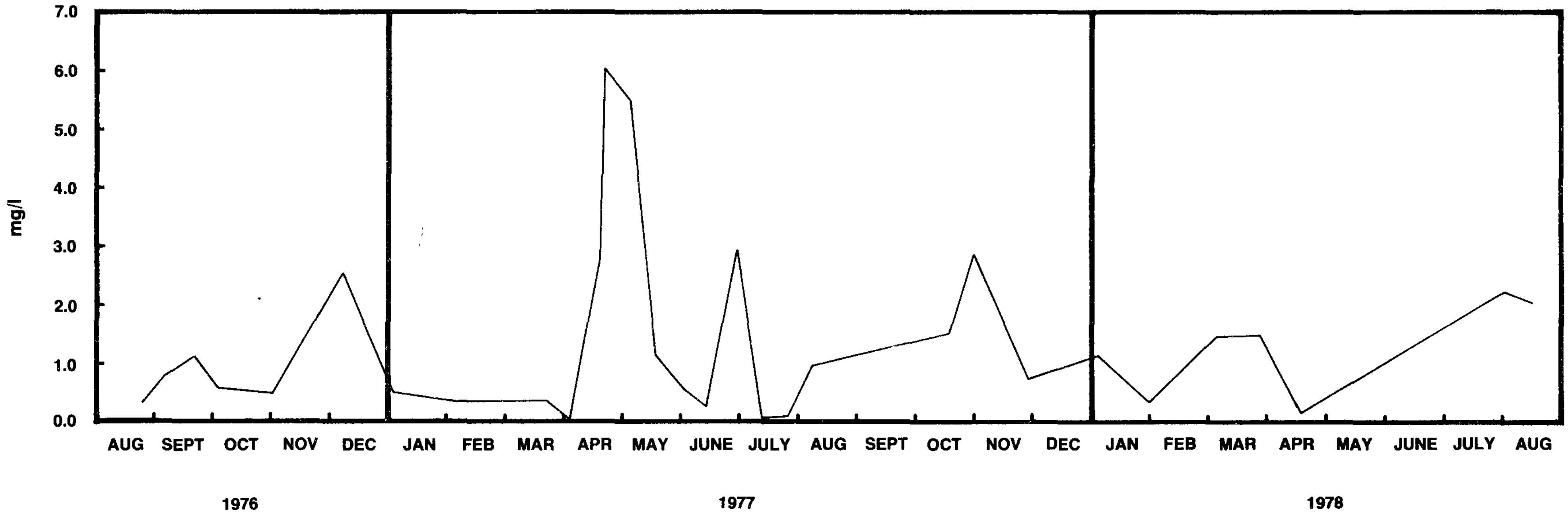
KJELDAHL NITROGEN (mg/l)

STATION 4



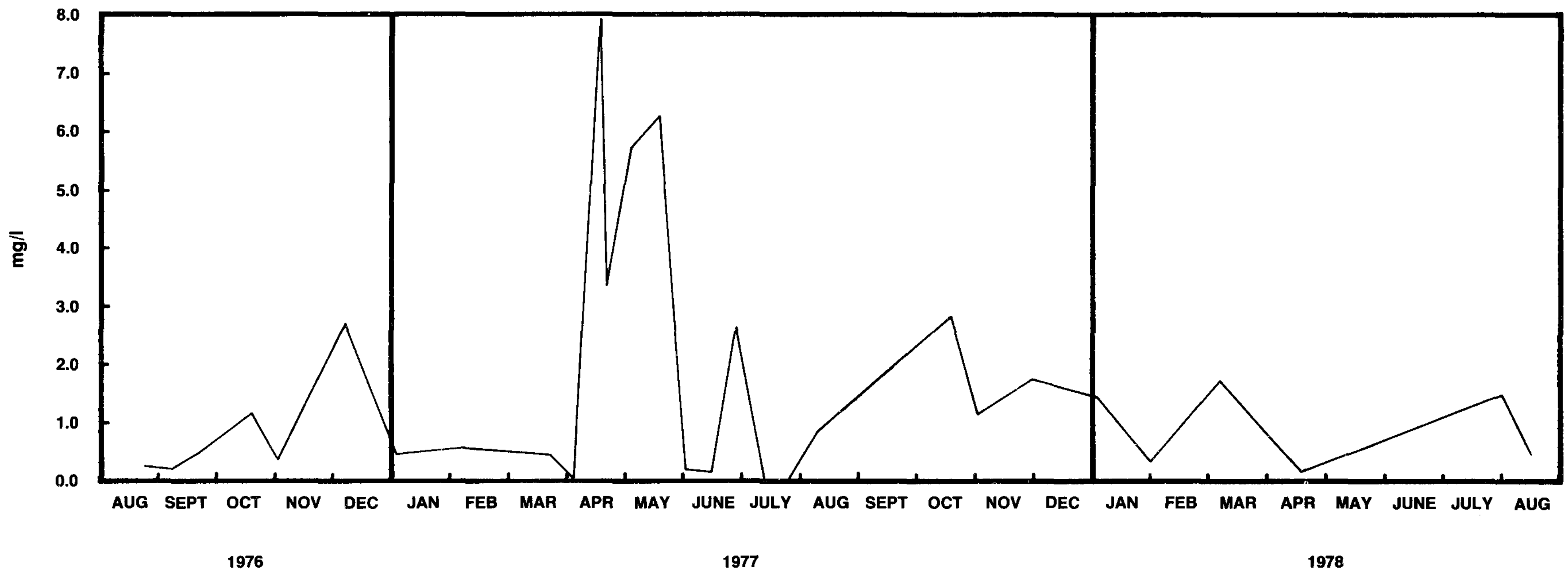
KJELDAHL NITROGEN (mg/l)

STATION 5



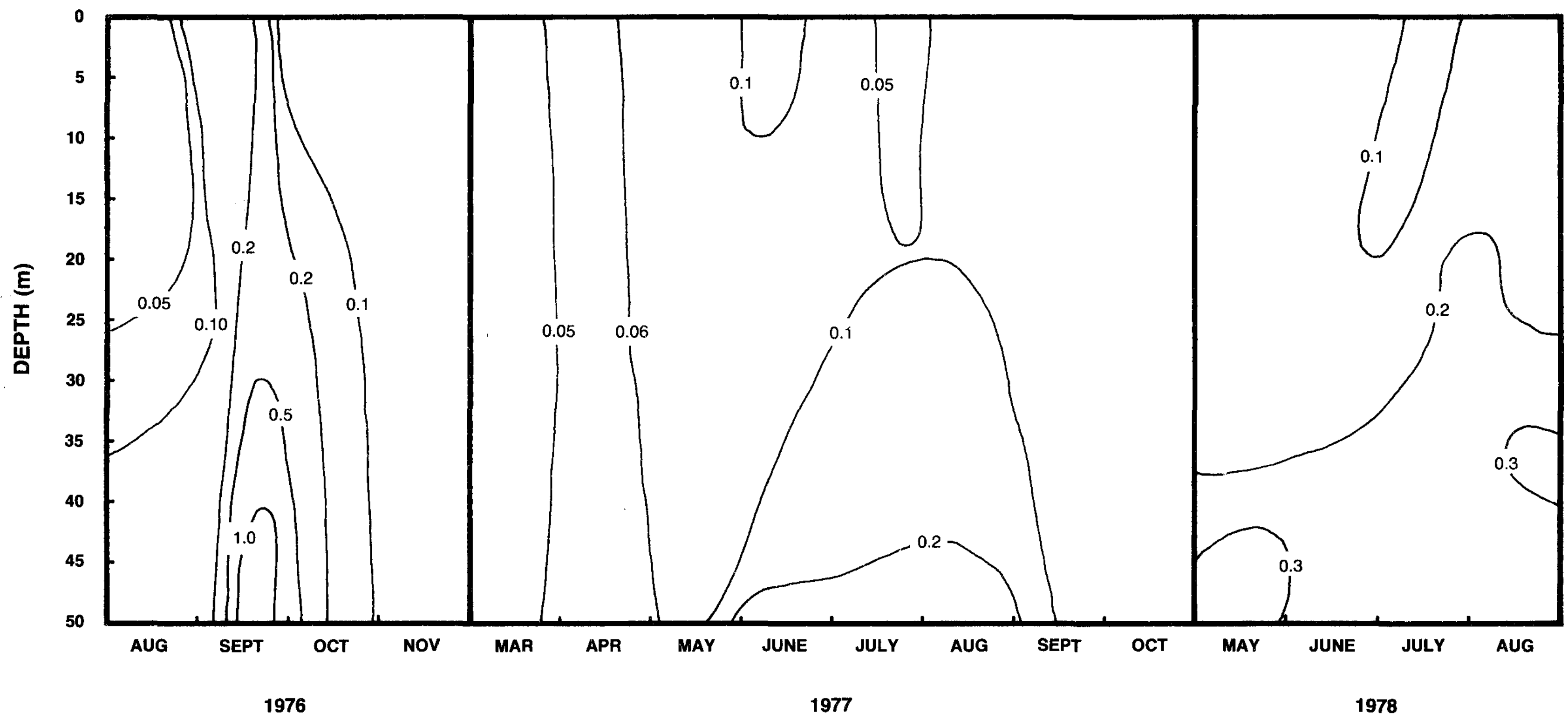
KJELDAHL NITROGEN (mg/l)

STATION 6



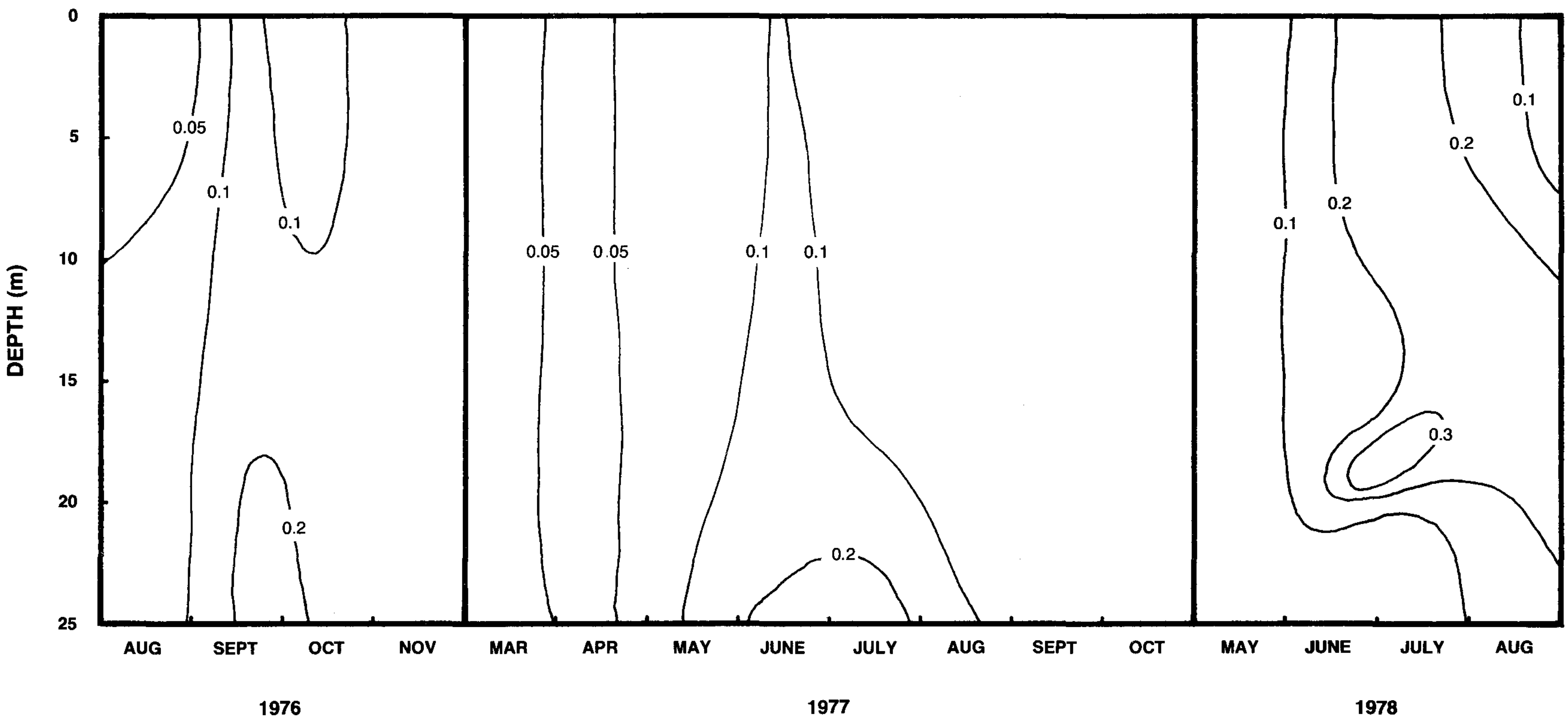
KJELDAHL NITROGEN (mg/l)

STATION 1



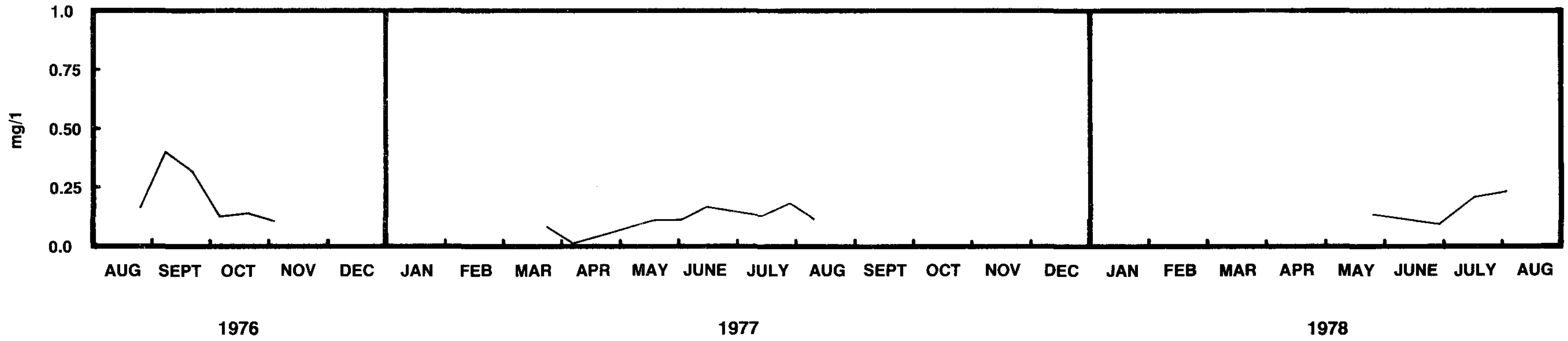
TOTAL PHSOPHATE (mg/1)

STATION 2



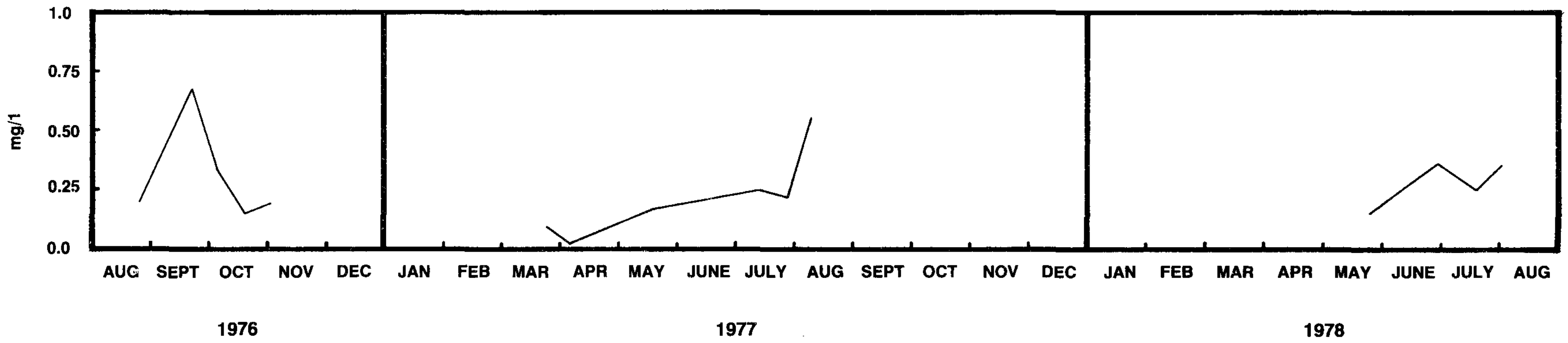
TOTAL PHSOPHATE (mg/1)

STATION 3



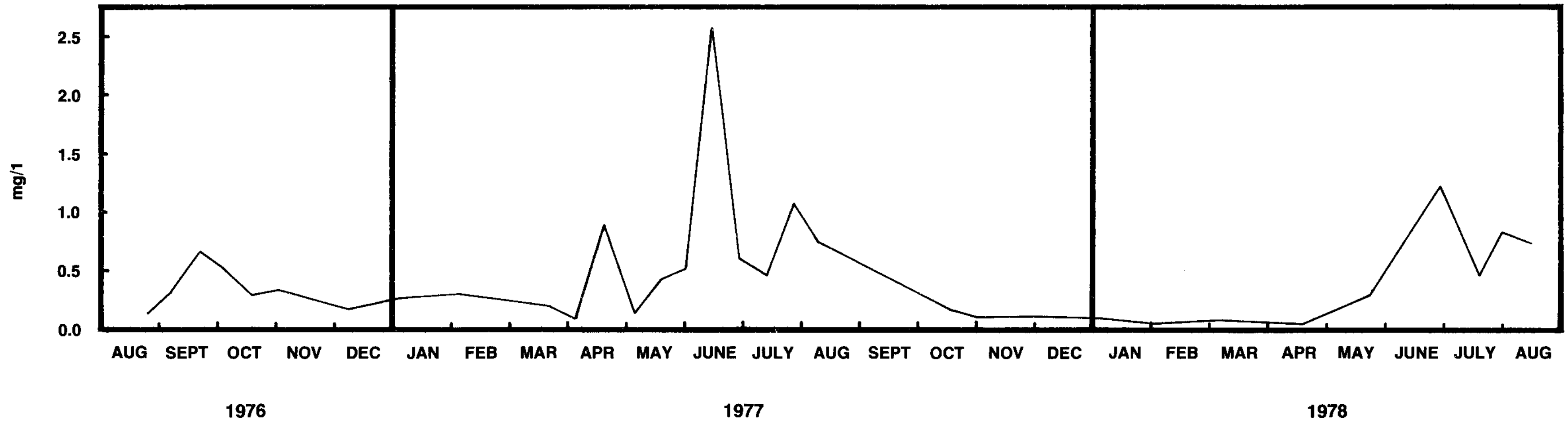
TOTAL PHSOPHATE (mg/1)

STATION 4



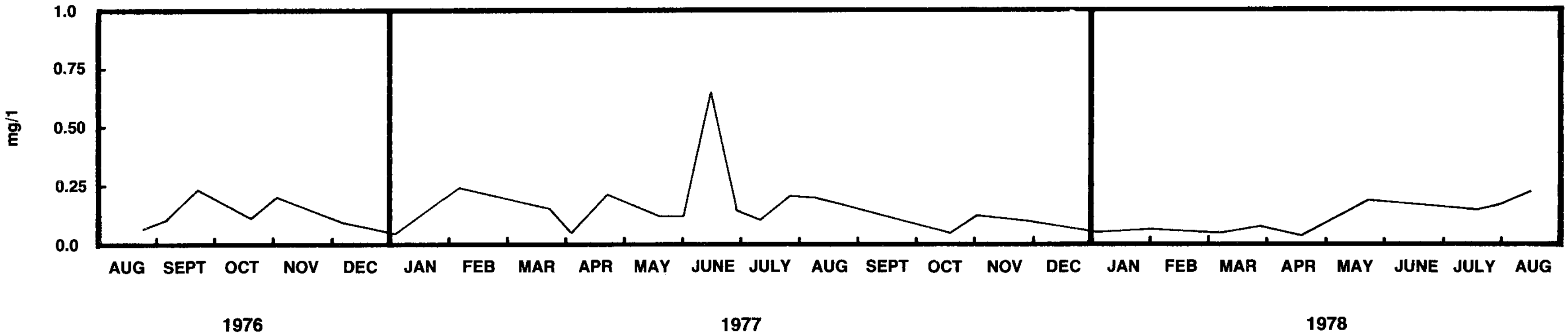
TOTAL PHSOPHATE (mg/1)

STATION 5

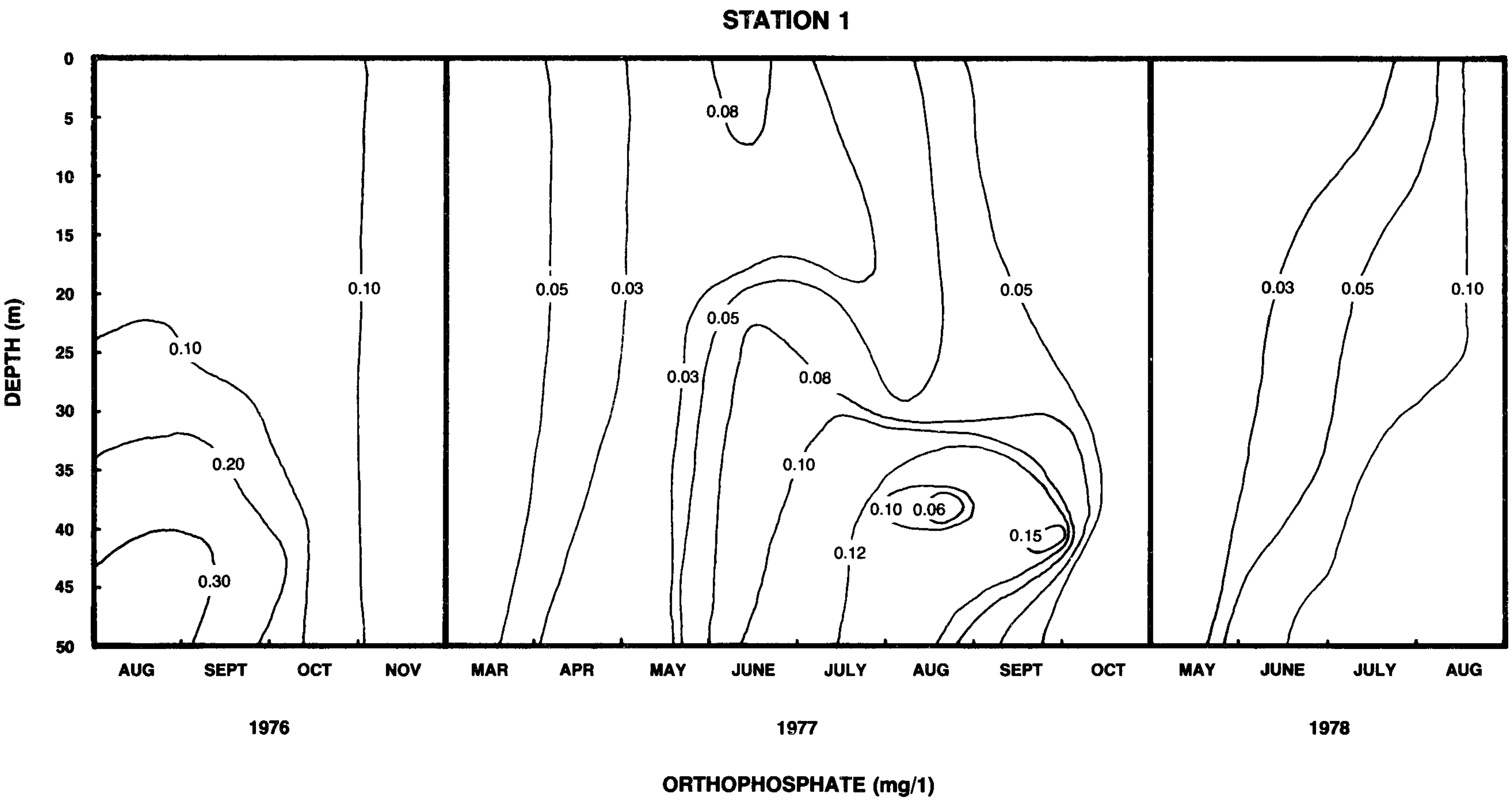


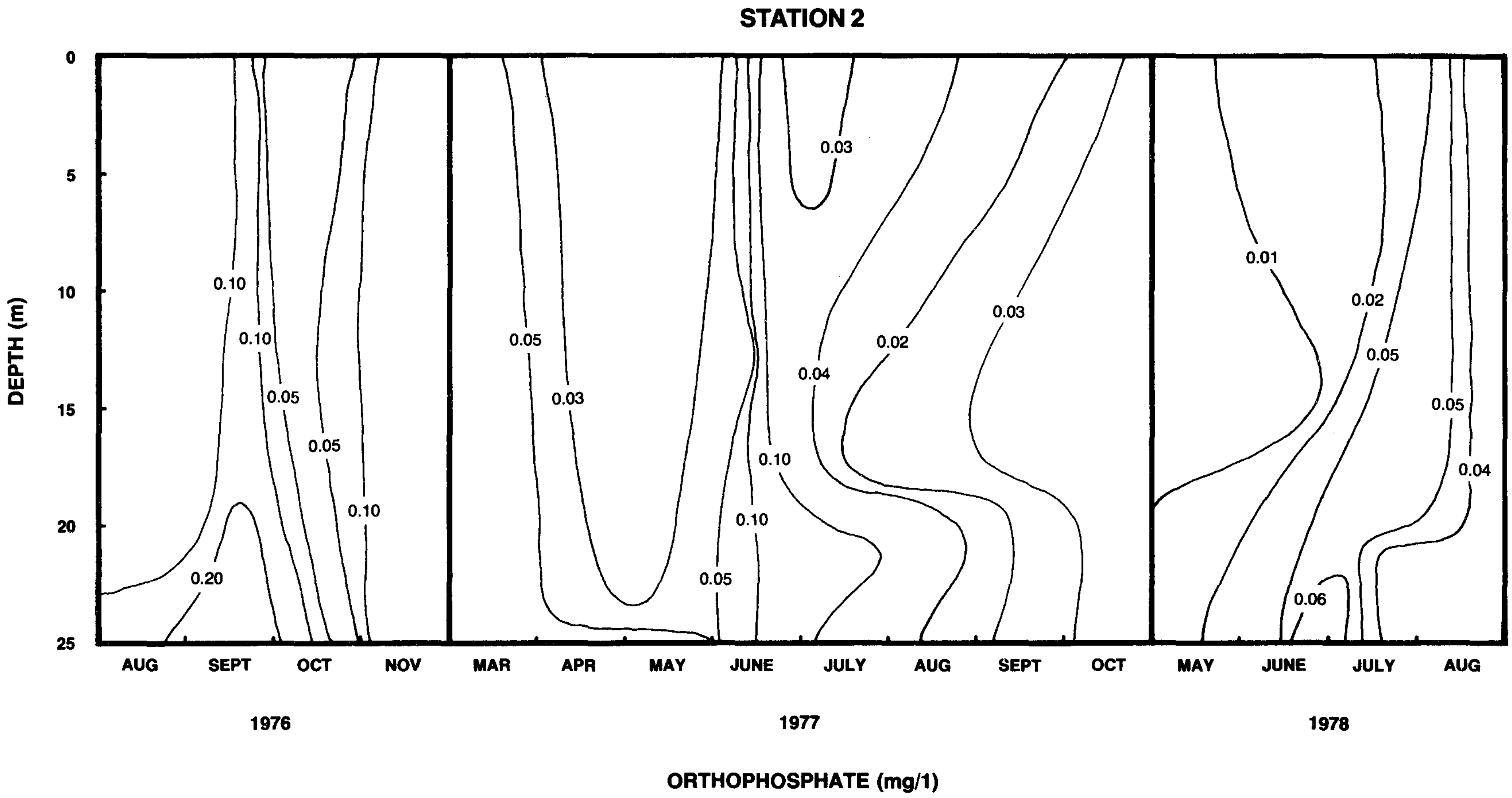
TOTAL PHSOPHATE (mg/1)

STATION 6

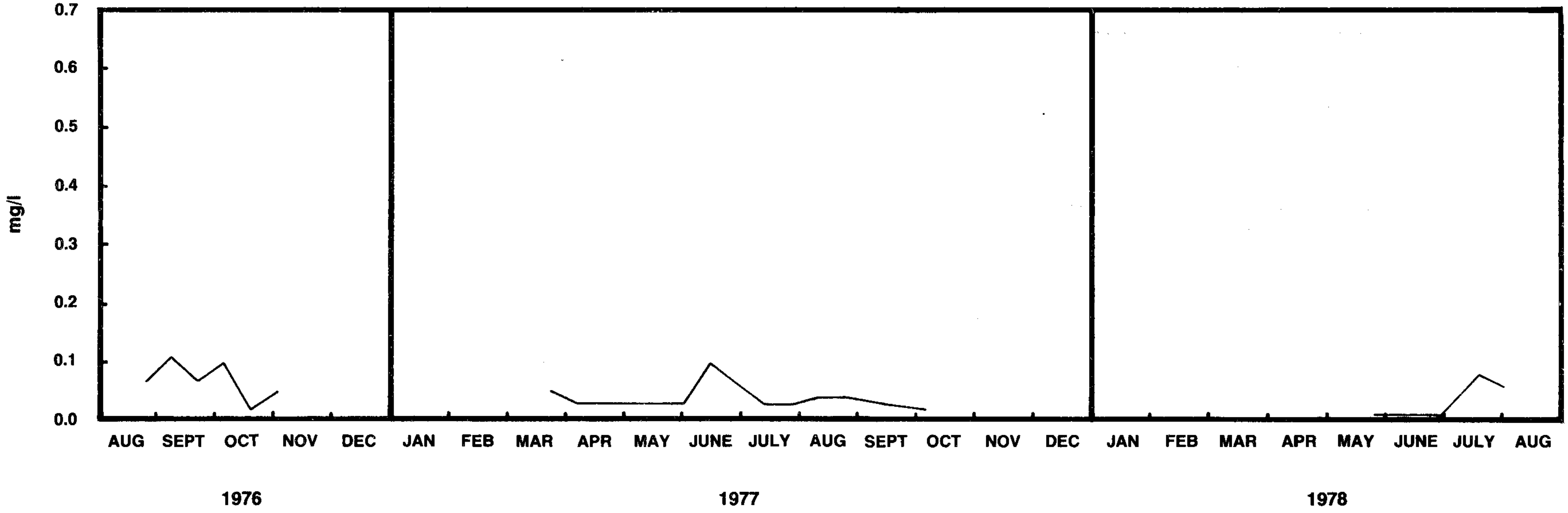


TOTAL PHSOPHATE (mg/1)


STATION 1
DEPTH (m)
0
5
10
15
20
25
30
35
40
45
50
0.10
0.20
0.30
0.10
0.05
0.03
0.08
0.05
0.03
0.08
0.10
0.10
0.06
0.12
0.15
0.05
0.03
0.05
0.10
AUG
SEPT
OCT
NOV
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
MAY
JUNE
JULY
AUG
1976
1977
1978
ORTHOPHOSPHATE (mg/1)

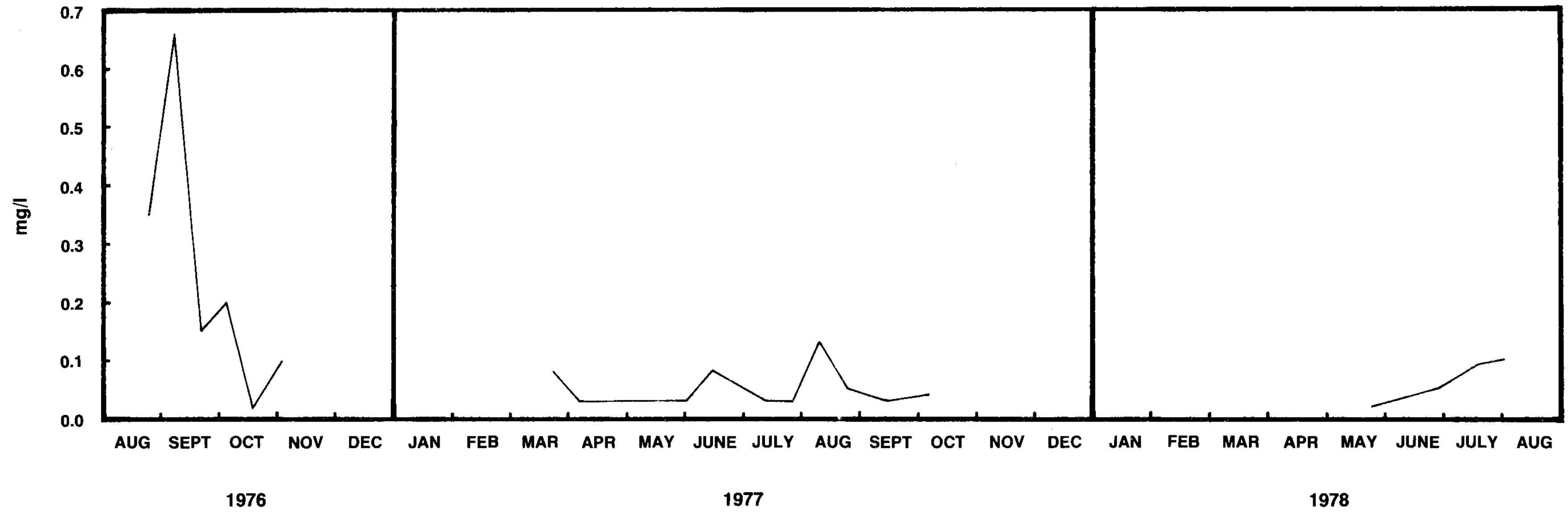

STATION 2
DEPTH (m)
0
5
10
15
20
25
0.10
0.10
0.05
0.05
0.10
0.20
0.05
0.03
0.05
0.03
0.04
0.10
0.10
0.02
0.03
0.01
0.02
0.05
0.05
0.04
0.06
AUG
SEPT
OCT
NOV
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
MAY
JUNE
JULY
AUG
1976
1977
1978
ORTHOPHOSPHATE (mg/1)

STATION 3

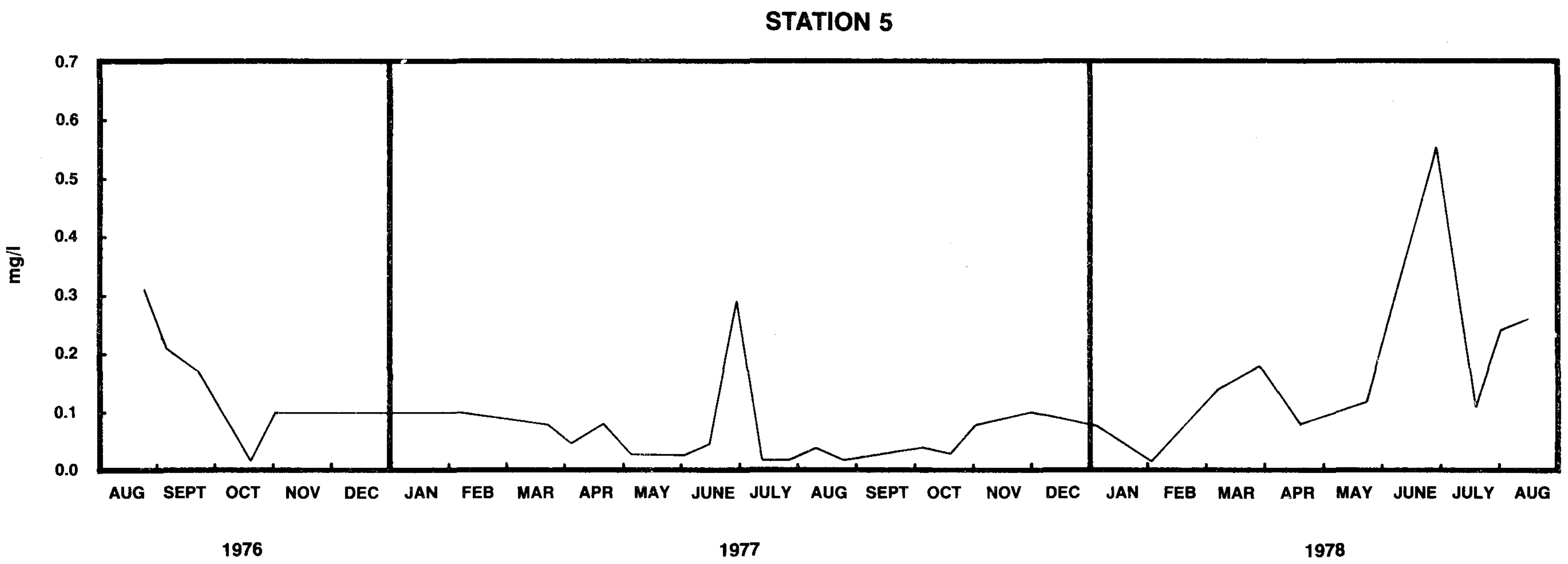


ORTHOPHOSPHATE (mg/1)

STATION 4

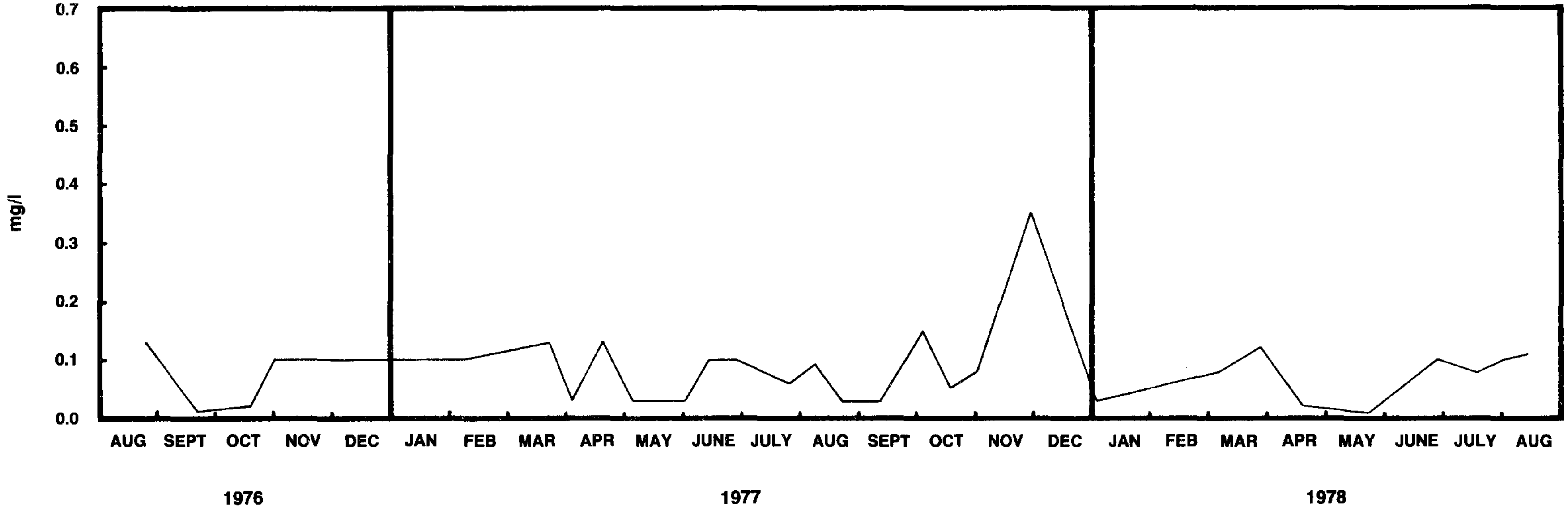


ORTHOPHOSPHATE (mg/1)



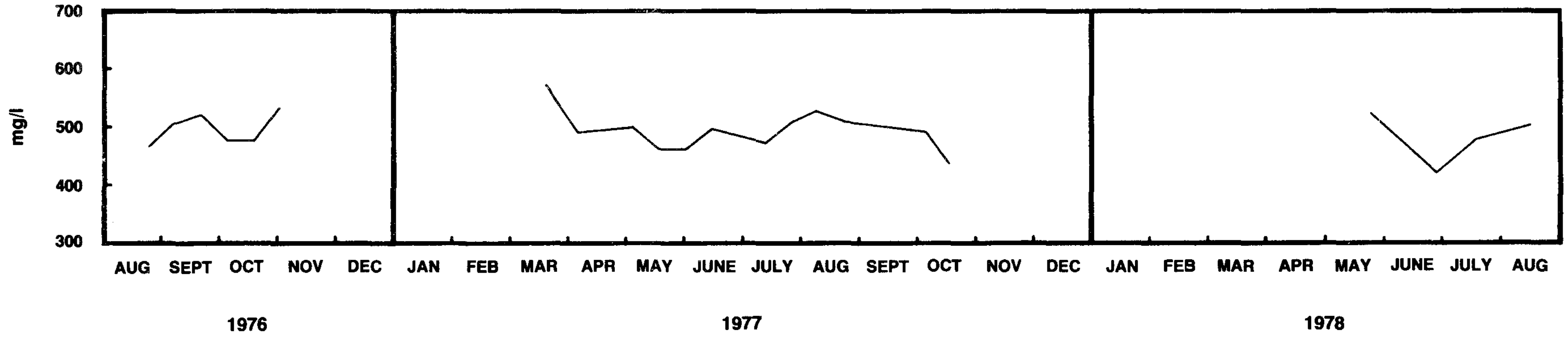
ORTHOPHOSPHATE (mg/1)

STATION 6



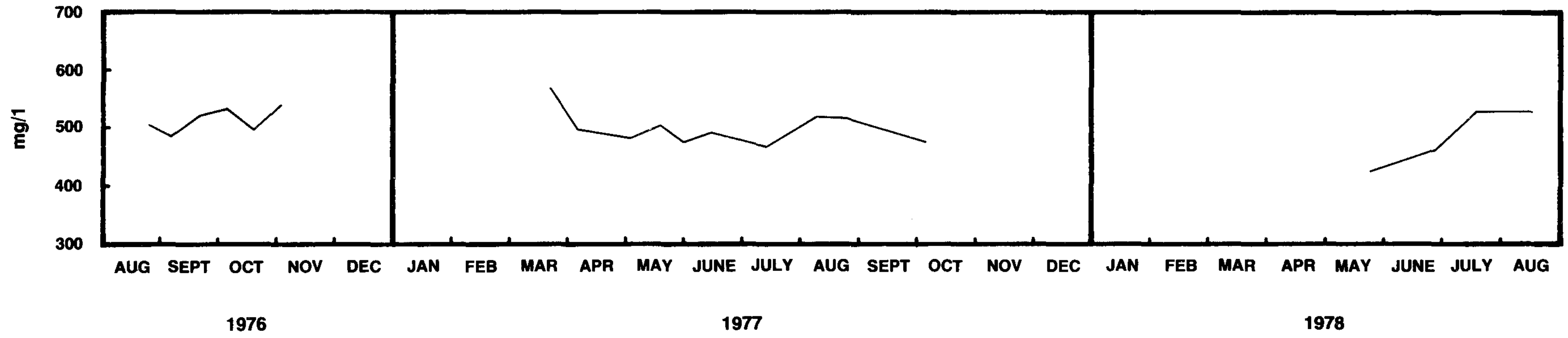
ORTHOPHOSPHATE (mg/1)

STATION 1



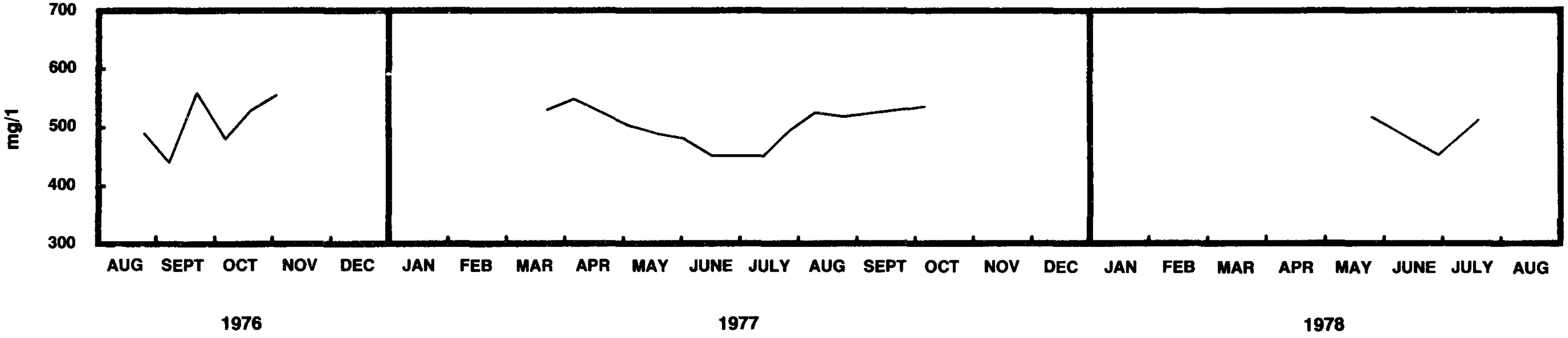
TOTAL DISSOLVED SOLIDS (mg/1)

STATION 2



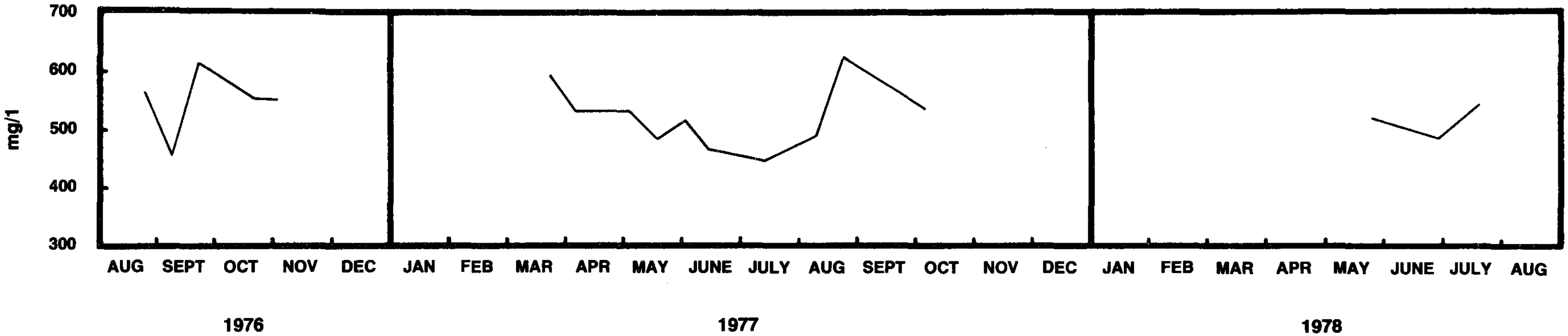
TOTAL DISSOLVED SOLIDS (mg/1)

STATION 3



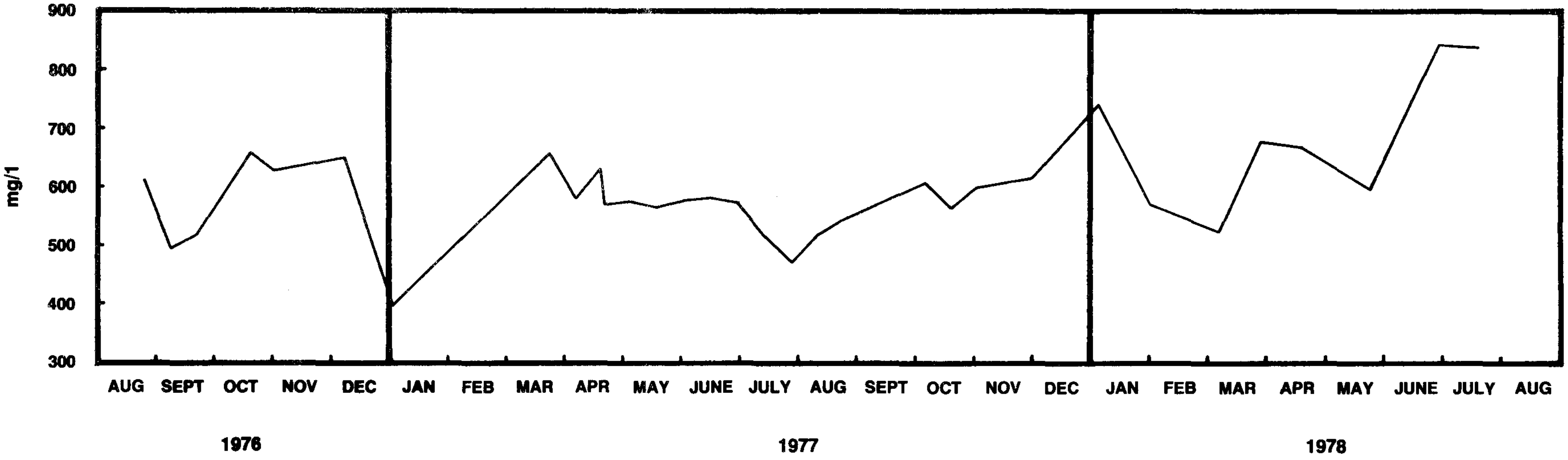
TOTAL DISSOLVED SOLIDS (mg/1)

STATION 4



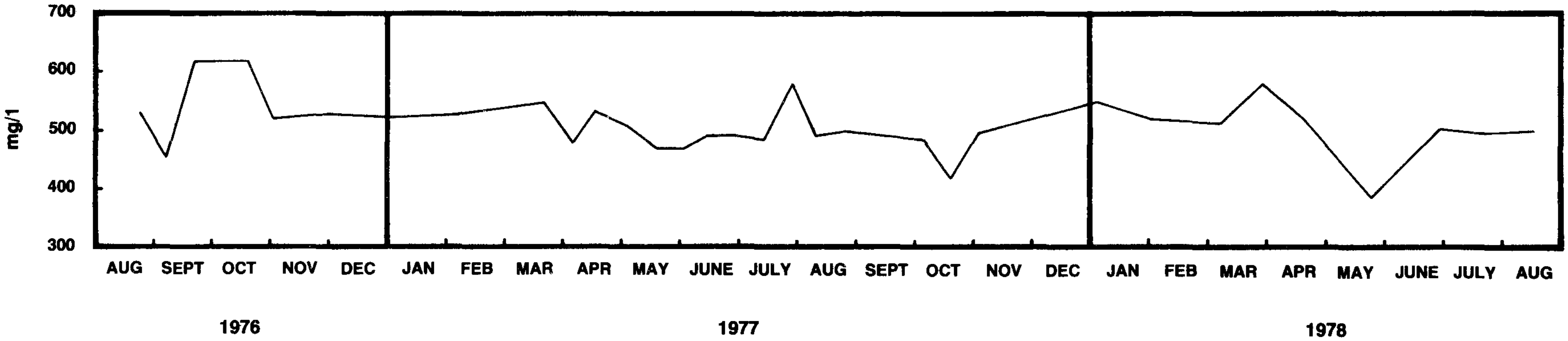
TOTAL DISSOLVED SOLIDS (mg/1)

STATION 5



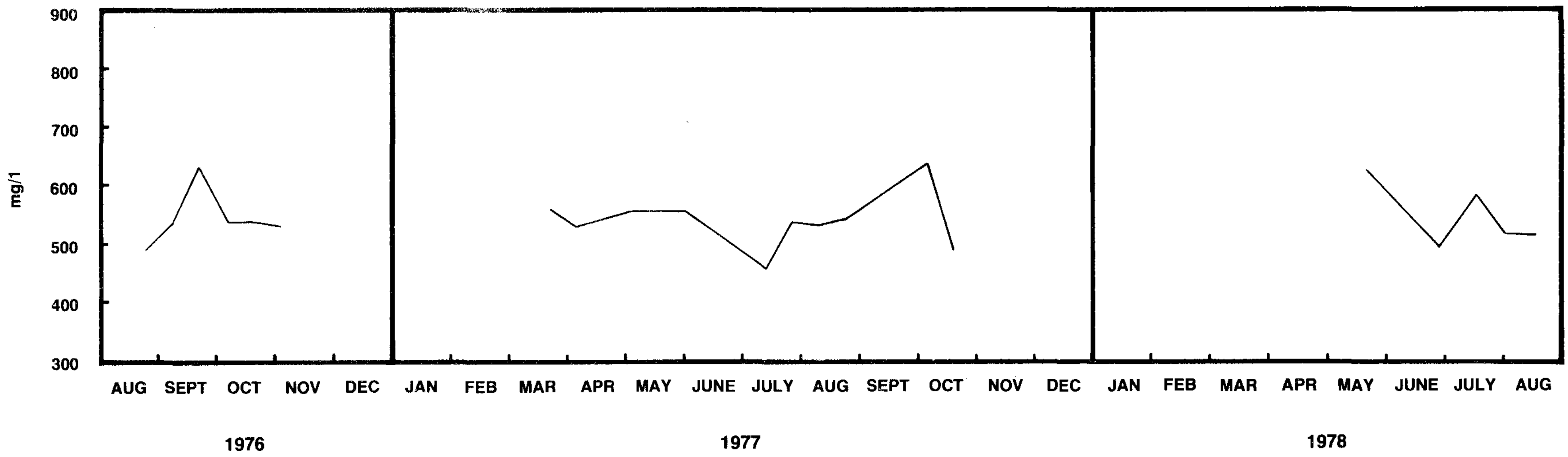
TOTAL DISSOLVED SOLIDS (mg/1)

STATION 6



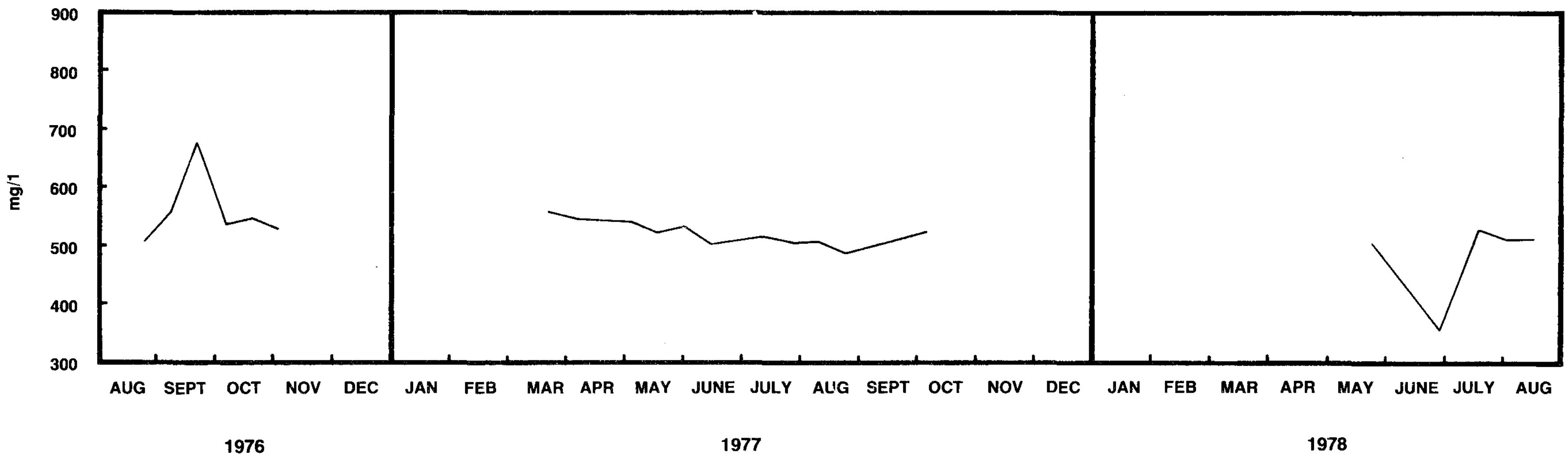
TOTAL DISSOLVED SOLIDS (mg/1)

STATION 1



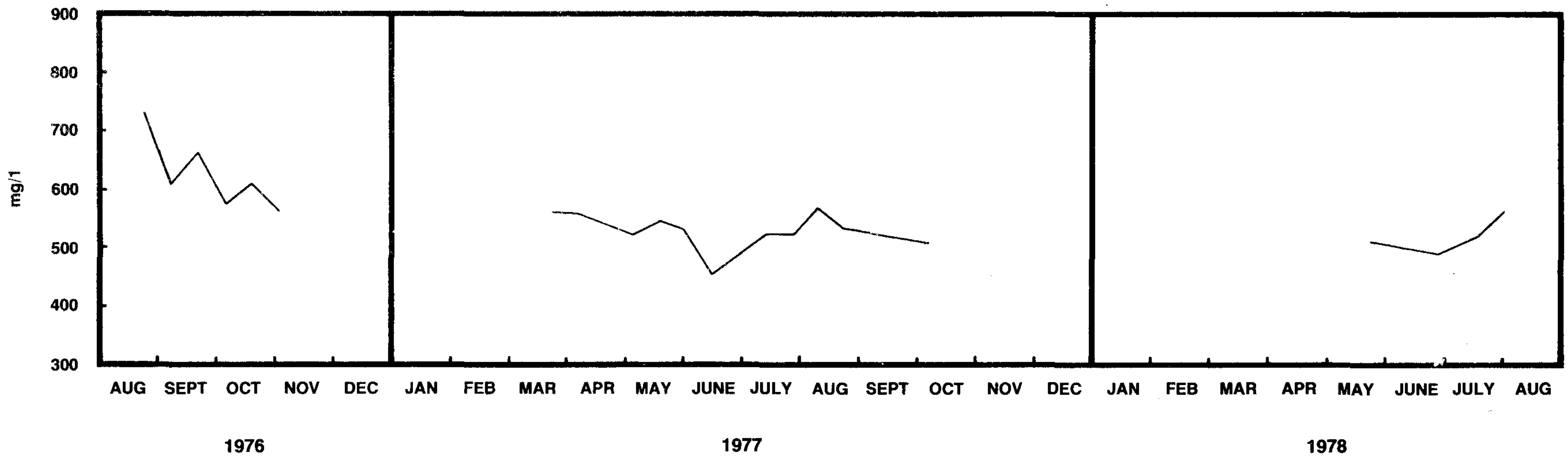
TOTAL SOLIDS (mg/1)

STATION 2



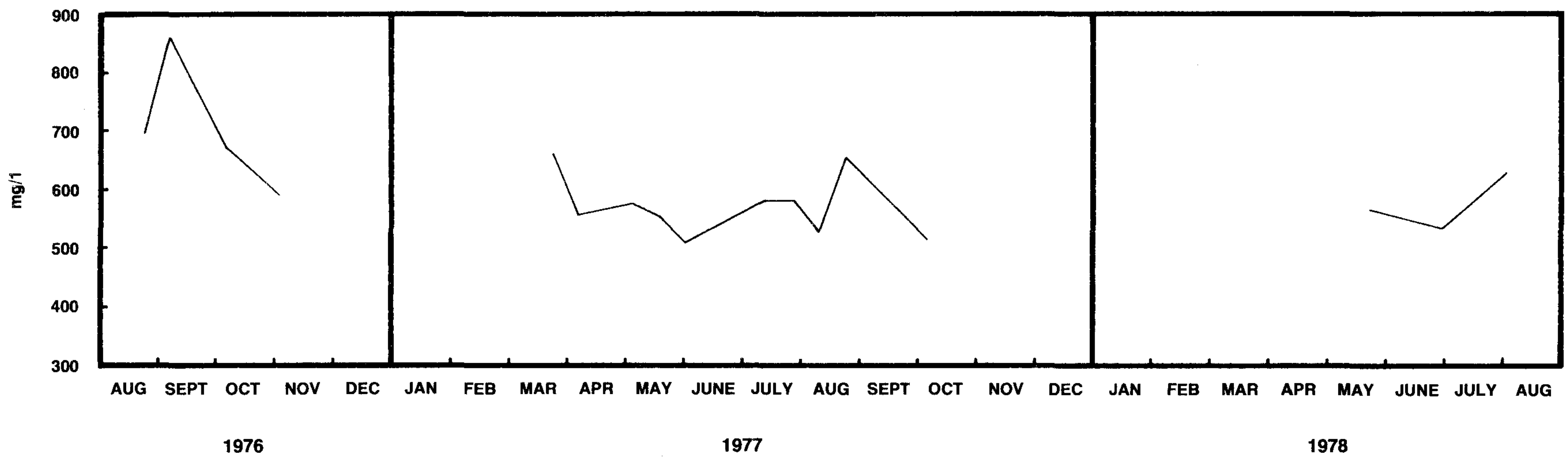
TOTAL SOLIDS (mg/1)

STATION 3

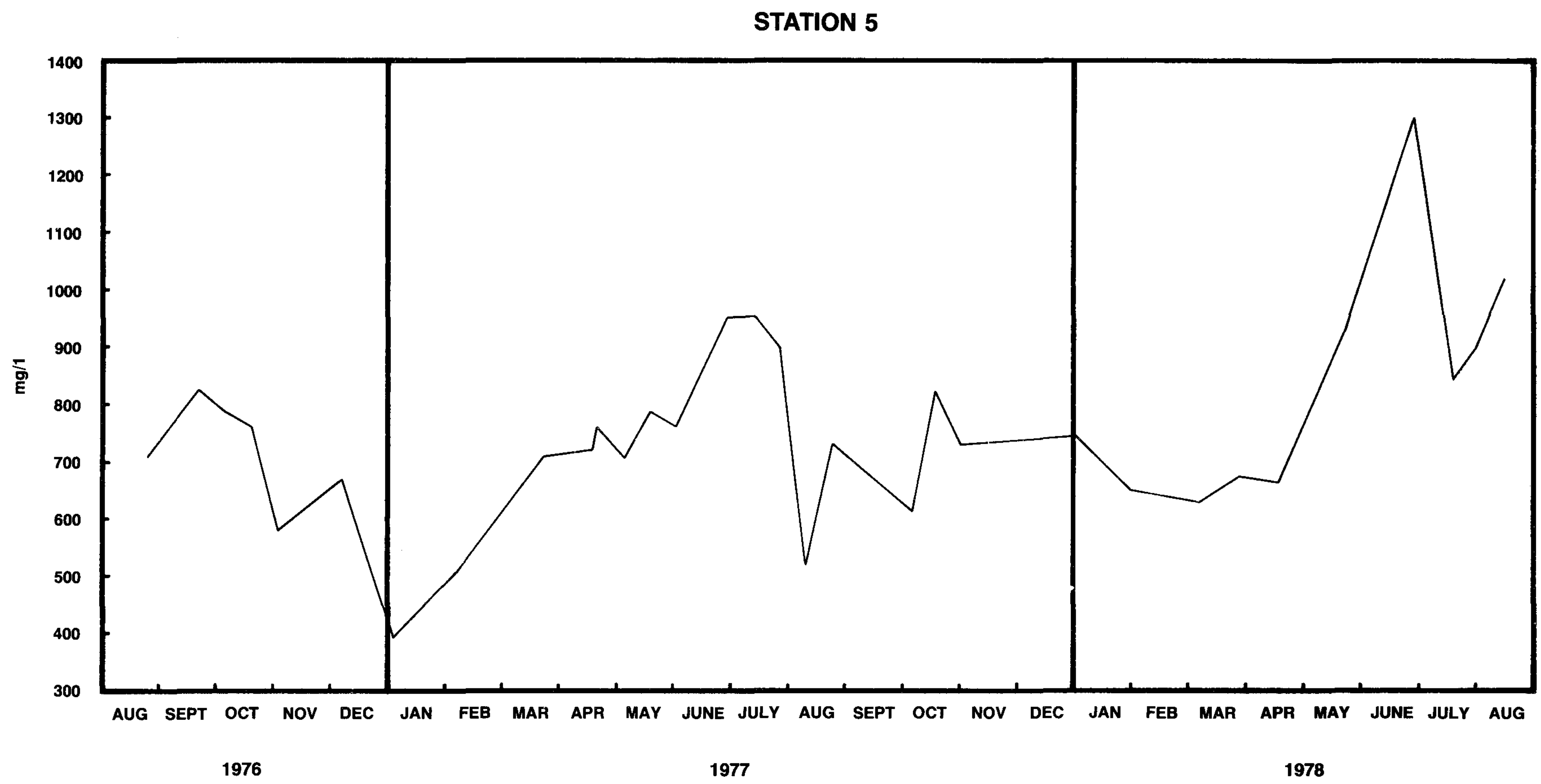


TOTAL SOLIDS (mg/1)

STATION 4

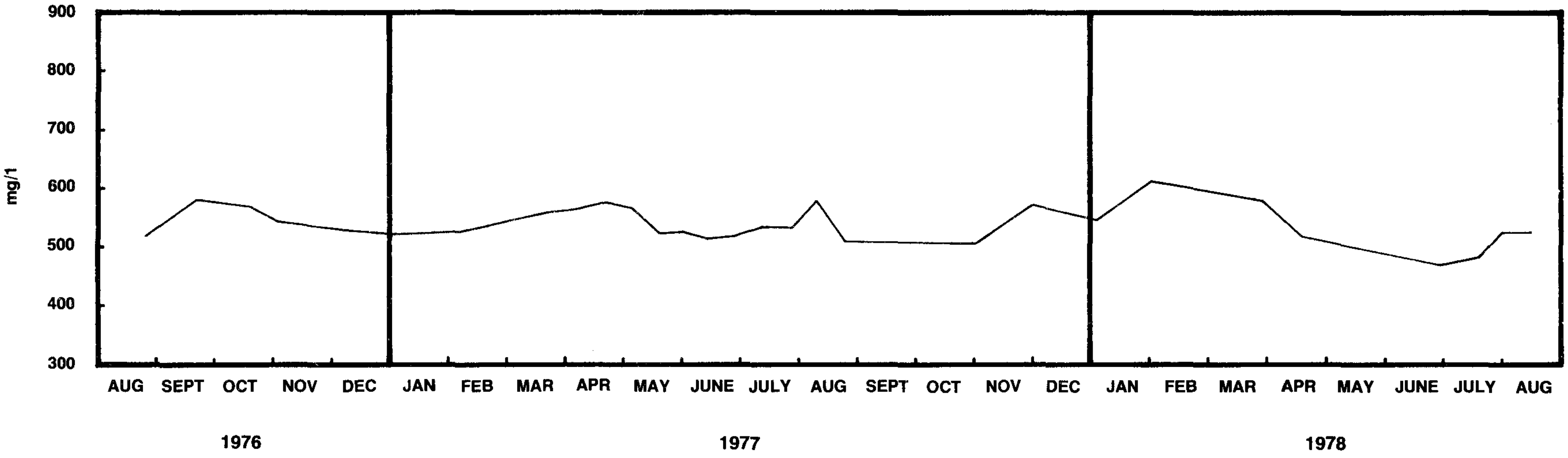


TOTAL SOLIDS (mg/1)



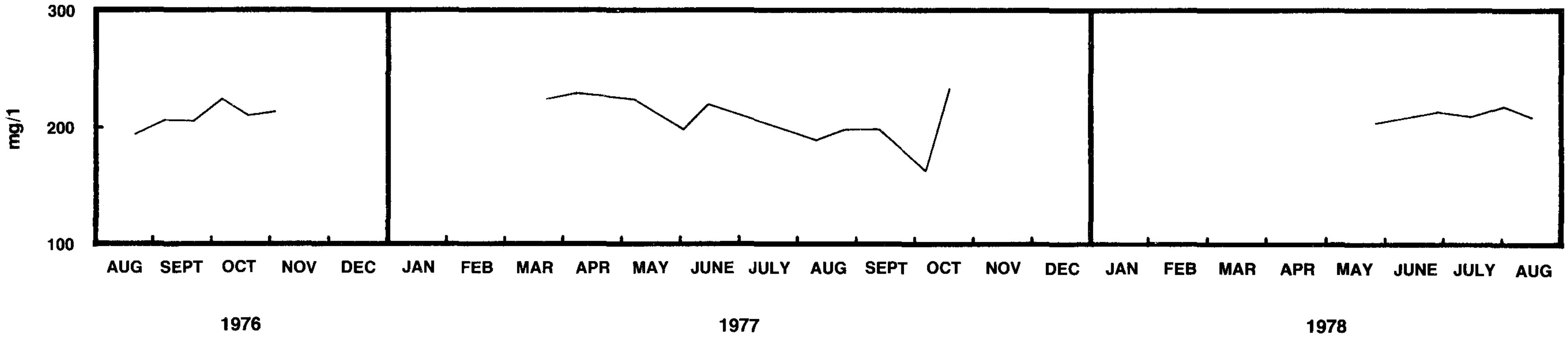
TOTAL SOLIDS (mg/1)

STATION 6



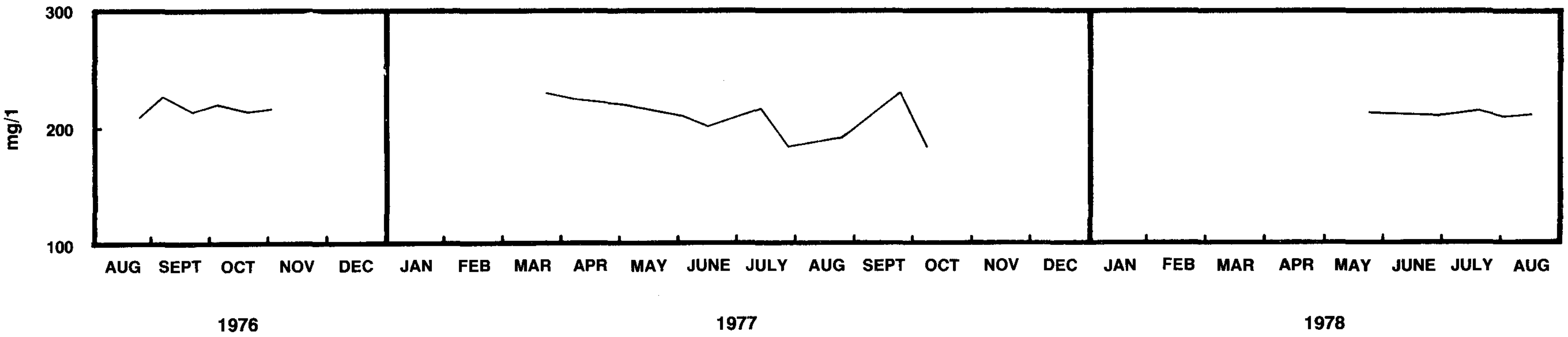
TOTAL SOLIDS (mg/1)

STATION 1



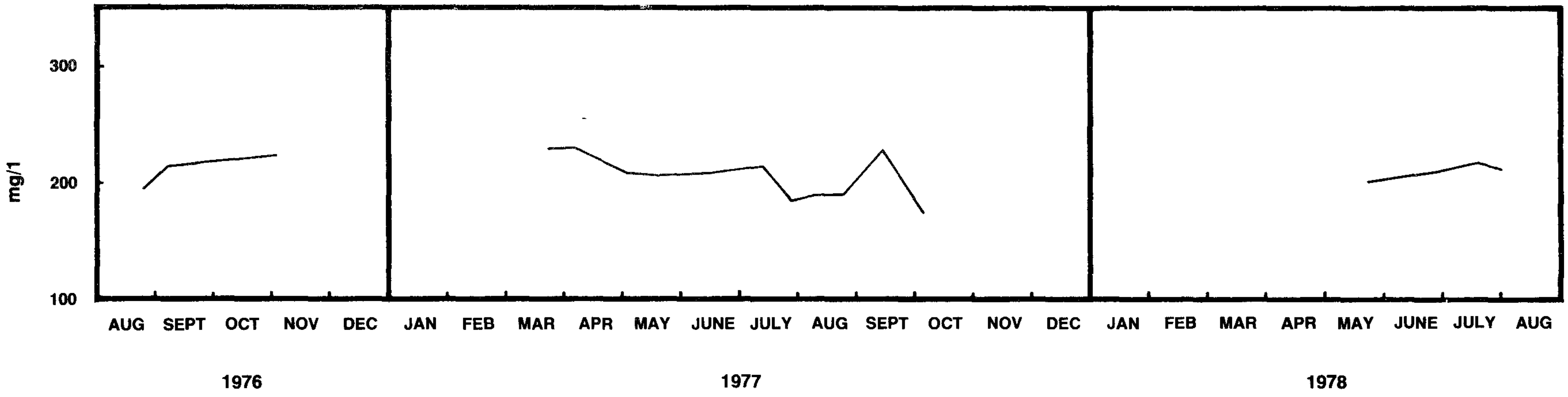
TOTAL HARDNESS (mg/1)

STATION 2



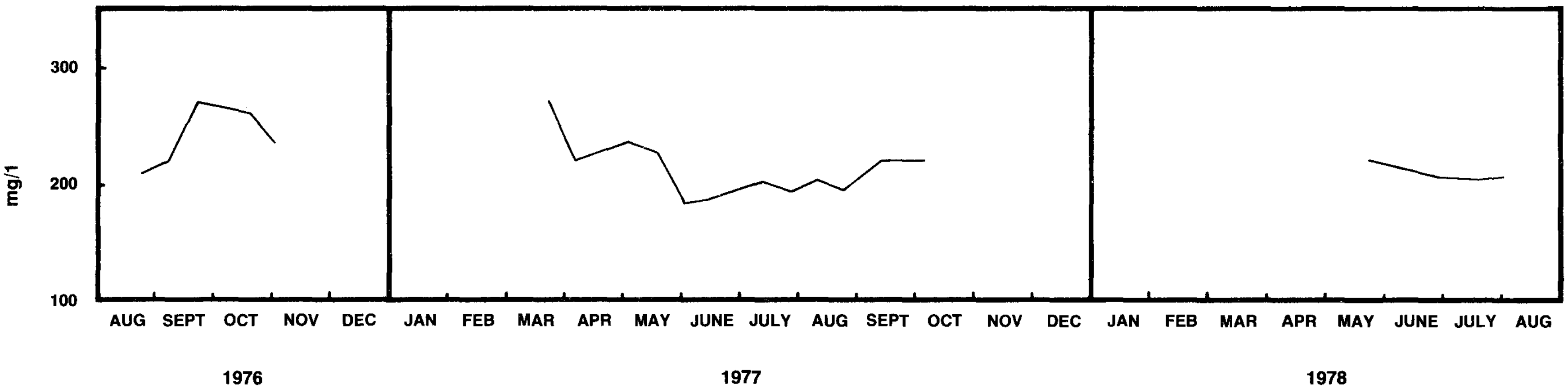
TOTAL HARDNESS (mg/1)

STATION 3



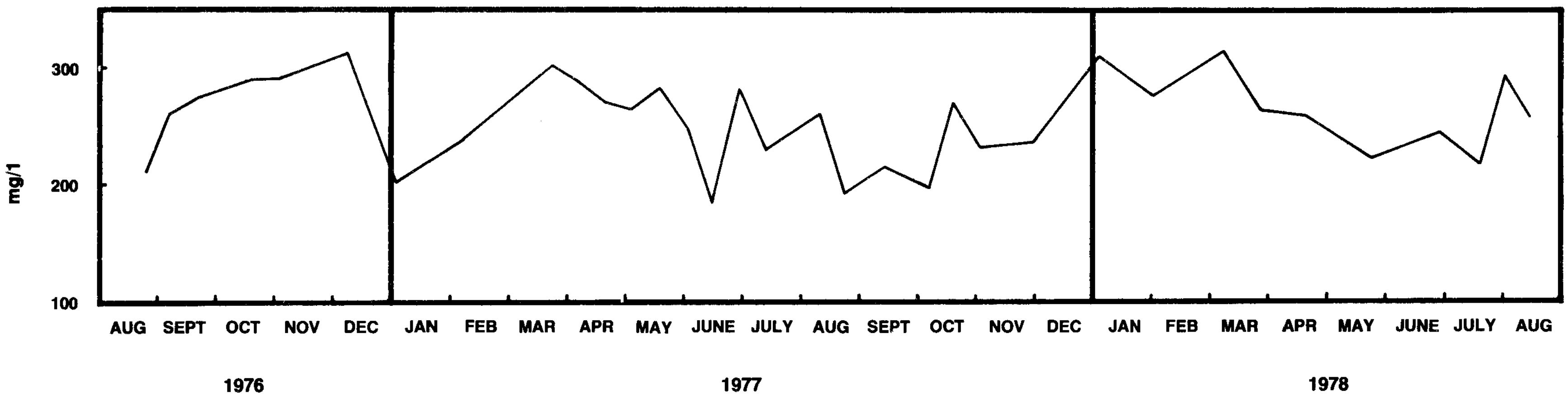
TOTAL HARDNESS (mg/1)

STATION 4



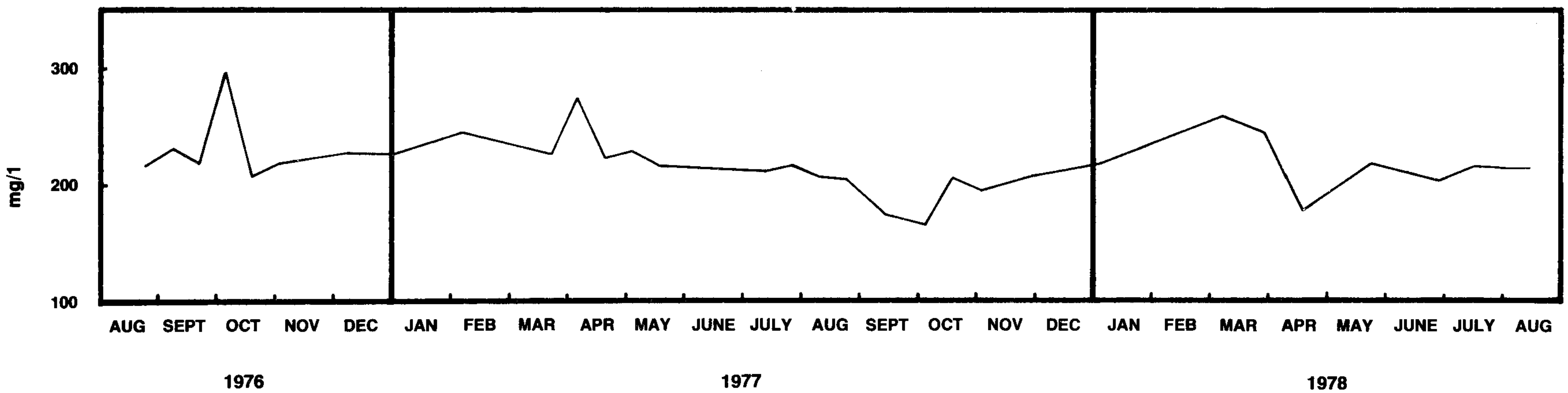
TOTAL HARDNESS (mg/1)

STATION 5

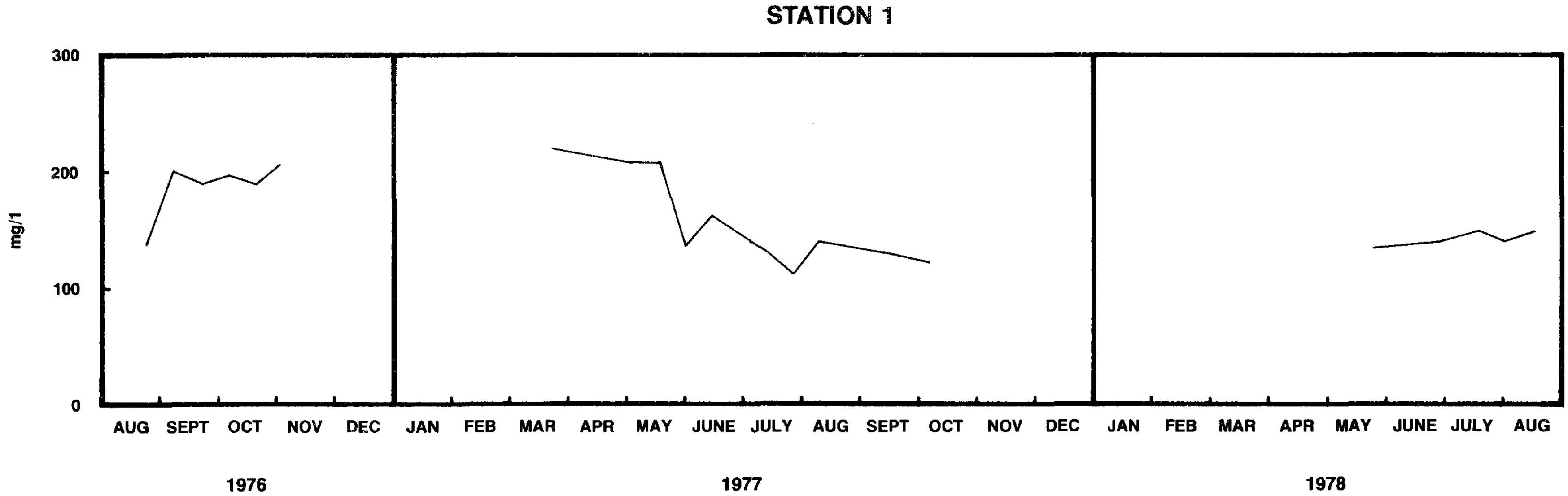


TOTAL HARDNESS (mg/1)

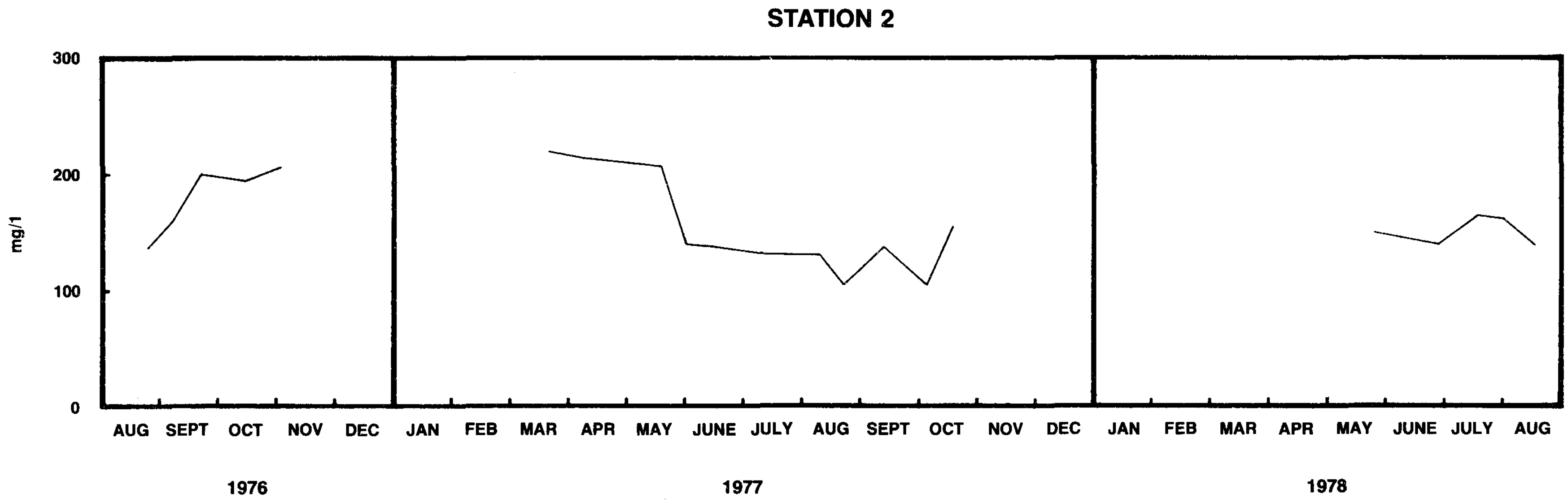
STATION 6



TOTAL HARDNESS (mg/1)

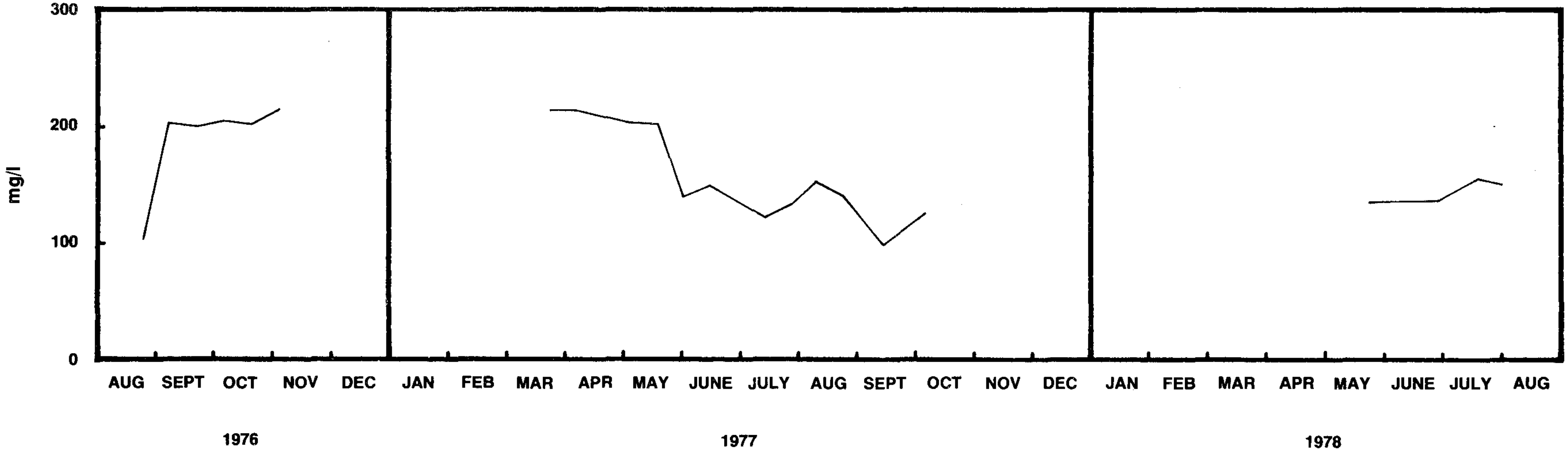


CALCIUM HARDNESS (mg/l)



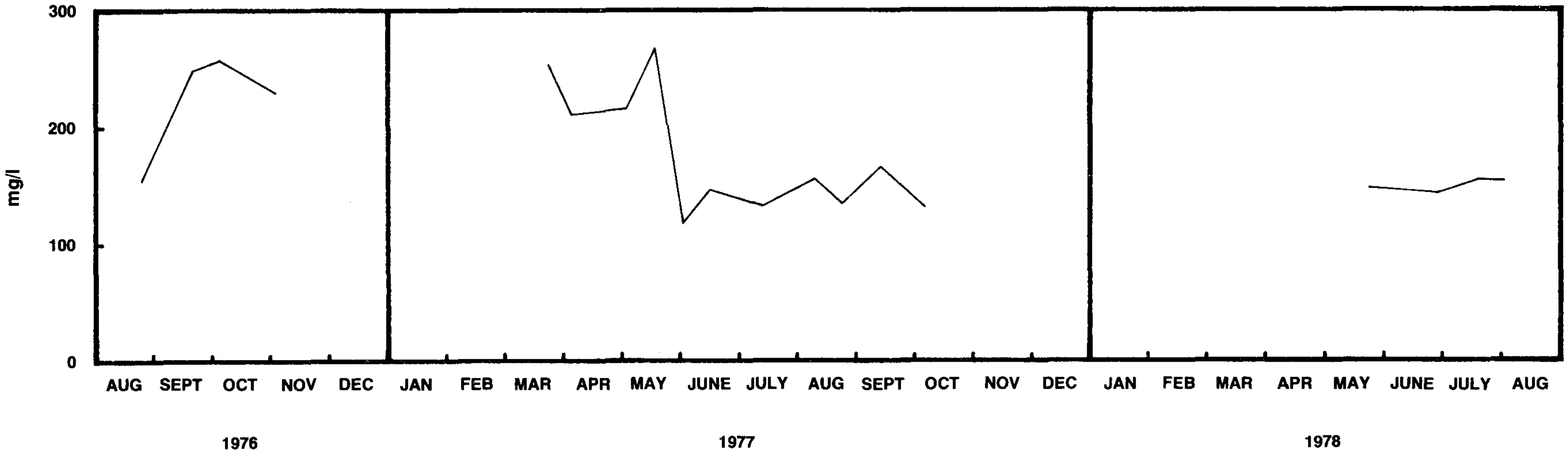
CALCIUM HARDNESS (mg/l)

STATION 3



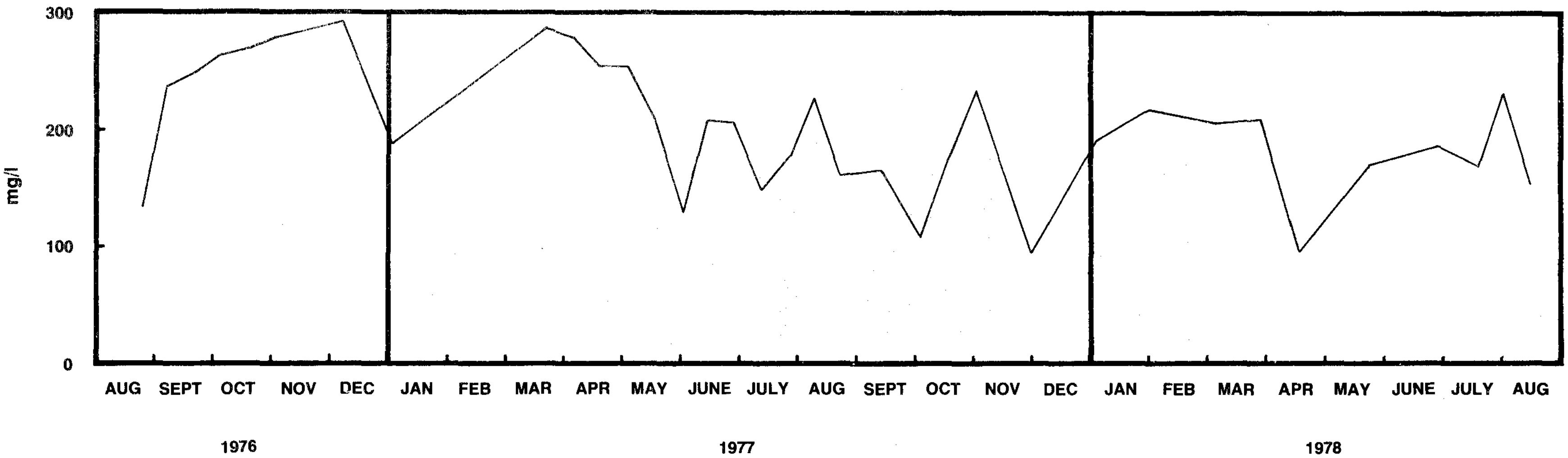
CALCIUM HARDNESS (mg/l)

STATION 4



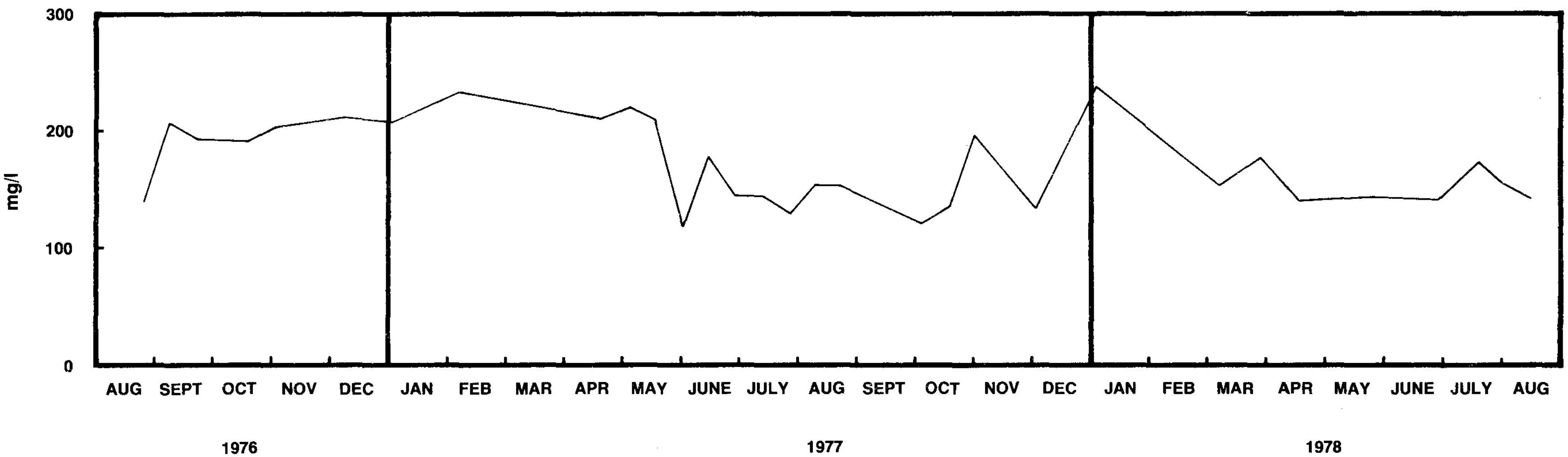
CALCIUM HARDNESS (mg/l)

STATION 5

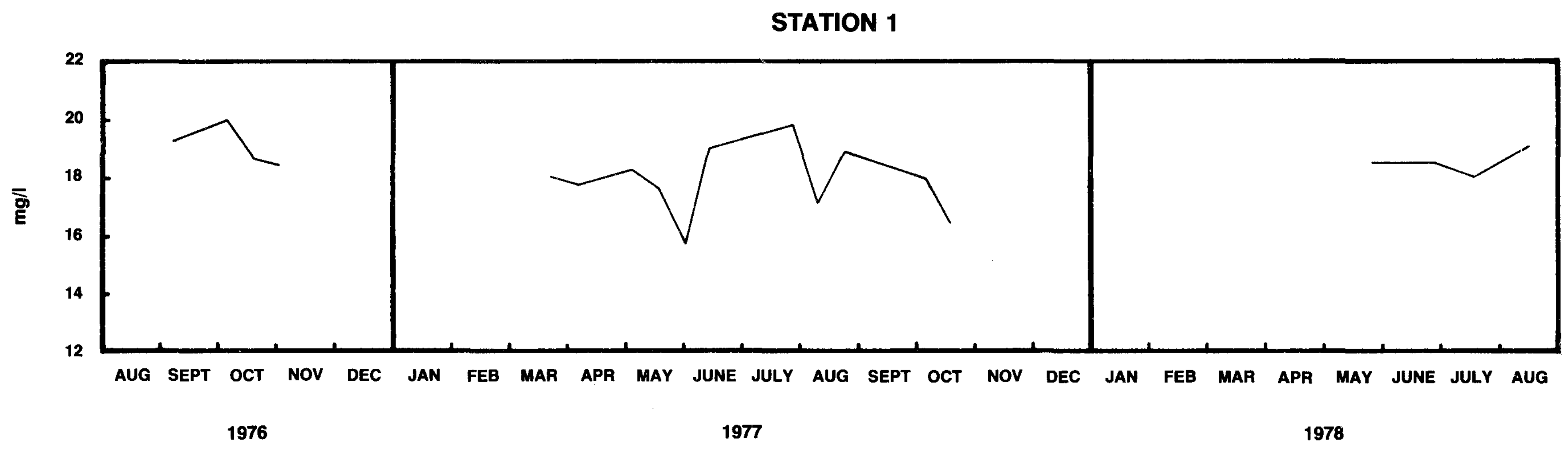


CALCIUM HARDNESS (mg/l)

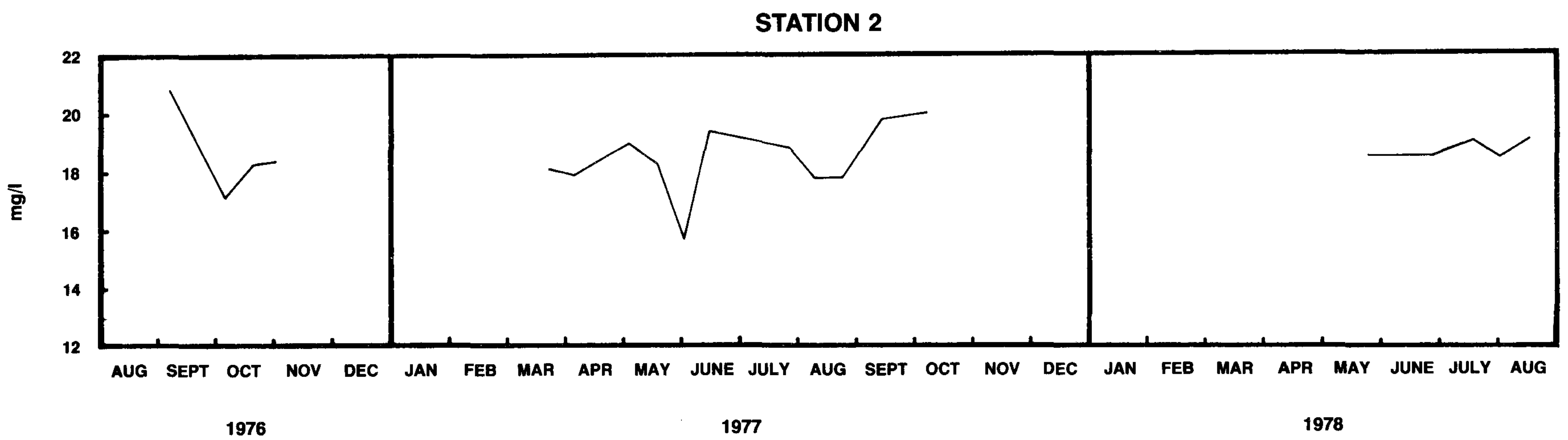
STATION 6



CALCIUM HARDNESS (mg/l)

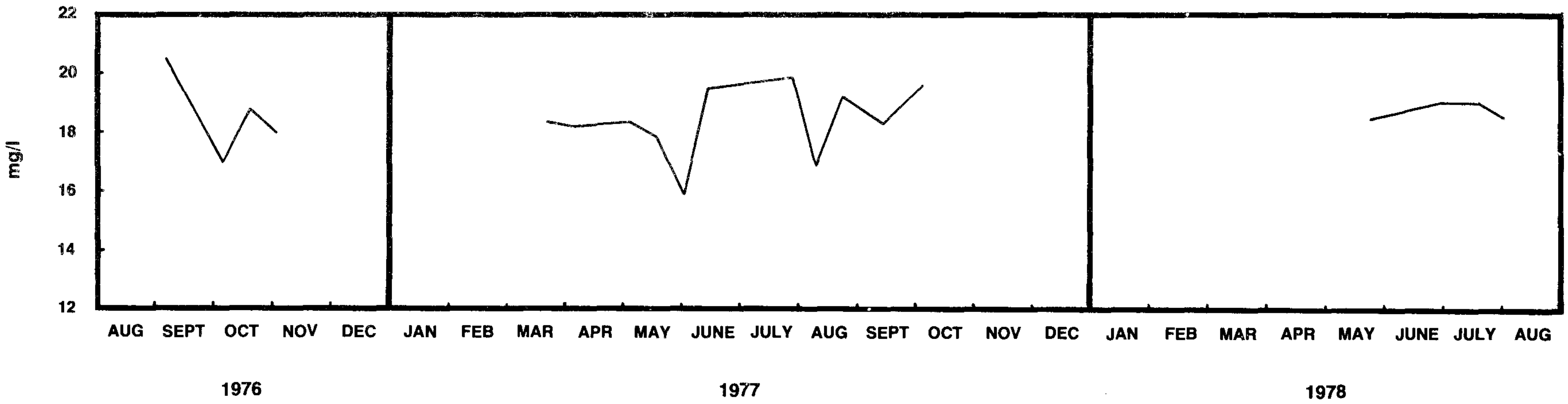


CHLORIDES /mg/1)



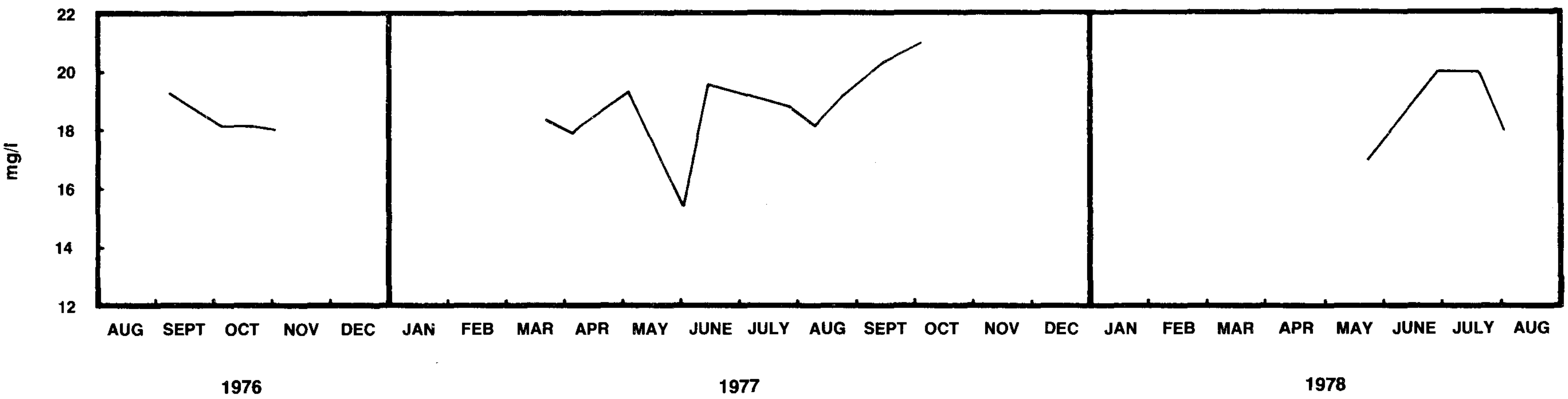
CHLORIDES /mg/1)

STATION 3



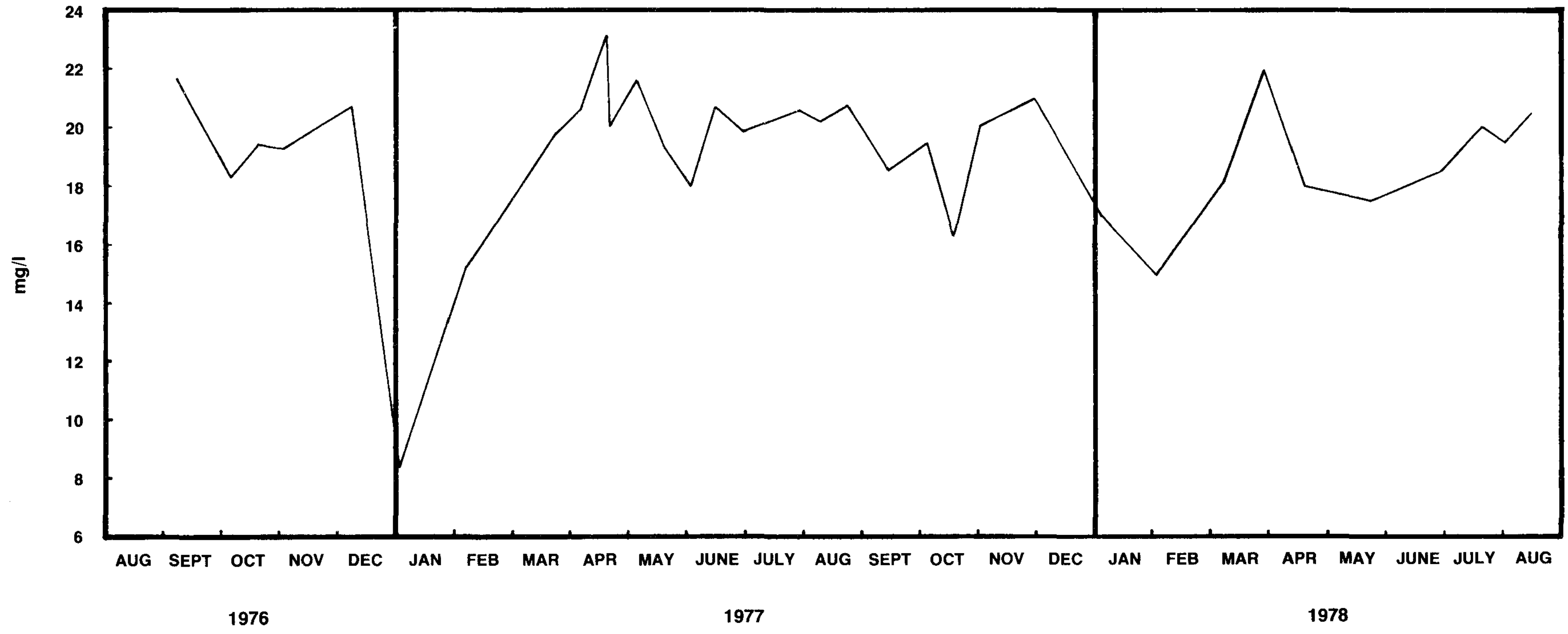
CHLORIDES (mg/l)

STATION 4



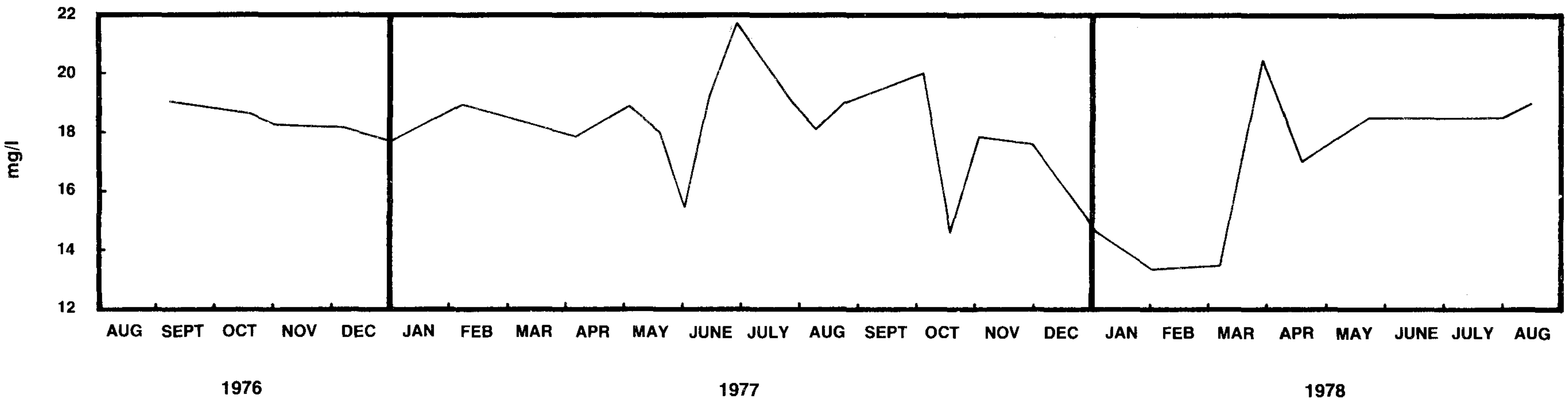
CHLORIDES (mg/l)

STATION 5



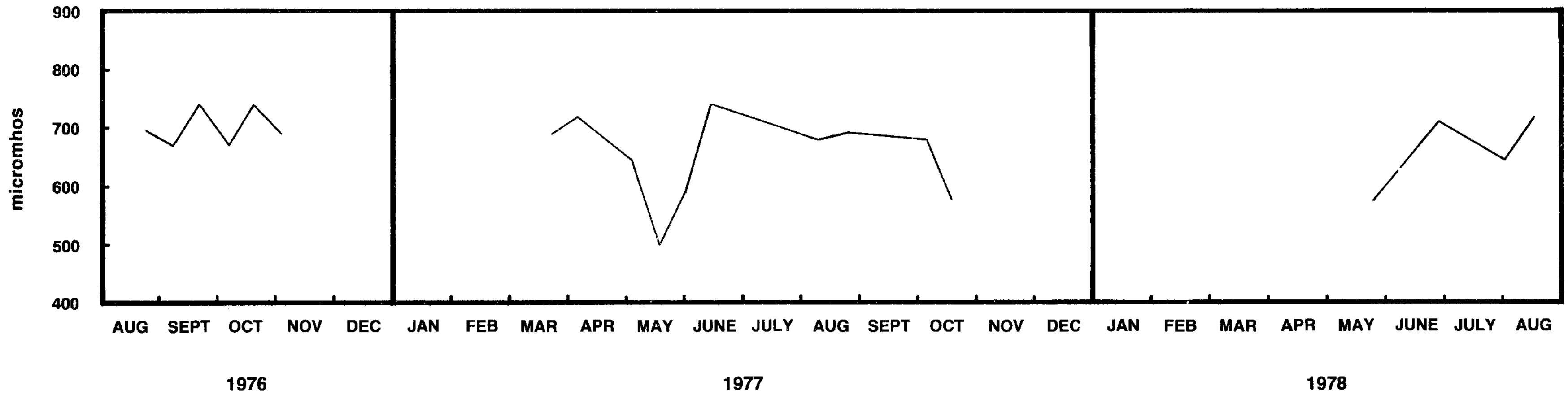
CHLORIDES (mg/l)

STATION 6



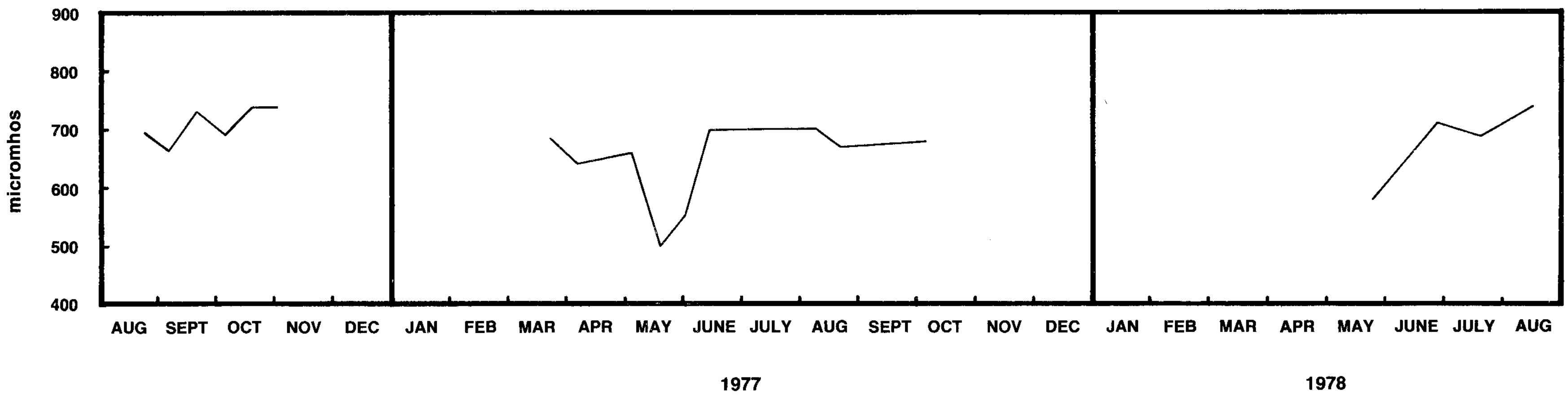
CHLORIDES (mg/l)

STATION 1



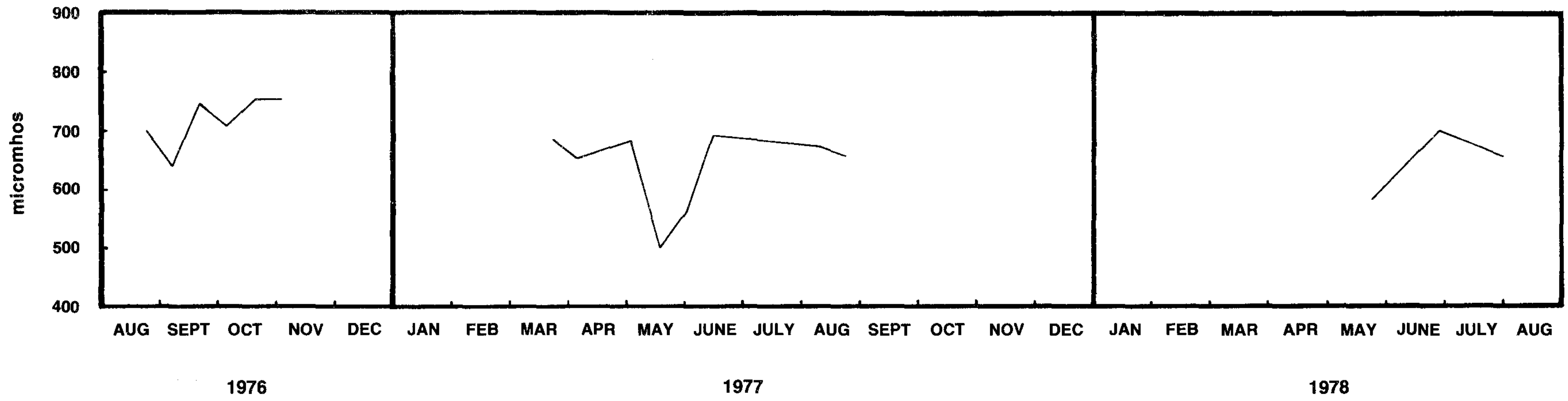
SPECIFIC CONDUCTANCE (μmhos)

STATION 2



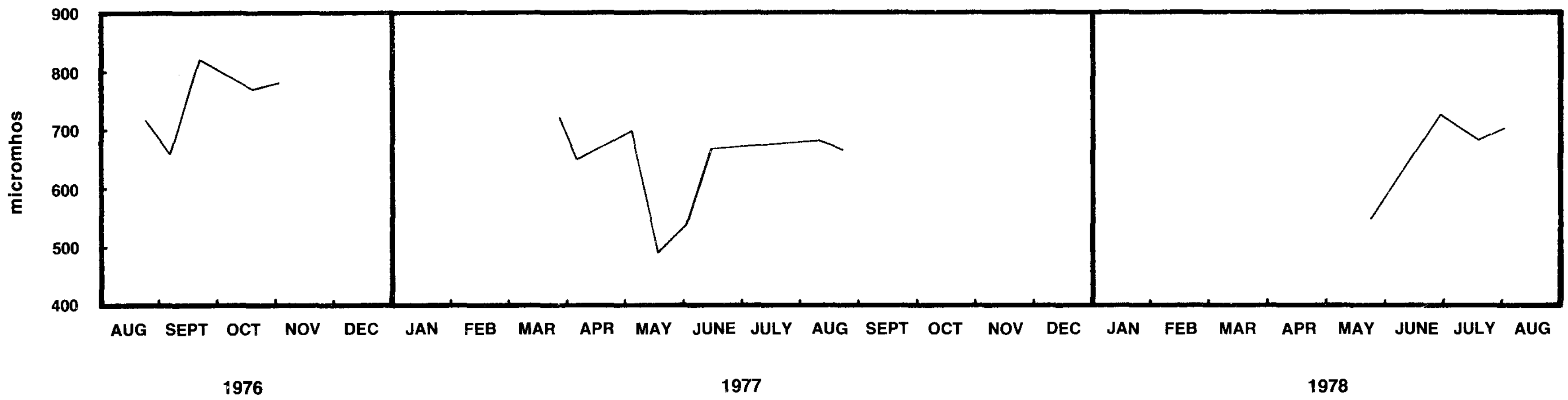
SPECIFIC CONDUCTANCE (μmhos)

STATION 3



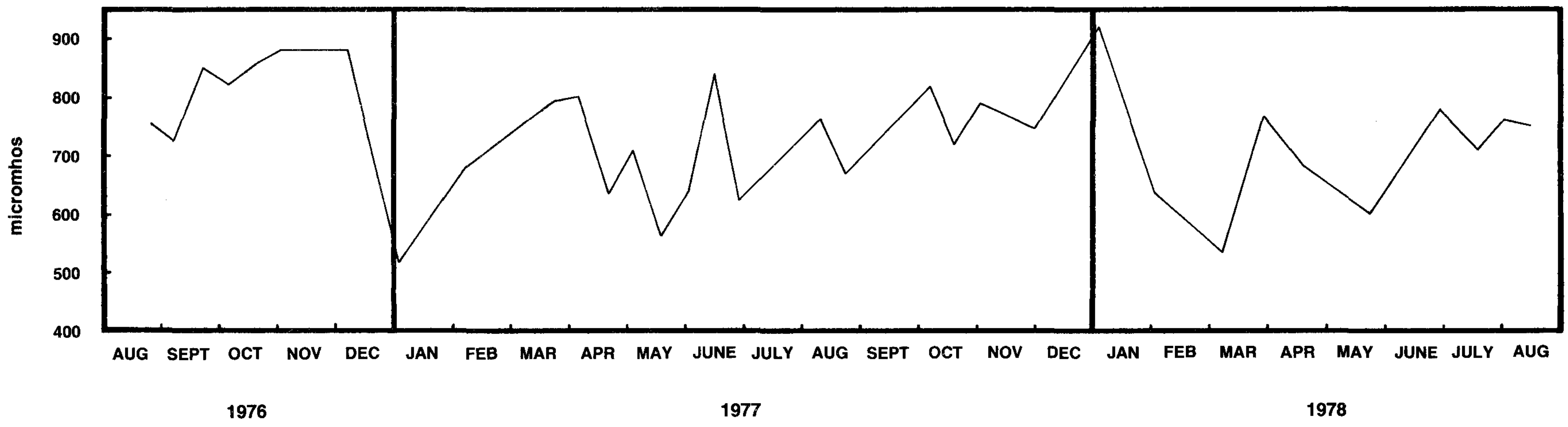
SPECIFIC CONDUCTANCE (μmhos)

STATION 4



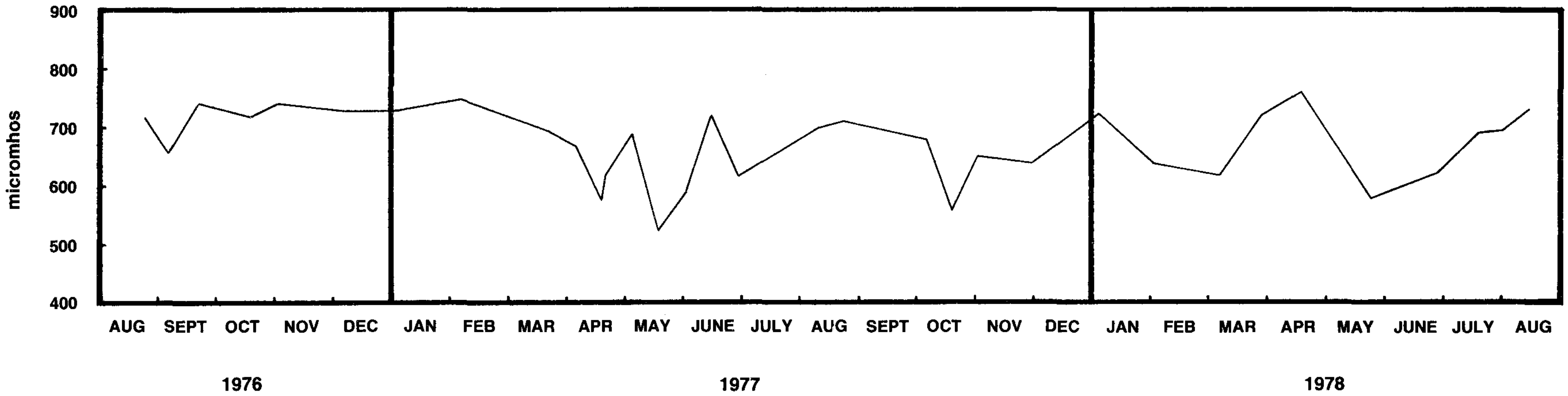
SPECIFIC CONDUCTANCE (μmhos)

STATION 5



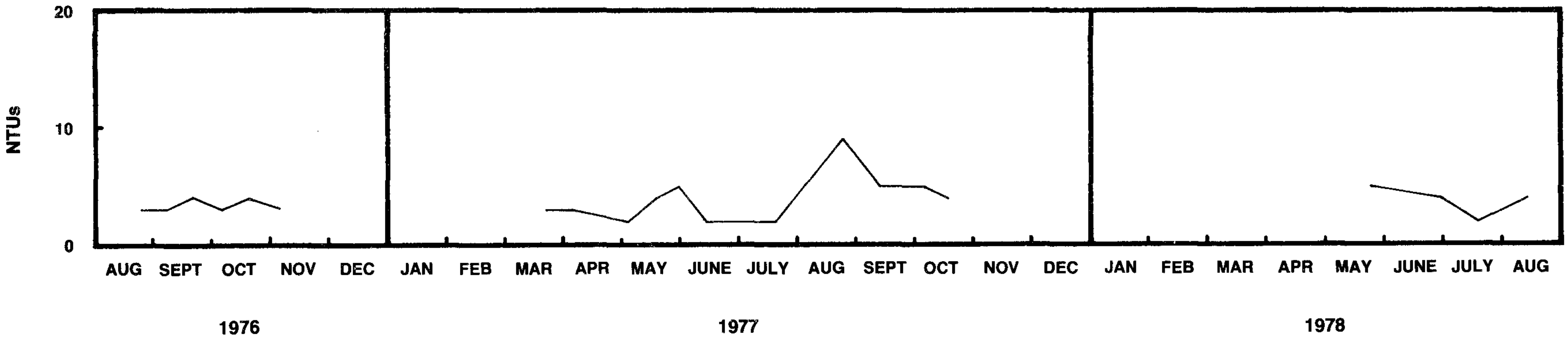
SPECIFIC CONDUCTANCE (μmhos)

STATION 6



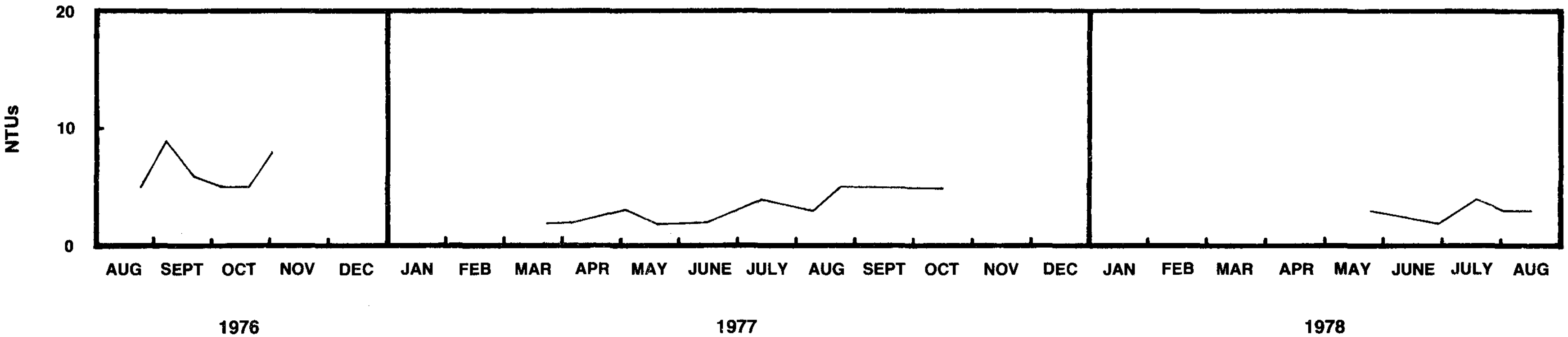
SPECIFIC CONDUCTANCE (μmhos)

STATION 1



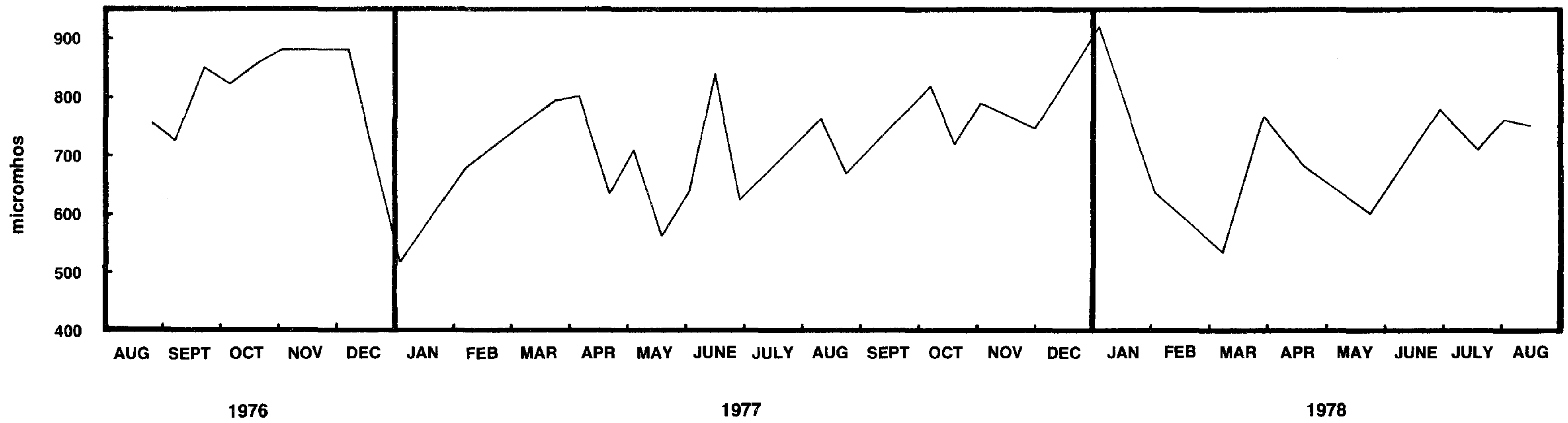
TURBIDITY (NTU)

STATION 2



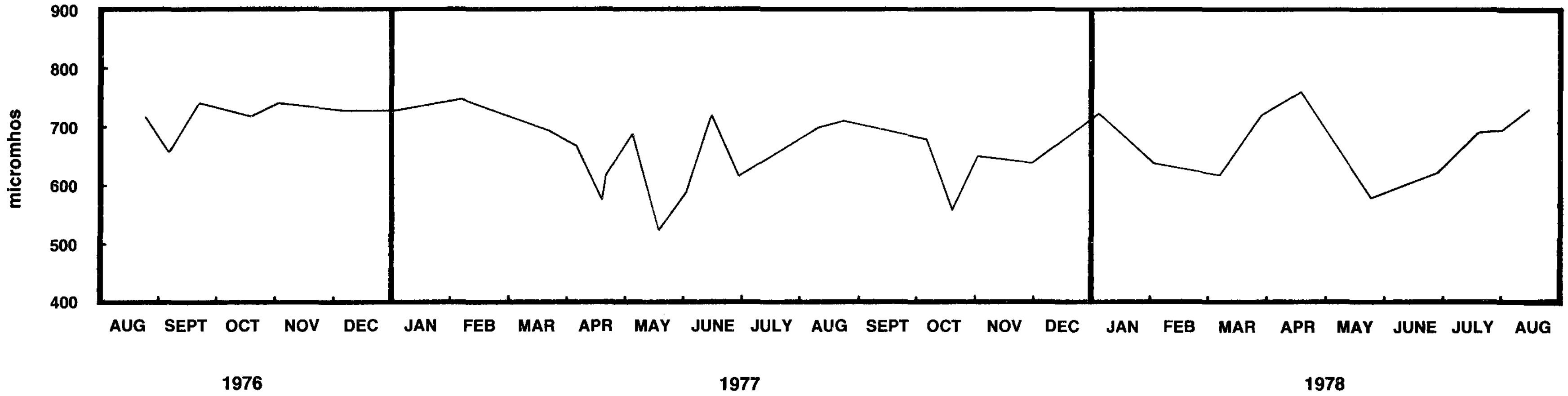
TURBIDITY (NTU)

STATION 5



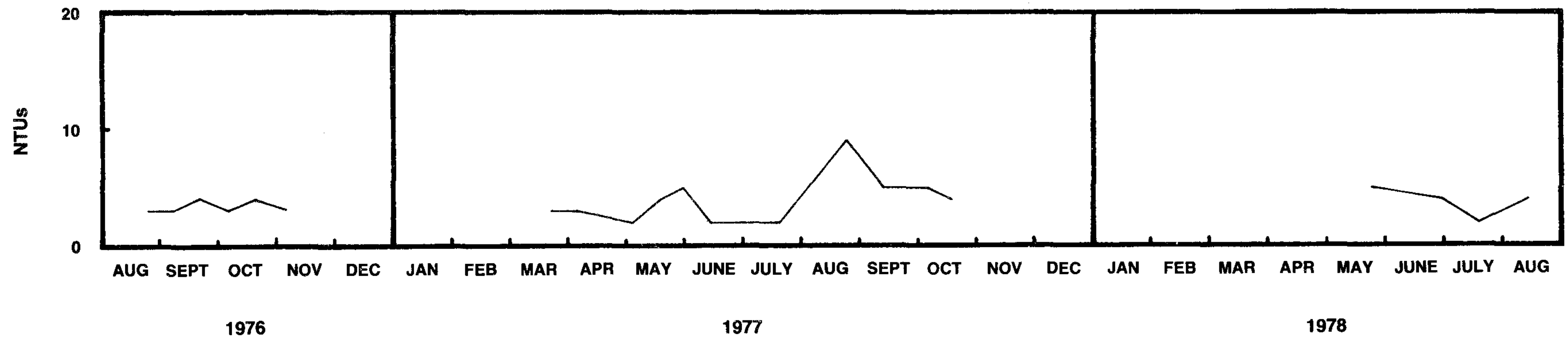
SPECIFIC CONDUCTANCE (μmhos)

STATION 6



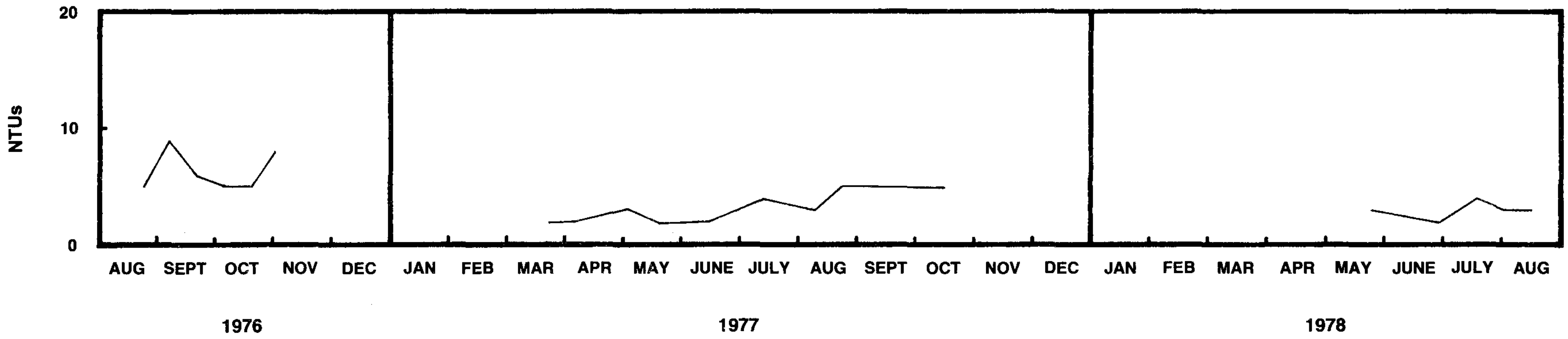
SPECIFIC CONDUCTANCE (μmhos)

STATION 1



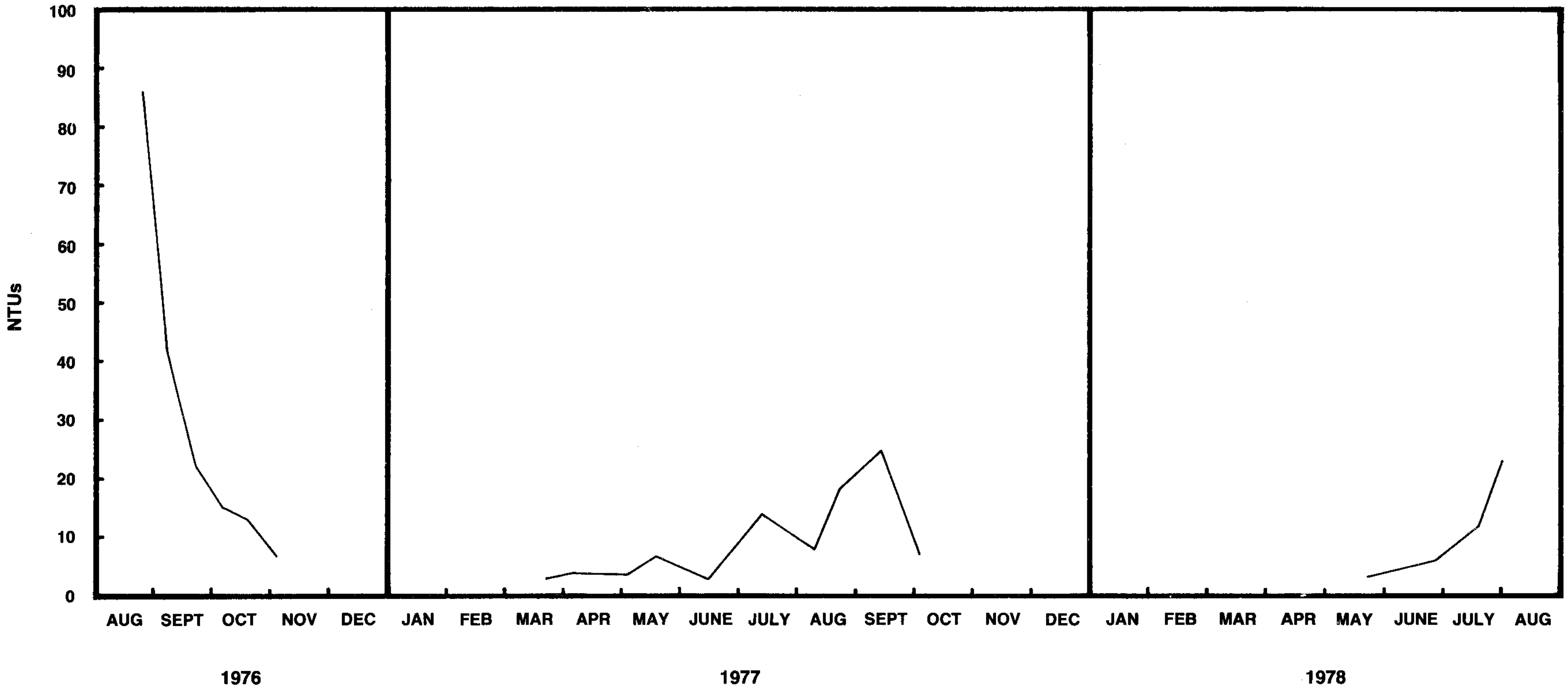
TURBIDITY (NTU)

STATION 2

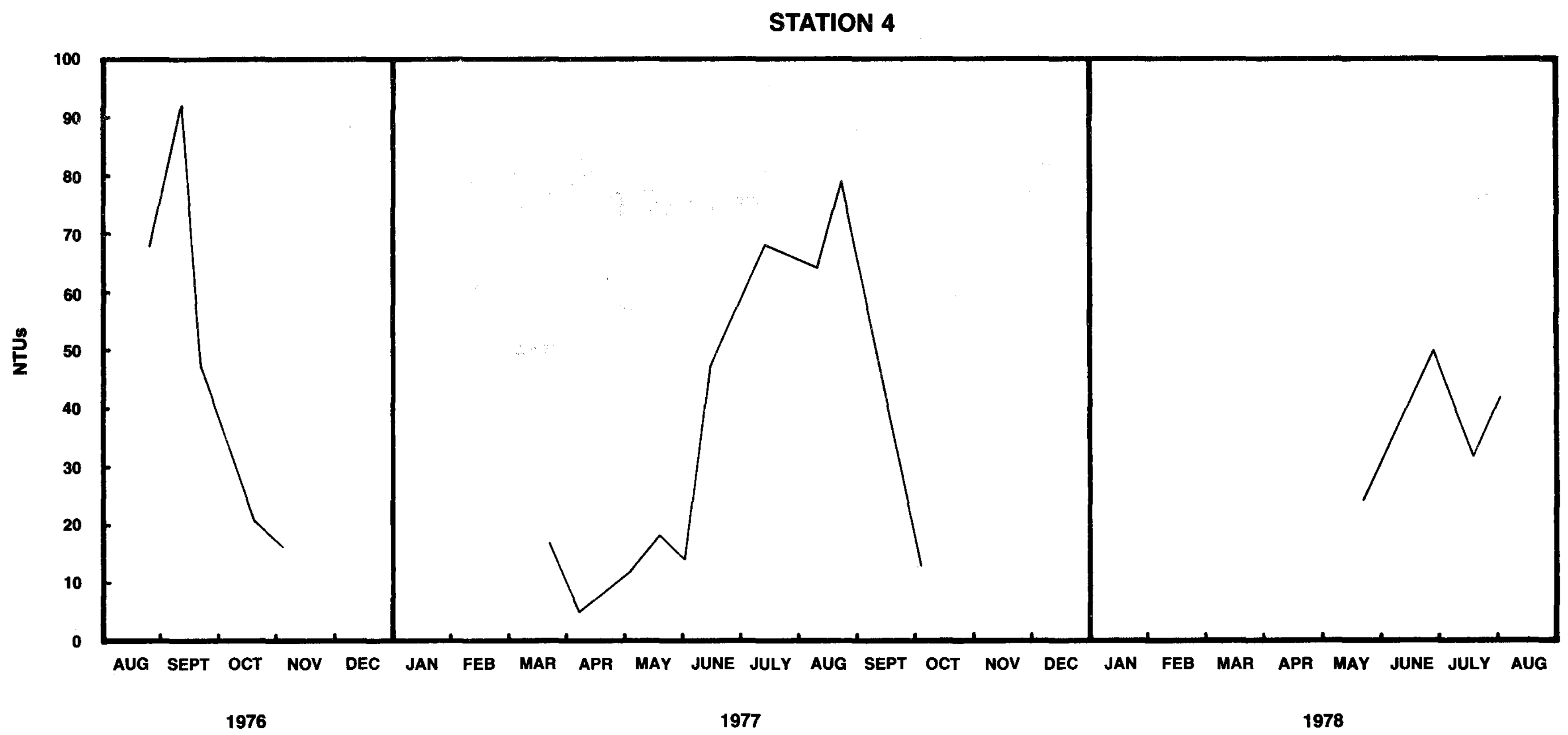


TURBIDITY (NTU)

STATION 3

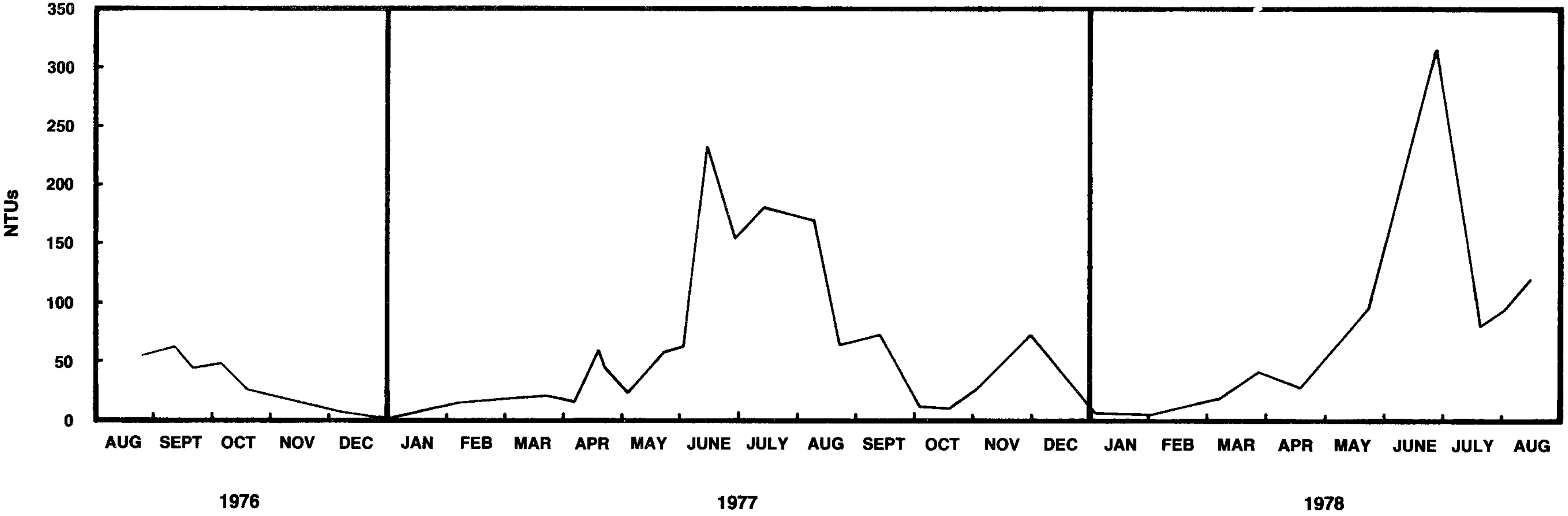


TURBIDITY (NTU)



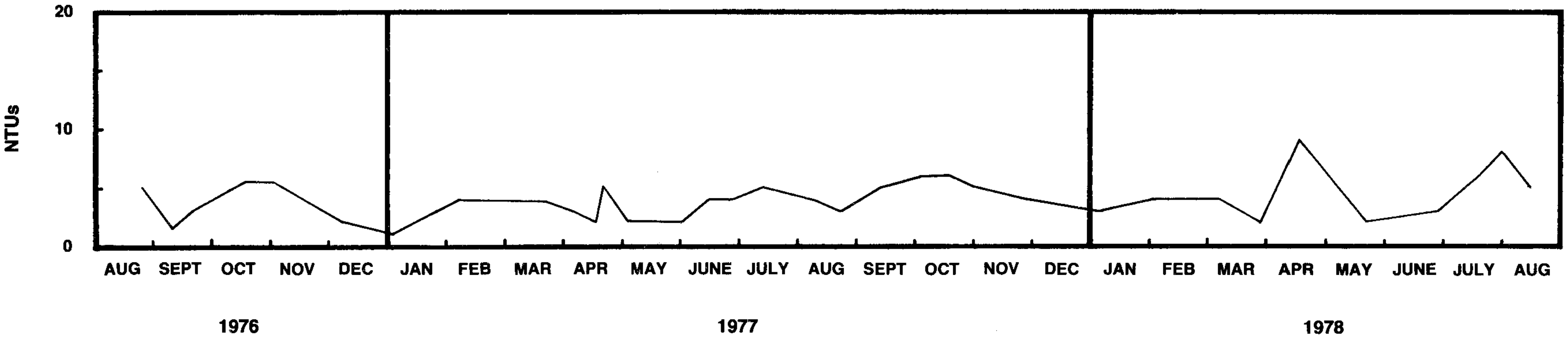
TURBIDITY (NTU)

STATION 5



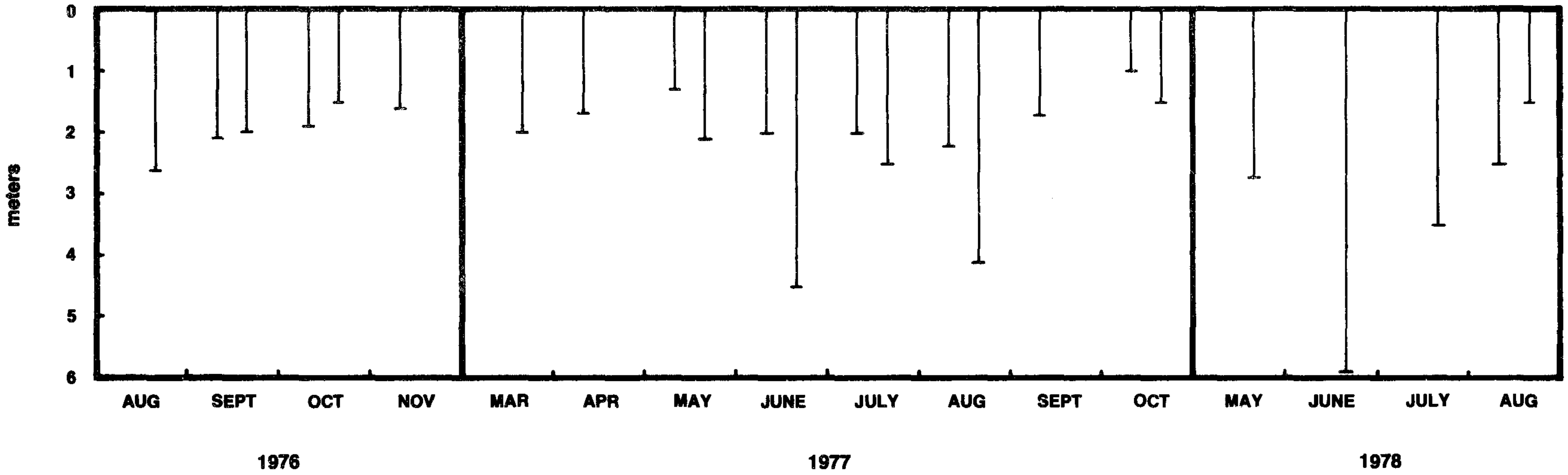
TURBIDITY (NTU)

STATION 6



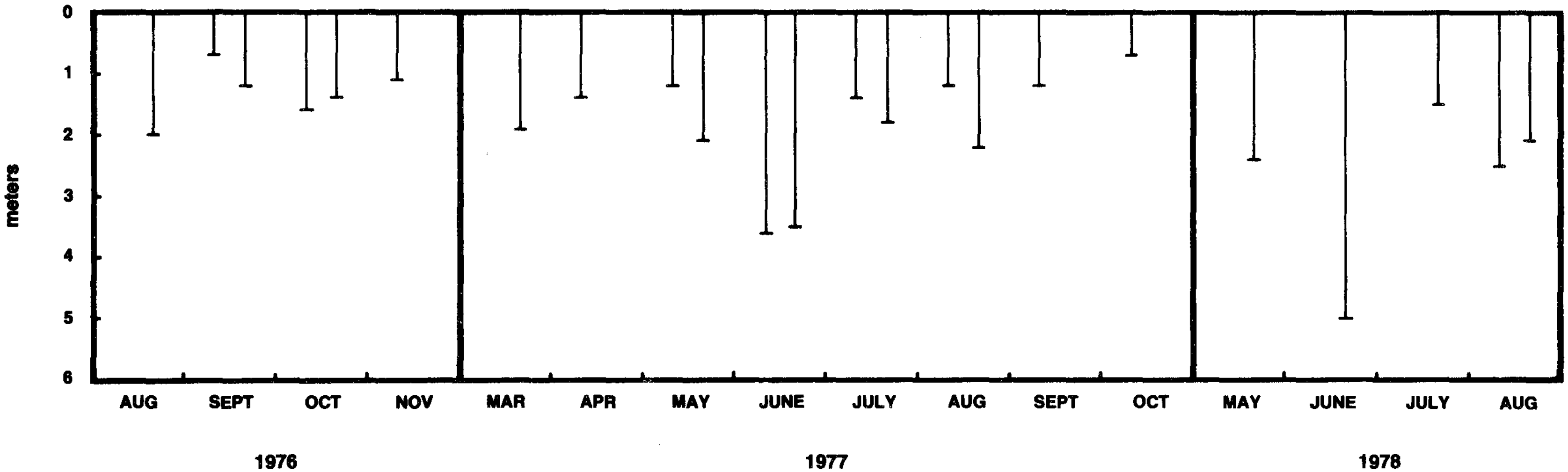
TURBIDITY (NTU)

STATION 1



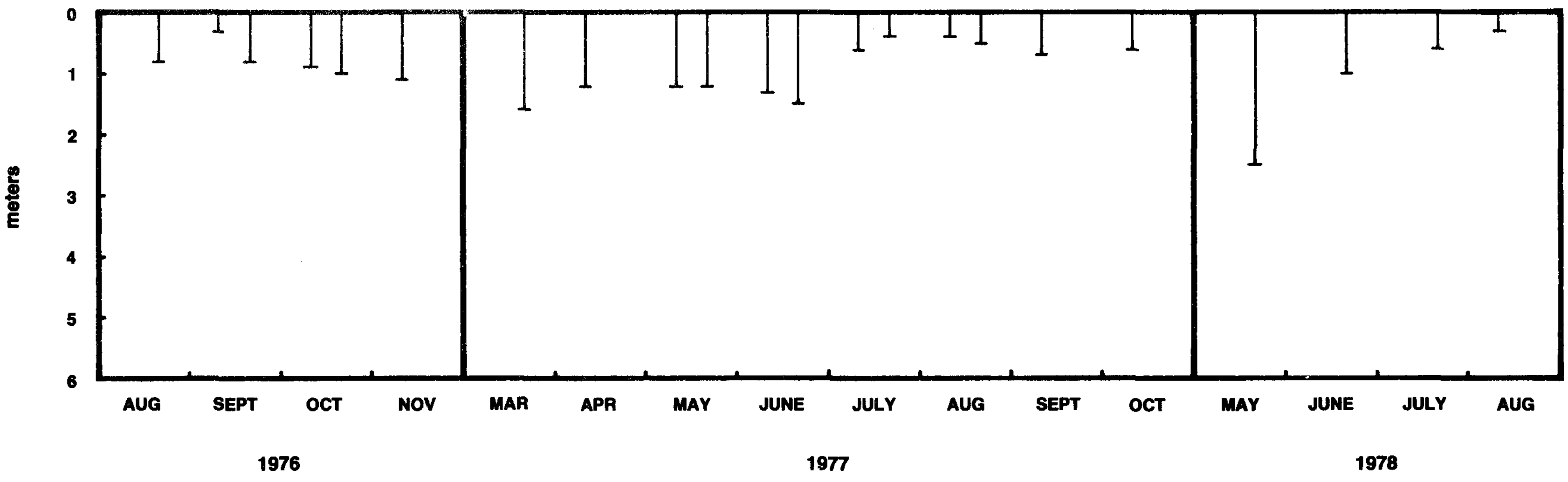
SECCHI DISK (m)

STATION 2



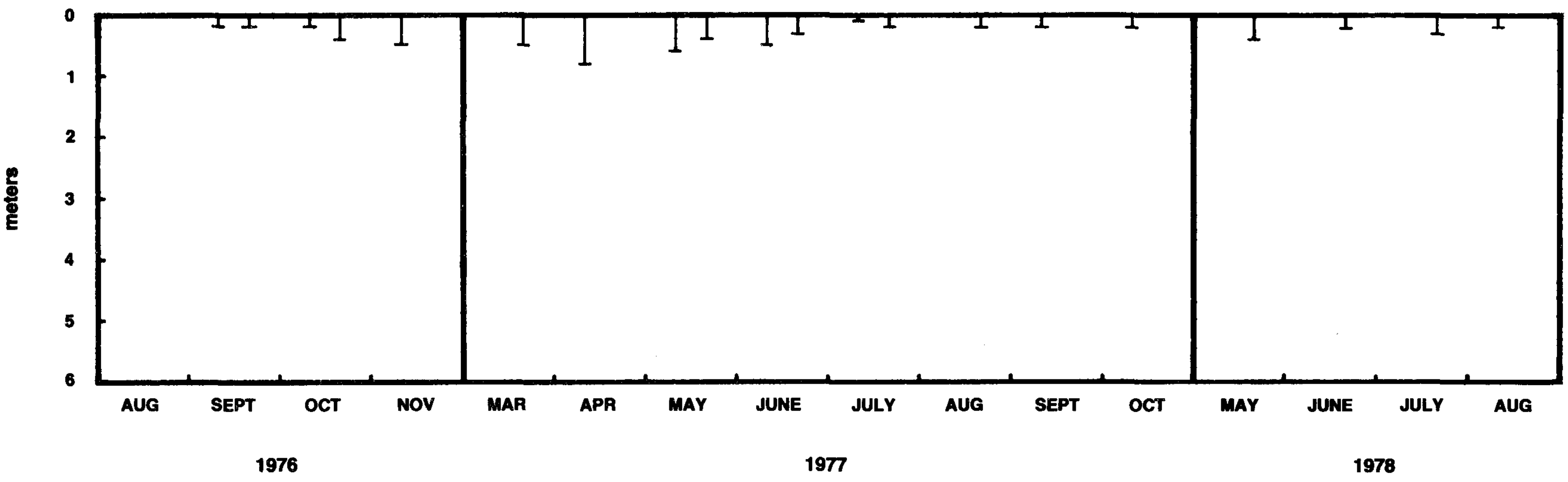
SECCHI DISK (m)

STATION 3



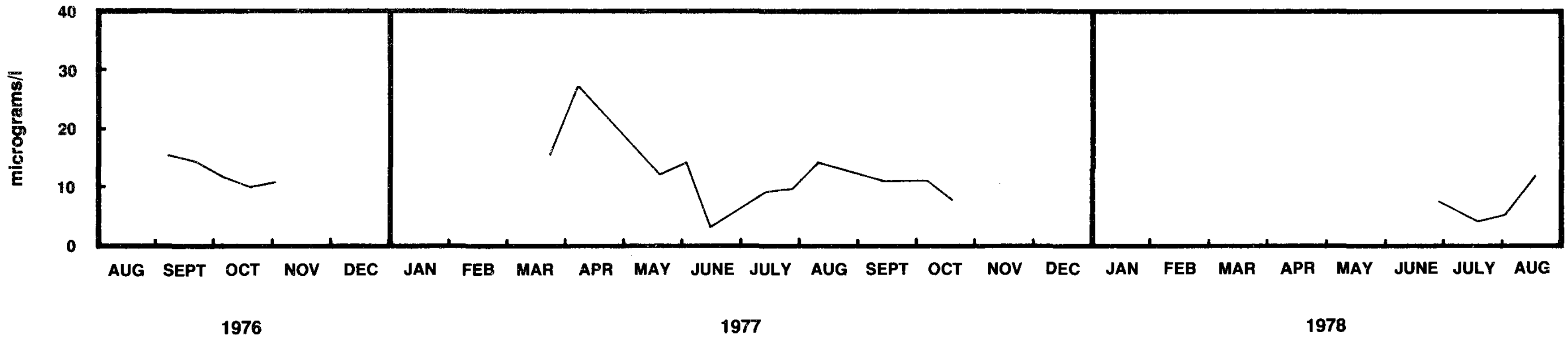
SECCHI DISK (m)

STATION 4



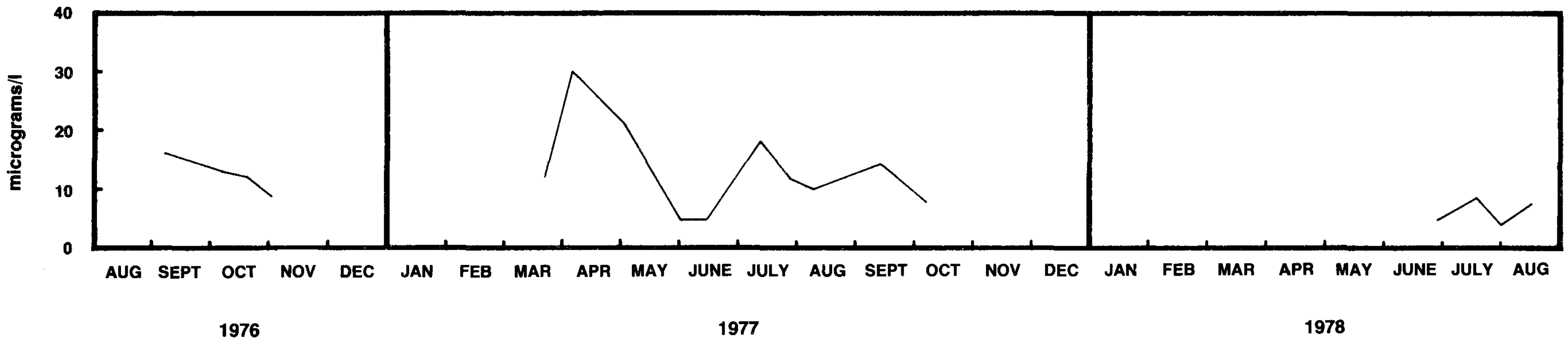
SECCHI DISK (m)

STATION 1



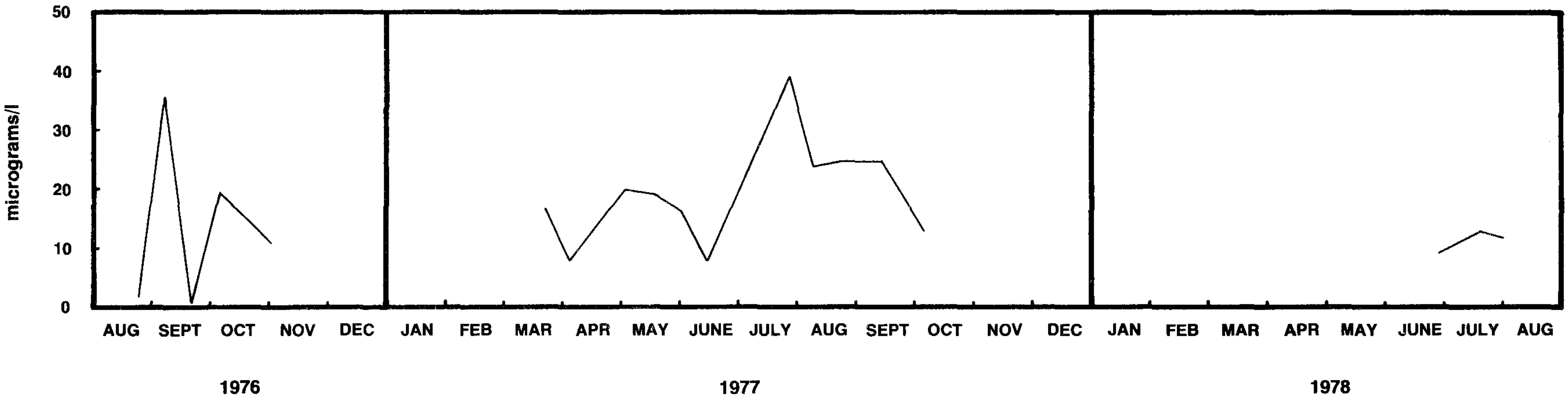
CHLOROPHYLL A (μg/l)

STATION 2



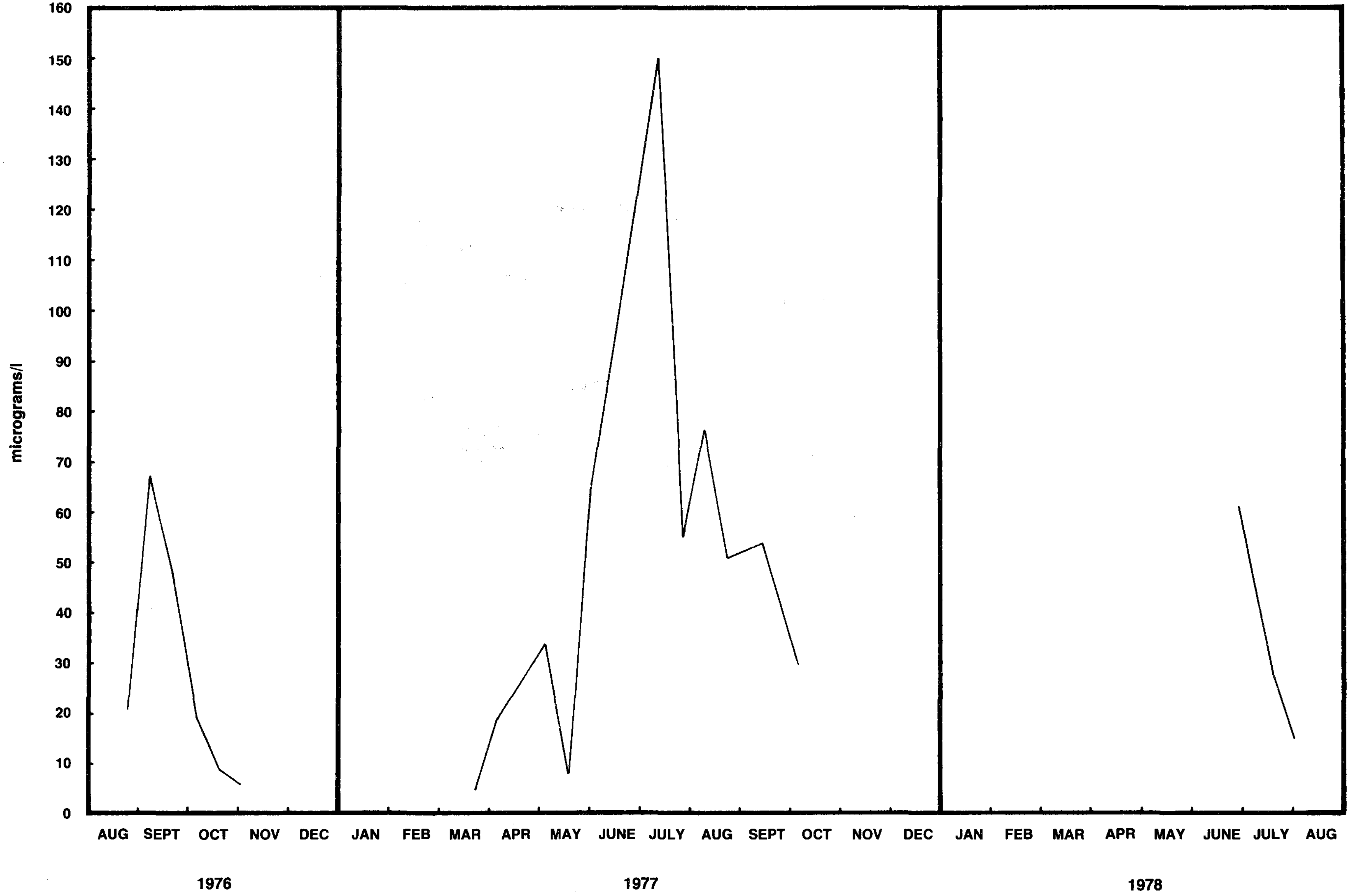
CHLOROPHYLL A (μg/l)

STATION 3



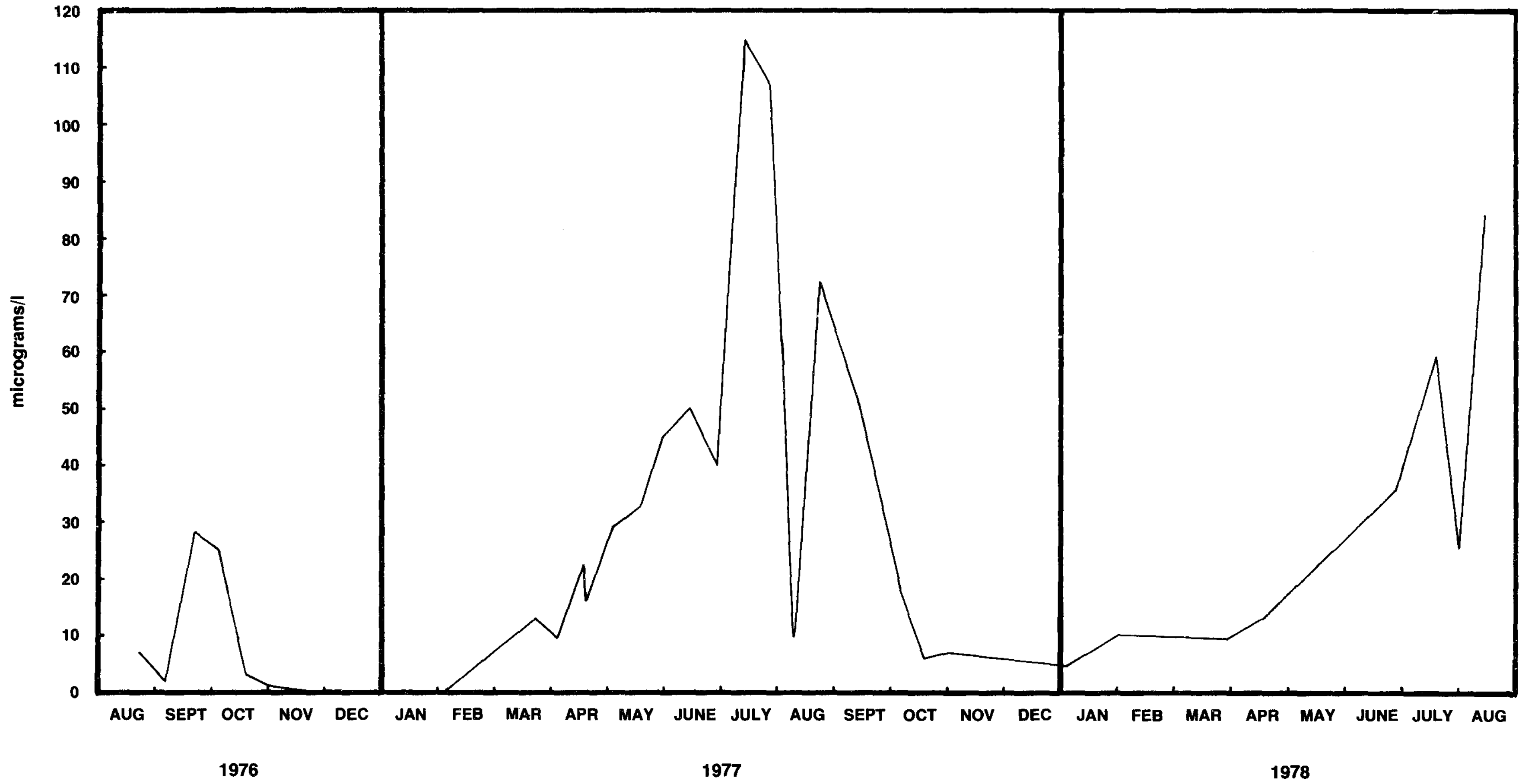
CHLOROPHYLL A ($\mu g/l$)

STATION 4



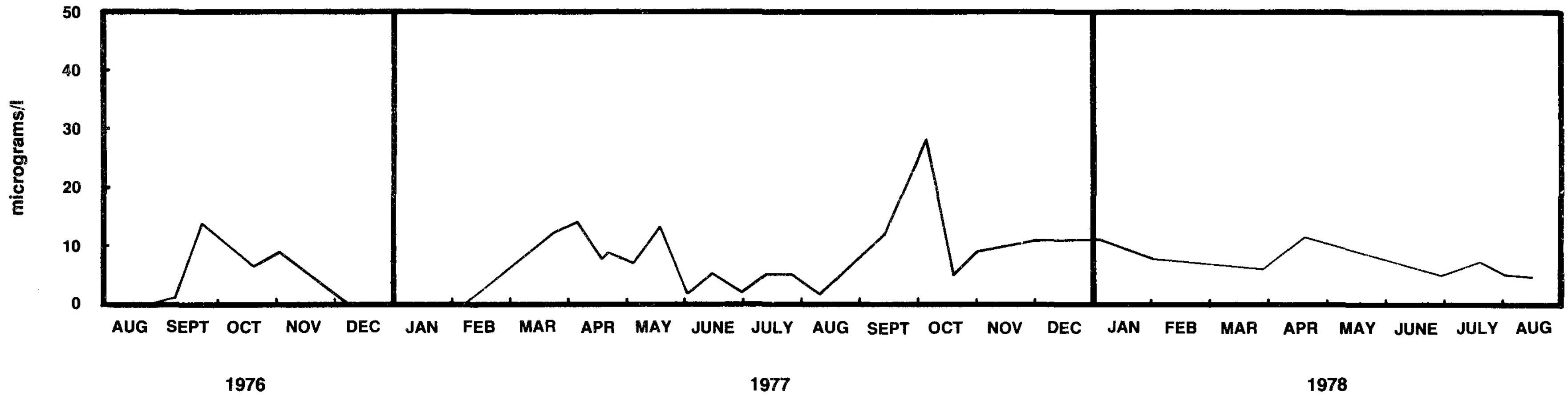
CHLOROPHYLL A ($\mu g/l$)

STATION 5



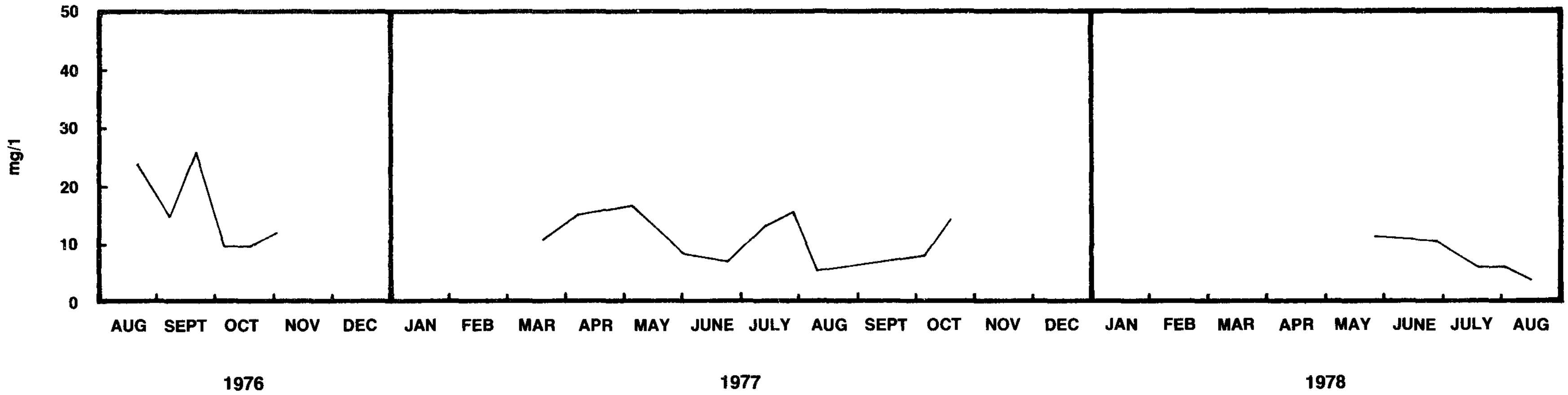
CHLOROPHYLL A (μg/l)

STATION 6



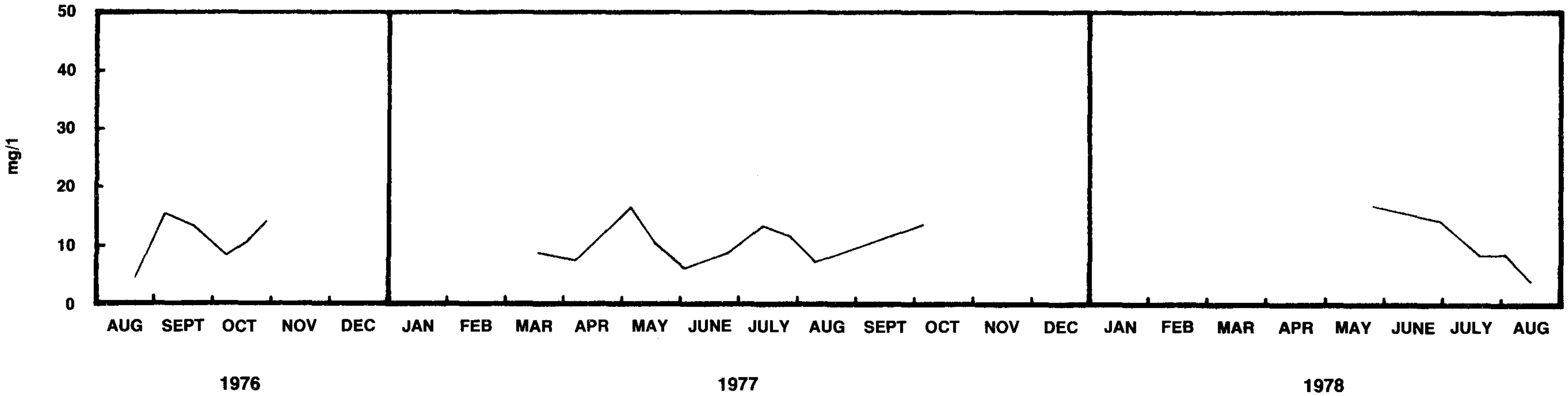
CHLOROPHYLL A (μg/l)

STATION 1

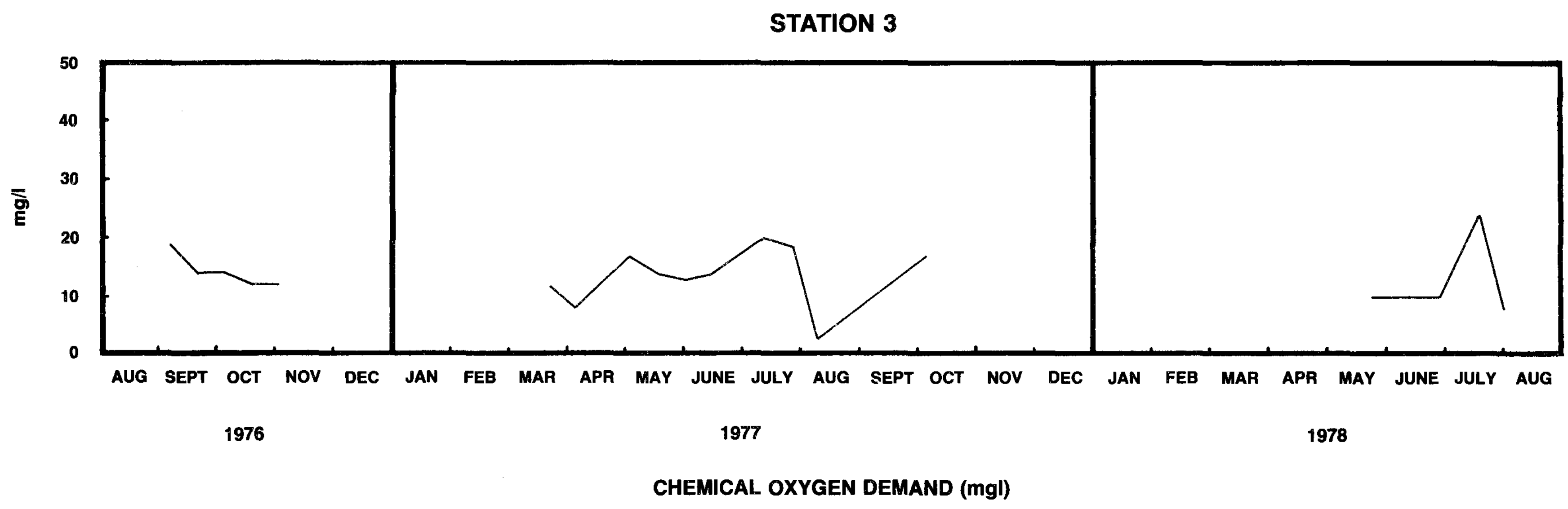


CHEMICAL OXYGEN DEMAND (mg/l)

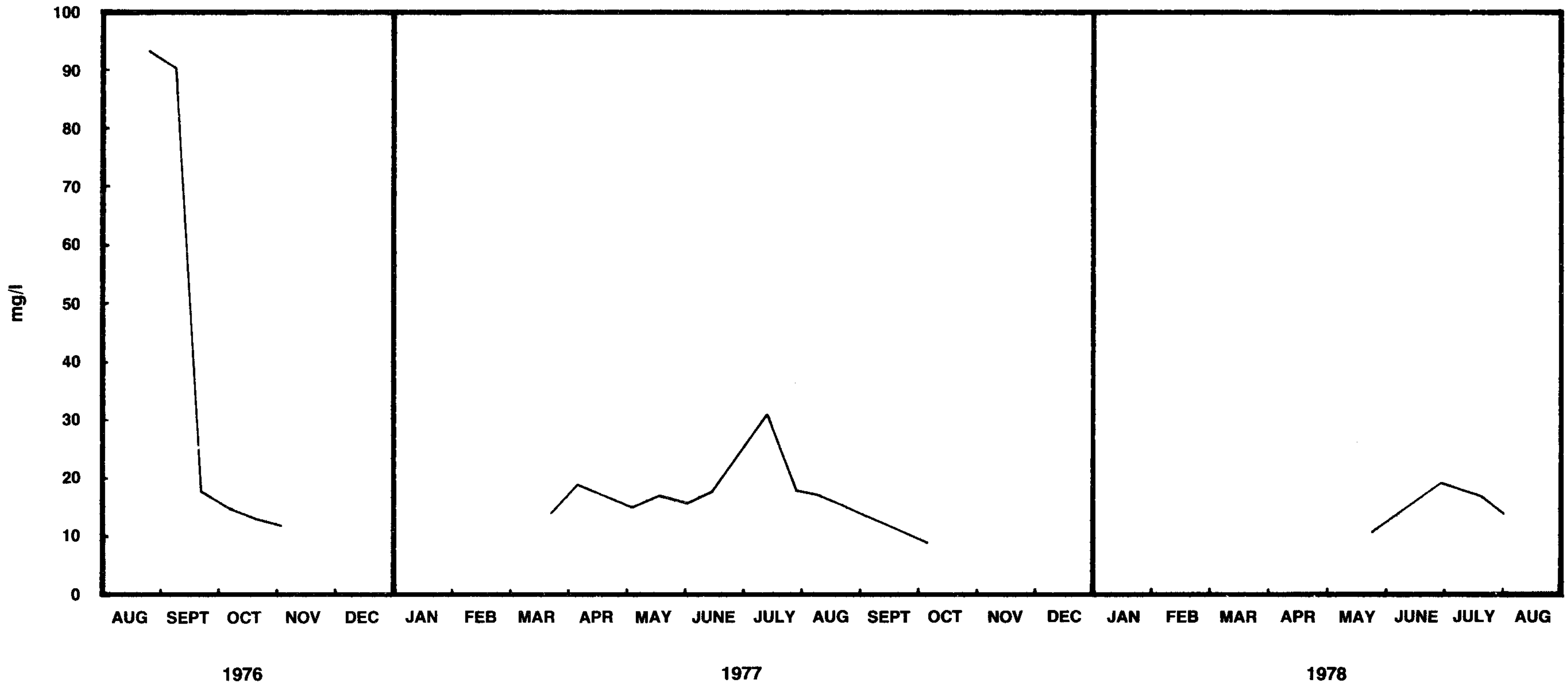
STATION 2



CHEMICAL OXYGEN DEMAND (mg/l)

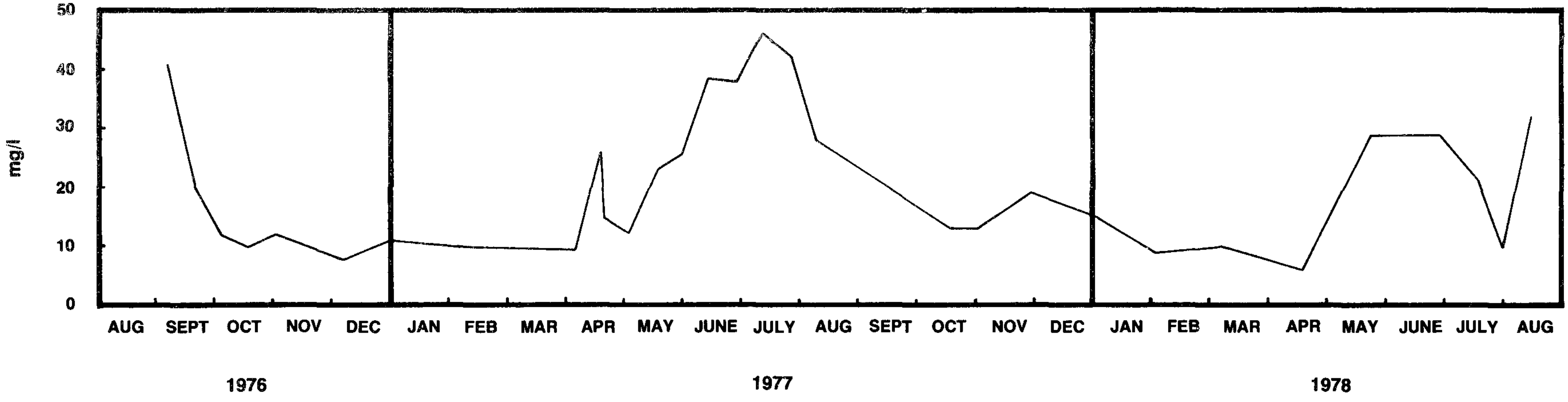

STATION 3
mg/l
50
40
30
20
10
0
AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG
1976
1977
1978
CHEMICAL OXYGEN DEMAND (mgl)

STATION 4



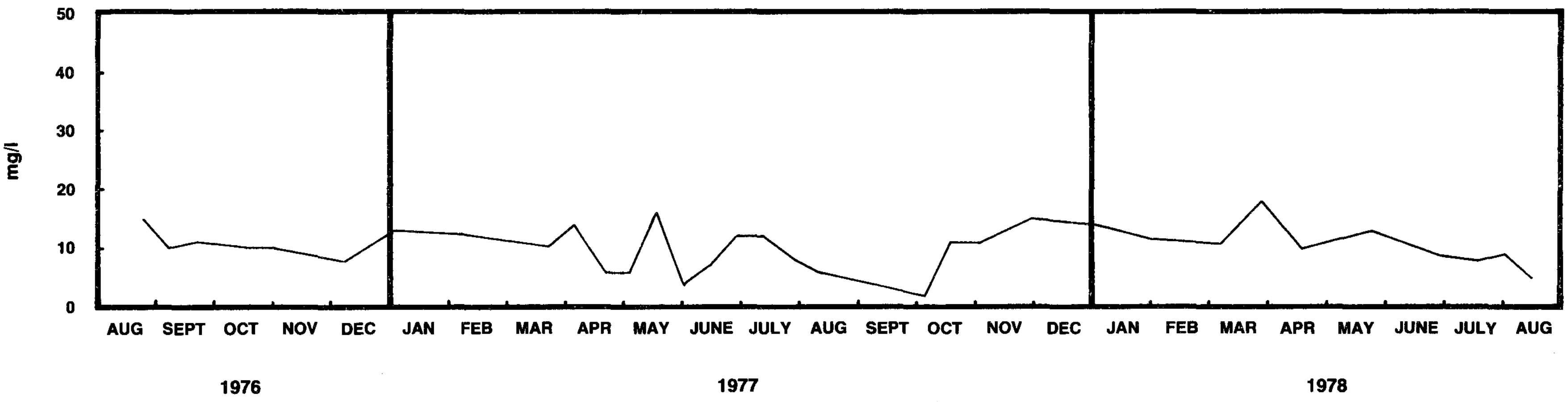
CHEMICAL OXYGEN DEMAND (mg/l)

STATION 5



CHEMICAL OXYGEN DEMAND (mg/l)

STATION 6



CHEMICAL OXYGEN DEMAND (mg/l)