MICROBIAL PLUGGING OF URANIUM MINE TAILINGS TO PREVENT ACID MINE DRAINAGE
FINAL REPORT

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by

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ABSTRACT

Four test conditions and a set of controls were used to examine the best conditions for microbial cap formation. The following conditions were executed in triplicate (1) inoculation of three columns with Ultramicrobacteria (UMB's) and addition of liquid nutrient (BHI + sucrose); (2) inoculation with UMB's, liquid and solid nutrients (Stillage concentrate), (3) addition of the same as the previous set plus calcium and (4) only liquid nutrient was added. The control maintained a constant pH around 3, an Eh higher than 415 mV, an oxygen level always higher than 5.1 mg/L. However, the Fe content in general decreased over time which was unexpected. The series with UMB's, liquid and solid nutrients maintained a lower Eh than the other series for the longest period of time followed by the series of columns with liquid nutrient only. All conditions tested were generally better than the controls in increasing the pH and also in reducing the Eh of the effluent but nothing can be concluded with respect to the dissolved oxygen and iron contents due to continuous variations in the results. There was a significant decrease in the redox potential of the permeates, however none of the conditions tested completely reduced the permeability of the tailings over a long period of time. The scavenging of the oxygen and the increase in pH by the heterotrophs help reduce AMD generation by preventing growth of **Thiobacillus ferrooxidans**. The use of the UMB, **Klebsiella oxytoca** a heterotrophic strain, is not essential since the results of uninoculated columns with liquid nutrient only were equivalent to the columns with liquid nutrients and UMB's. It is likely that the nutrients increased the metabolic activity of the indigenous heterotrophs already present in the tailings.

Keywords: Acid Mine Drainage, Ultramicrobacteria, Microbial Plugging, Microbial Capping

PRÉVENIR LA FORMATION DE DRAINAGE MINIER ACIDE - RAPPORT FINAL

par

L. Lortie, M. Skaff et W.D. Gould

RÉSUMÉ

Quatre conditions expérimentales avec témoins ont été étudiées pour déterminer laquelle permettrait de mieux former une couche microbienne. Les analyses ont été effectuées en triplicata (1) trois colonnes ont été inoculées avec des ultramicrobactéries (UMB) et additionnées de nutriments liquides (BHI + sucrose); (2) trois ont été inoculées avec des UMB, et additionnées de nutriments liquides et solides (Concentré de brasserie); (3) trois ont été préparées comme (2) avec en plus du calcium et (4) trois ont été additionnées de nutriments liquides sans être inoculées. Le pH des témoins s'est maintenu à environ 3, le Eh à plus de 415 mV et le niveau d'oxygène à plus de 5.1 mg/L. Cependant, le contenu en Fe a en général diminué avec le temps, ce qui n'était pas prévu. Les colonnes inoculées et additionnées de nutriments liquides et solides ont conservé un Eh plus bas que celui des autres colonnes pour une plus longue durée de temps, suivi par les colonnes avec seulement des nutriments liquides. Toutes les conditions étudiées permettaient en général de mieux augmenter le pH et réduire le Eh de l'effluent que ne le faisaient les témoins, mais on ne peut pas tirer de conclusion pour l'oxygène dissout et le contenu en fer car les résultats variaient continuellement. Il y avait une baisse significative du potentiel d'oxydo-réduction des perméats, cependant aucune des conditions étudiées n'a complètement permis de réduire la perméabilité des résidus sur une longue période de temps. L'utilisation de l'oxygène et l'augmentation du pH par les hétérotrophes aident à réduire la production de DMA en empêchant la croissance de **Thiobacillus ferrooxidans**. L'utilisation d' UMB, **Klebsiella oxytoca** une souche hétérotrophe, n'est pas essentielle puisque les résultats des colonnes avec seulement des nutriments liquides, étaient semblables aux résultats obtenus avec les colonnes inoculées. Les nutriments augmentent probablement l'activité métabolique des bactéries hétérotrophes qui sont déjà présentes dans les résidus.

Mots-clés: Drainage minier acide, Ultramicrobactéries, Recouvrement bactérien

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OBJECTIVE

Previous results have shown that a bacterial cap can be formed consisting of more than 10^5 bacteria per gram of tailings and is capable of scavenging oxygen from the interstitial water. However, since it did not reduce the permeability of the coarse tailings, the cap was not considered completely satisfactory. The objective of the present study was to determine if a microbial cap capable of reducing both the penetration of oxygen and water can be formed. A successful cap would reduce both the water permeability of the tailings as well as the oxygen content of the permeate.

BACKGROUND

Acid mine drainage results from the production of H_2SO_4 in sulphide containing tailings derived from ores bearing pyrite and pyrrhotite minerals via chemical and biological processes that require the presence of oxygen. In natural soils, pyrite is not oxidized because of the vigorous growth of bacteria in the nutrient-rich surface horizons. The heterotrophic bacterial activity in natural soils scavenges oxygen that would otherwise be available for the oxidation of sulphide minerals. A strategy is proposed to develop an oxygen excluding surface layer (bacterial cap) on tailings by top dressing tailings with ultramicrobacteria (UMB's) and nutrients. Already, ultramicrobacteria have shown success in the plugging of permeable formations in oil reservoirs in order to prevent a breakthrough during water injection in secondary oil recovery. In the present study, the bacterial growth of UMB's would consume oxygen and the biomass produced would block the pore spaces. Oxygen diffusion would be decreased due to the reduced permeability so that deeper layers of soil become anaerobic, preventing growth of **Thiobacillus ferrooxidans**, which would oxidize metal sulphides to sulphuric acid and soluble metals. This would greatly reduce or prevent the oxidation of metal sulphides within the tailings and thereby prevent the formation of acid mine drainage (AMD). Once the cap has been developed, it is expected that cap integrity would be maintained for a period of six months to a year. Incremental nutrient additions would probably be necessary to maintain the microbial cap. If a vegetative cover was established on the tailings, sufficient nutrients from the vegetation root exudates would be produced to maintain a metabolically active cap.

MATERIALS AND METHODS

Procedures

The experimental design and the procedures used in these studies were discussed with Mr. Ken Wheeland of Noranda and Dr. Ron McCready of C.A.R.E. before the experiments were initiated.

Tailings

Coarse oxidized uranium mill tailings from Denison Mines in Elliot Lake were tested. Their particle size distribution, general mineralogical and chemical properties were given by C.A.R.E. in the previous update report of September 1992 (Appendix - E). New tailings samples were also analyzed for calcium, iron, sulphate and sulphide contents. The results showed variations in the calcium content depending where the sample was taken. For example a sample taken at the top of the bucket had an average of 0.27 % Ca by weight, if taken in the middle 0.57% and at the bottom 0.19%. The average of these results was found to be 0.34% which is very close to the C.A.R.E result of 0.28%. The percentage by weight of Fe, S and SO_4 were 1.0, 1.3 and 2.2%, respectively.

Set-up of Columns

Five series of different conditions performed in triplicate including a series of controls were tested to verify the formation of the best cap. A total of fifteen columns (6.2 cm I.D. x 31 cm height) were filled with 1.5 kg wet weight of unoxidized tailings. The bottom of each column was packed with quartz (+¼ -⅜") and glass wool to retain the tailings in the columns. Each column was prepared independently. A slurry consisting of 500 mL tap water and 1.5 kg tailings was mixed and poured into each column. Another 500 mL was used to rinse residual tailings in the bucket. Columns which did not visually appear to be homogeneous were repacked. When all the columns were packed, water was added to the top of the tailings and allowed to settle overnight. The water was completely drained to remove any oxidation products and thereafter water was constantly kept on the tailings until the beginning of the experiments.

The day before the inoculation of the columns, a volume of 200 mL of tap water was added to each column and allowed to drain. Samples were taken at specific times in order to determine their initial permeability prior to the addition of bacteria and nutrients.

Inoculation and Nutrient Feeding

A volume of 100 mL of bacterial solution of UMB's (10^8 starved bacteria/mL of **Klebsiella oxytoca**) prepared by C.A.R.E was added to columns 4 to 12 while 100 mL of water was added to column series (1, 2, 3) and (13, 14, 13) on May 27th. The columns were all drained until the inoculum or water level was below the surface of the tailings then nutrients were added on May 28th. A volume of 100 mL of liquid nutrients (Brain Heart Infusion broth (BHI) 1/10 + sucrose (1%) was added to column series 4, 5, 6 and 13, 14, 15. To columns 7, 8, and 9, 100 mL of a preparation of liquid nutrients and solid nutrient (Stillage concentrate 0.2%, pH 3.5 with BHI final pH is 7.3). One hundred mL of the preceding nutrients with $CaSO_4$ (17%) in addition was poured into columns 10, 11 and 12. A chemical analysis of the stillage concentrate used as the solid nutrient was performed as mentioned in the proposal. The acetic acid content was 2.3 g/L, lactic acid content 7.6 g/L, propionic acid 3 g/L, and organic carbon 42 g/L. The percentage of calcium, nitrogen and sodium were respectively 0.04, 0.21 and 0.03%.

The nutrients were all drained until they reached the surface level of the tailings before shutting off the clamps. Once all clamps were closed, 5 mL of water was added to the top of the tailings in each column. Thus, the surface of the tailings was consistently kept moist for the duration of the experiments. Another nutrient addition was carried out one week after the initial addition on June 4th, this day corresponded to the first day of measurements. Oxygen permeability was monitored by measuring Eh and dissolved oxygen. Water quality was monitored by pH and total iron. At this time no more calcium was added to columns 10, 11, and 12. Nutrients were also added on July 29th, August 26th and September 16th.

Precipitation Events

A volume of 100 mL of tap water was added to each of the columns, June 17th, three weeks after the initial inoculation to simulate precipitation events. Once all columns were set, a timer was started to measure the flow rate. The volume of permeate recovered during the time elapsed for the water level to reach the surface of the tailings was used to calculate the flow rate in mL/min. This procedure was carried out on a weekly basis. The permeates were collected in narrow-mouth bottles to minimize infiltration of atmospheric O_2. Once the water was drained, the dissolved oxygen was immediately measured with a portable oxygen probe (Orion Research Model # 97-08) followed by the measurement of Eh and pH. The permeates were then acidified with H_2SO_4 to stabilize the iron. The total iron was determined by Atomic Absorption Spectrophotometry.

RESULTS AND DISCUSSION

The project began on May 28th with the inoculation and the first addition of nutrients to the columns (Table 1). Results were recorded from June 4th until September 16th, they are listed in Tables 2 to 6. The minutes from the meeting held on September 30th are provided in Appendix - A. The economics of the process written by Dr. Ron McCready is in Appendix - B. Table 7 in Appendix - C includes the averages and standard deviations used for Figures 1 to 16. In order to improve clarity and ease of interpretation the error bars are only included in the figures when the experimental values are significantly different from the controls.Graphs comparing different treatments to the controls for each parameter tested are given in Appendix - D. Appendix - E is a summary of results for each of the columns versus time.

Two of the treatments; one with UMB's plus liquid and solid nutrients (Figure 2) and the other one with liquid nutrient alone (Figure 4) both caused a consistent increase in effluent pH. An increase in effluent pH was observed between days 20 to 55 for UMB's plus liquid (Figure 1) and between days 20 to 40 followed by a decrease and increase again between days 62 to 83 for UMB's plus liquid and solid nutrients and calcium (Figure 3). Except for the addition of the UMB's plus nutrients and calcium (Figure 7) a consistent decrease in Eh was observed for all of the treatments (Figures 5, 6 and 8). No significant difference in permeability (measured flow rate) was observed between the controls and the various treatments (Figures 9, 10, 11 and 12). Although no consistent decrease in oxygen was observed for the various treatments, all of them did show significant lower dissolved oxygen values than the controls at the end of the experiment (Figures 13, 14, 15 and 16). The soluble iron in the effluent from the controls and all of the treatments decreased during the course of the experiment except for column 4, 5 and 6 (Figures 17, 18, 19 and 20). No differences were observed between the control columns and the various treatments with respect to the total iron contents of the effluent.

Most of the data shows high variability for most of the experimental time period. In future work it would be important to closely control the level of the water table and the timing of nutrient addition. Only the pH and Eh were significantly affected by the treatments of the parameters measured. Some decrease in dissolved oxygen was observed for the nutrient treatments at the end of the experiment. Of the two major criteria for successful cap formation (1) decreased permeability and (2) oxygen scavenging by the bacteria only the latter criterion was attained with some degree of success. The addition of liquid nutrients alone was equally as successful as the treatment in which UMB's were also added. It appears that the addition of UMB's is not necessary as the indigenous bacterial population will carry out the same function. The treatment costs will be significantly lower if a bacterial inoculant does not need to be added to the tailings.

CONCLUSIONS

It was not demonstrated that a microbial cap could significantly reduce the permeability of the tailings. Removal of oxygen from the permeates was noticeable as Eh values as low as -181 mV and low dissolved oxygen values were obtained. The results obtained from the inoculated columns with added nutrients were equivalent to the columns with nutrients plus UMB's. The addition of UMB's to the tailings is not necessary because indigenous bacteria are also able to colonize the surface of the tailings. It would be less expensive if the inoculation step could be avoided. Although a reduction in permeability was not observed in our experiments, it is possible that in fine-textured tailings a significant reduction in water permeability would be observed.

RECOMMENDATIONS

1. Microbial plugging of fine tailings should be evaluated further with the following experimental modifications:
    - (a) Use of humidity cells;
    - (b) Experimentation with different acid generating tailings;
    - (c) Longer term experiments;
    - (d) More frequent nutrient addition; and
    - (e) Analyze sulphate content of leachates.

2. Because microbial plugging of tailings is presently being investigated further by private industry we recommend that no further studies be undertaken by CANMET at the present time.

Table 1. Project schedule

Dates	Inoculation and feeding days	# Days after first sampling	# Weeks since inoculation
May 28	Inoculation and first feeding		0
June 4	Feeding and beginning of sampling	0	1
June 17		13	3
June 24		20	4
July 2		28	5
July 8		34	6
July 15		41	7
July 22		48	8
July 29	Feeding	55	9
August 5		62	10
August 12		69	11
August 19		76	12
August 26	Feeding	83	13
September 2		90	14
September 9		97	15
September 16	Feeding	104	16

Table 2. Data summary for columns 1, 2, 3

CONTROLS															
DAYS	RATE (mL / min.)			OXYGEN (ppm)			Eh (mV)			pH			Fe (ppm)		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	1.1	0.6	1.1	5.17	6.63	6.13	452	456	467	2.73	2.58	2.77	182.0	395.0	72.0
13	0.6	0.6	0.5	7.67	7.67	6.14	438	438	441	2.77	2.77	2.67	176.0	261.0	187.0
20	1.3	1.6	1.5	7.76	5.80	7.35	430	451	453	2.79	2.86	3.54	124.0	175.0	129.0
28	1.0	1.0	1.6	7.69	5.54	6.11	425	435	441	2.82	2.63	2.81	117.0	170.0	116.0
34	1.2	1.3	1.3	6.45	5.63	6.38	437	459	469	2.77	2.52	2.85	126.0	233.0	97.0
41	1.6	1.7	1.3	5.53	6.96	6.23	445	417	443	2.49	2.69	2.91	248.0	146.0	93.0
48	1.4	1.4	1.3	6.18	7.40	7.08	434	429	432	2.40	2.59	2.73	131.0	240.0	93.0
55	1.7	1.8	1.5	5.70	6.55	5.78	437	434	431	2.65	2.72	2.85	177.0	92.0	88.0
62	1.7	1.0	1.4	6.40	7.67	6.38	444	446	455	2.70	2.80	2.68	84.4	60.5	106.0
69	2.2	0.8	1.5	6.14	8.40	6.05	486	503	505	2.79	2.72	2.69	52.9	56.6	94.0
76	2.0	0.8	1.3	6.28	6.26	5.94	437	445	451	2.94	2.91	2.72	35.8	43.6	115.0
83	2.0	1.1	1.7	5.35	6.76	5.76	436	443	451	2.99	3.09	2.74	26.2	17.2	92.2
90	1.8	0.7	1.2	7.24	6.64	6.35	430	441	459	3.00	3.18	2.77	30.8	16.3	93.5
97	1.6	0.6	1.2	7.14	8.19	6.75	424	456	466	3.04	3.28	2.85	28.6	7.7	69.5
104	2.0	0.4	1.3	6.56	7.92	6.75	441	533	570	3.02	3.15	2.83	26.2	8.9	55.0

Table 3. Data summary of columns 4, 5, 6

UMB + LIQUID NUTRIENTS															
DAYS	RATE (mL / min.)			OXYGEN (ppm)			Eh (mV)			pH			Fe (ppm)		
	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
0	0.0	0.1	0.1	7.80	7.80	7.80	475	511	451	2.41	2.57	2.88	393.0	259.0	189.0
13	0.5	0.1	0.1	6.27	NA	NA	338	NA	NA	2.90	NA	NA	154.0	62.0	57.0
20	0.2	0.0	0.6	5.67	6.40	6.73	355	403	280	3.52	2.85	3.45	56.0	42.0	34.0
28	0.1	0.0	0.4	6.63	6.85	7.15	127	180	103	4.57	4.33	4.71	177.0	44.0	35.0
34	0.2	0.2	0.6	4.49	5.13	6.57	44	113	40	5.11	5.15	5.35	214.0	104.0	95.0
41	0.0	0.8	0.6	4.38	2.56	4.43	-46	-75	69	6.05	6.24	4.84	87.0	35.0	278.0
48	0.0	0.8	1.4	6.40	4.02	3.64	-35	-54	379	7.11	6.15	2.35	27.5	68.0	505.0
55	0.4	1.2	1.3	4.04	4.68	1.26	-49	391	4	6.32	5.55	2.43	36.0	44.0	720.0
62	1.0	0.9	0.9	5.19	6.03	0.55	-26	242	434	6.22	3.22	2.60	51.4	370.0	408.0
69	0.5	0.6	2.0	5.88	4.63	4.48	-53	388	387	5.83	2.80	2.78	214.0	490.0	262.0
76	0.8	0.5	0.9	5.32	1.32	4.23	-82	416	393	5.27	2.65	2.90	312.0	310.0	109.0
83	0.7	1.1	1.4	5.13	4.64	6.00	-72	368	307	5.64	2.57	3.17	33.3	122.0	55.6
90	1.2	0.5	2.0	4.02	4.33	5.83	-50	393	283	6.19	2.42	3.30	16.5	298.0	110.0
97	1.1	0.3	1.6	3.28	5.18	4.13	-121	420	20	5.68	2.56	4.87	28.0	282.0	197.0
104	1.2	0.3	1.9	3.70	1.48	4.11	-46	433	15	5.06	2.76	5.06	99.0	202.0	167.0

Table 4. Data summary for columns 7, 8, 9

UMB + LIQUID & SOLID NUTRIENTS															
DAYS	RATE (mL / min.)			OXYGEN (ppm)			Eh (mV)			pH			Fe (ppm)		
	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9
0	0.4	1.3	0.0	6.09	5.70	7.03	451	413	569	2.69	2.80	2.57	269.0	282.0	187.0
13	1.9	1.5	0.0	6.06	6.78	NA	327	297	NA	2.85	3.03	NA	98.0	102.0	NA
20	0.8	0.8	0.0	7.05	7.82	NA	238	195	NA	3.59	4.01	2.47	37.0	49.0	157.0
28	0.4	0.5	0.0	7.73	7.89	5.45	18	44	320	4.65	4.71	2.96	103.0	101.0	0.7
34	0.6	0.6	0.0	4.97	6.89	0.73	2	56	-97	5.31	5.10	6.69	113.0	166.0	4.3
41	0.7	0.8	0.0	4.95	4.45	5.73	-60	-55	117	6.15	5.76	7.54	54.0	144.0	5.1
48	1.4	0.9	0.0	4.62	5.11	0.39	-44	-34	-126	6.16	6.02	1.53	36.5	79.0	14.5
55	1.9	0.7	0.0	4.49	6.12	1.38	-35	8	61	4.95	5.94	6.92	161.0	81.0	8.5
62	2.0	0.6	0.7	6.53	7.23	6.25	42	-39	-38	4.12	5.91	6.45	230.0	65.1	14.3
69	2.2	0.9	0.8	4.86	4.50	5.22	-135	-136	-59	4.86	5.57	6.31	109.0	47.0	51.0
76	1.3	0.8	0.9	2.41	4.81	4.68	-142	-119	-66	4.96	5.01	5.92	66.0	65.0	94.0
83	1.2	0.7	1.1	2.87	3.06	6.56	-158	-147	-41	5.49	5.51	7.28	3.3	20.0	6.3
90	2.2	1.1	0.4	4.36	2.10	7.22	-160	-165	-52	5.66	5.68	6.89	3.3	8.3	13.5
97	0.9	0.9	0.5	5.84	5.58	6.67	-150	-126	10	5.84	5.58	5.76	2.1	6.8	97.5
104	1.3	1.0	0.6	4.13	3.96	2.38	-72	-74	-7	5.05	4.91	5.27	29.8	33.7	220.0

Table 5. Data summary for columns 10, 11, 12

UMB + LIQUID & SOLID NUTRIENTS + CALCIUM															
DAYS	RATE (mL / min.)			OXYGEN (ppm)			Eh (mV)			pH			Fe (ppm)		
	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12
0	0.2	1.2	0.1	7.80	5.52	8.83	467	454	548	2.80	2.82	2.76	146.0	103.0	57.0
13	0.4	1.6	1.7	7.73	5.22	7.29	446	505	362	2.71	2.56	2.91	86.0	96.0	18.0
20	0.3	1.7	0.1	8.37	3.97	8.36	260	284	393	3.02	3.22	3.31	19.0	44.0	6.0
28	1.0	1.0	0.3	7.53	7.31	6.80	186	126	110	4.07	4.51	4.72	21.0	84.0	11.0
34	0.5	0.6	0.3	7.37	6.03	6.65	210	51	67	4.85	5.35	5.28	52.0	101.0	13.0
41	2.2	1.6	0.0	4.83	3.78	3.31	-56	-38	-68	5.42	5.70	7.55	112.0	188.0	6.6
48	1.4	0.8	0.7	4.41	5.33	7.24	-21	14	-8	5.58	5.29	5.85	189.5	270.0	56.5
55	1.3	1.1	1.0	6.25	6.32	3.90	75	270	442	4.59	3.05	2.93	229.0	101.0	95.0
62	2.1	0.4	0.1	5.04	4.93	6.62	382	404	547	3.28	3.07	2.73	135.0	184.0	43.7
69	1.6	2.3	0.1	5.44	5.07	8.05	-8	29	520	4.06	3.31	2.82	116.0	115.0	40.7
76	1.5	1.9	0.4	3.84	4.24	6.98	-86	-83	253	4.94	4.62	3.96	346.0	172.0	33.2
83	1.8	1.7	1.6	3.62	2.91	4.10	-22	-75	3	5.49	5.29	5.33	65.1	182.0	103.0
90	1.6	1.5	1.1	1.73	1.85	5.43	-181	-92	-2	6.26	5.92	5.53	5.6	24.0	175.0
97	1.4	1.2	0.8	2.15	3.87	6.47	-160	-125	30	6.27	5.53	4.99	3.4	14.3	224.0
104	1.6	1.2	2.0	1.08	4.03	3.75	-138	-32	23	5.42	4.91	4.89	30.0	81.5	260.0

Table 6. Data summary for columns 13, 14, 15

LIQUID NUTRIENTS																
DAYS	RATE (mL / min.)			OXYGEN (ppm)			Eh (mV)			pH			Fe (ppm)			
	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15
0	0.3	1.3	0.8	6.09	6.19	5.91	473	155	475	2.87	2.74	2.87	122.0	390.0	77.0
13	1.7	1.7	0.7	6.67	6.83	5.88	404	403	402	3.06	3.01	3.06	150.0	332.0	142.0
20	0.7	1.6	0.7	7.12	7.35	7.12	386	375	386	3.34	3.33	3.34	148.0	267.0	65.0
28	1.9	1.6	1.0	5.80	6.70	7.36	361	244	228	3.47	4.37	4.13	50.0	166.0	62.0
34	1.7	1.3	1.2	5.83	6.85	6.84	325	163	79	3.58	5.31	4.59	43.0	180.0	89.0
41	1.7	1.5	1.7	5.94	6.62	5.62	90	-15	60	3.44	6.36	4.25	60.0	49.0	169.0
48	0.2	1.3	1.4	7.02	5.31	5.59	79	-69	414	3.38	6.55	2.44	99.0	65.0	310.0
55	0.1	1.5	1.5	7.90	4.96	3.91	339	-67	420	3.88	6.38	2.52	138.0	62.0	104.0
62	0.5	2.2	1.8	6.83	6.39	4.04	24	-33	447	5.40	6.52	3.58	162.0	31.7	313.0
69	0.7	2.2	1.6	6.62	5.32	5.97	-68	-116	391	5.49	6.43	2.85	140.0	39.4	209.0
76	0.6	1.9	1.5	3.66	5.60	5.01	-127	-111	392	5.13	5.91	2.94	97.0	108.0	61.8
83	0.7	2.1	1.8	2.82	2.38	4.47	-138	-52	11	5.69	5.63	3.74	17.4	50.0	32.1
90	0.8	1.6	2.0	3.98	2.58	3.26	-117	-178	-103	6.08	6.12	4.98	5.1	3.9	59.0
97	0.6	1.4	1.5	2.05	3.48	2.65	-161	-168	-119	5.59	6.30	5.75	8.4	3.8	57.5
104	0.9	1.8	1.7	0.32	4.37	0.78	-99	-107	-154	4.83	5.33	5.44	55.8	29.4	61.5

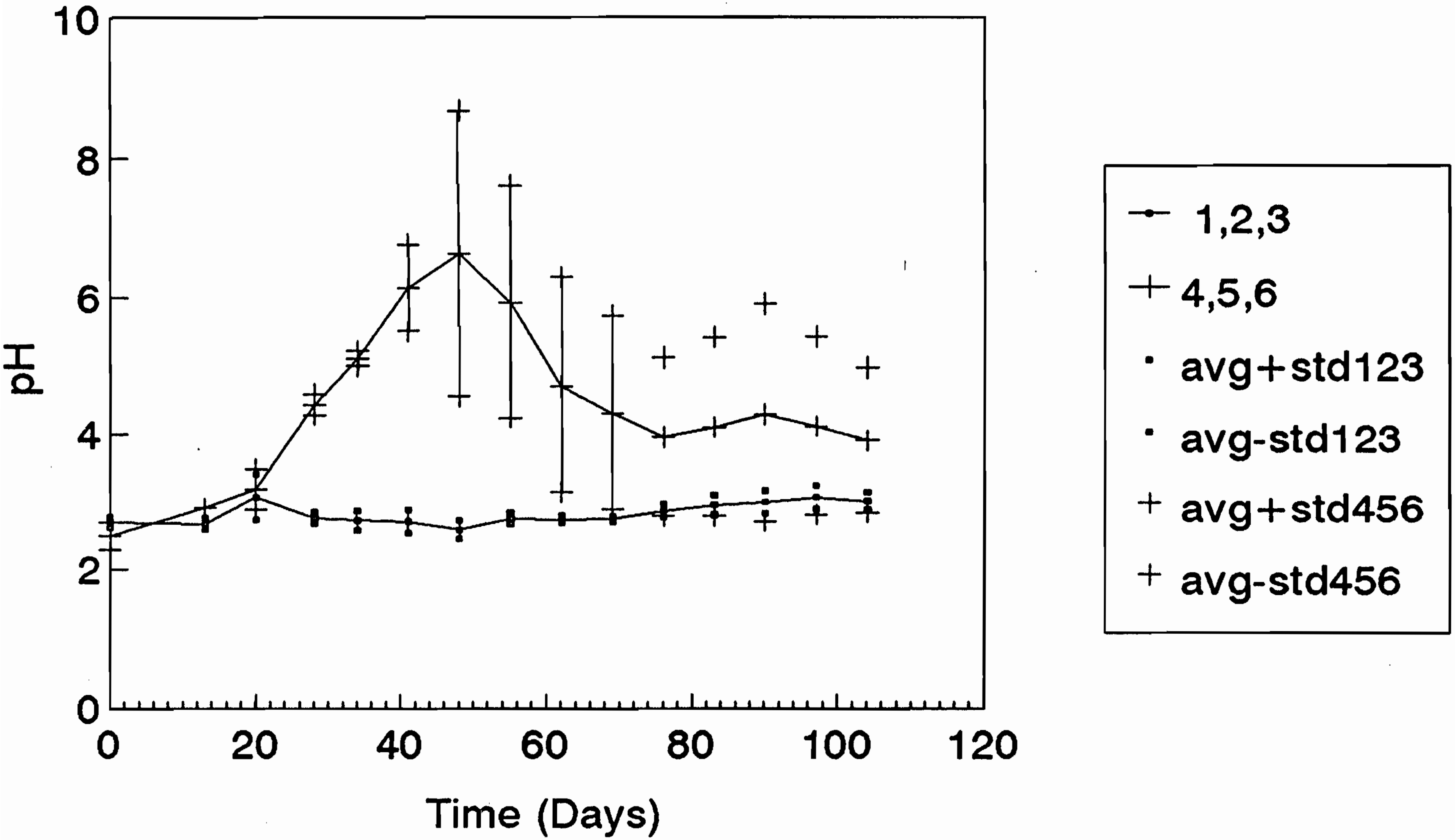

Figure 1. Control pH average compared to columns 4, 5, 6

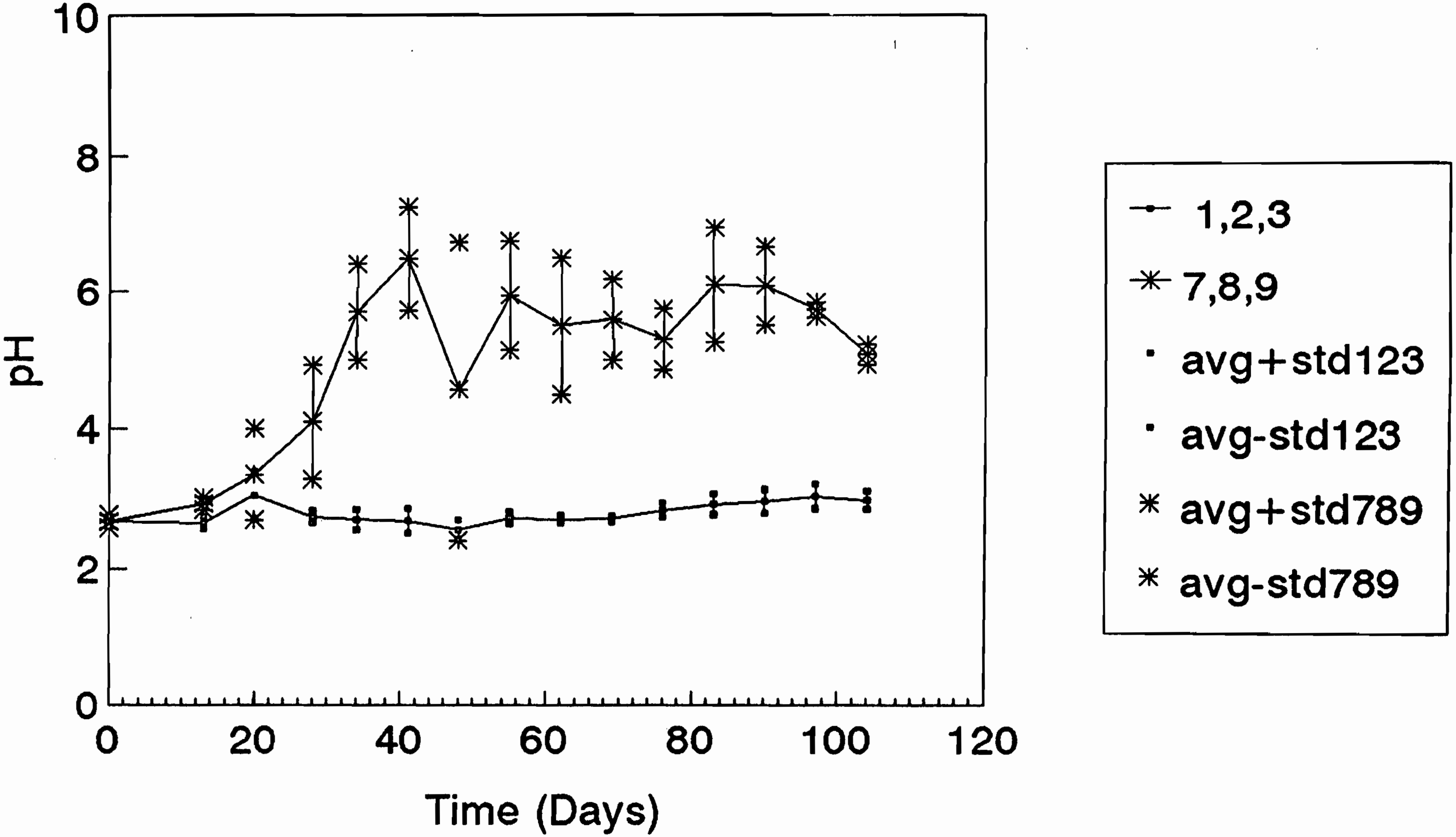

Figure 2. Control pH average compared to columns 7, 8, 9

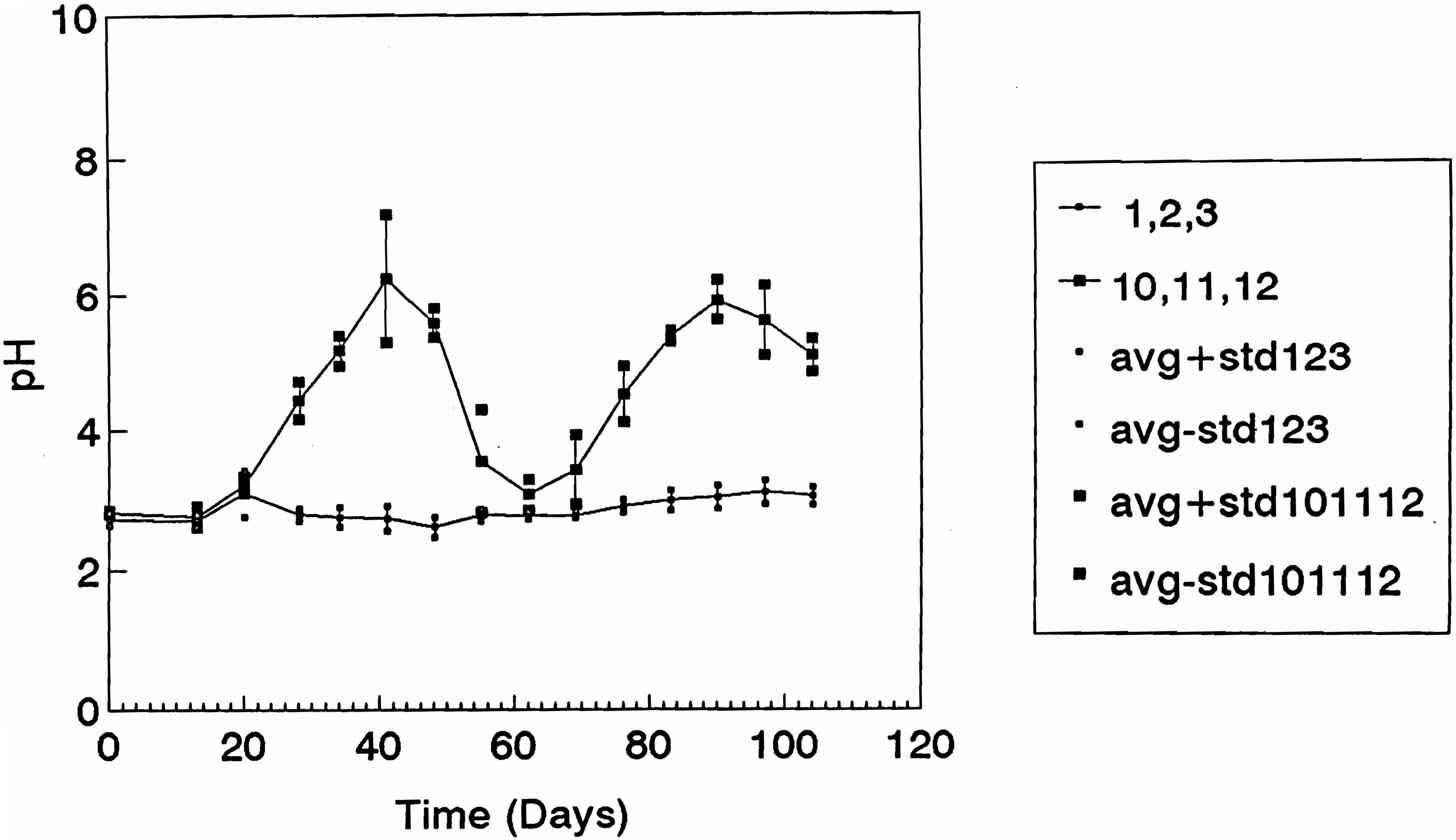

Figure 3. Control pH compared to columns 10, 11, 12

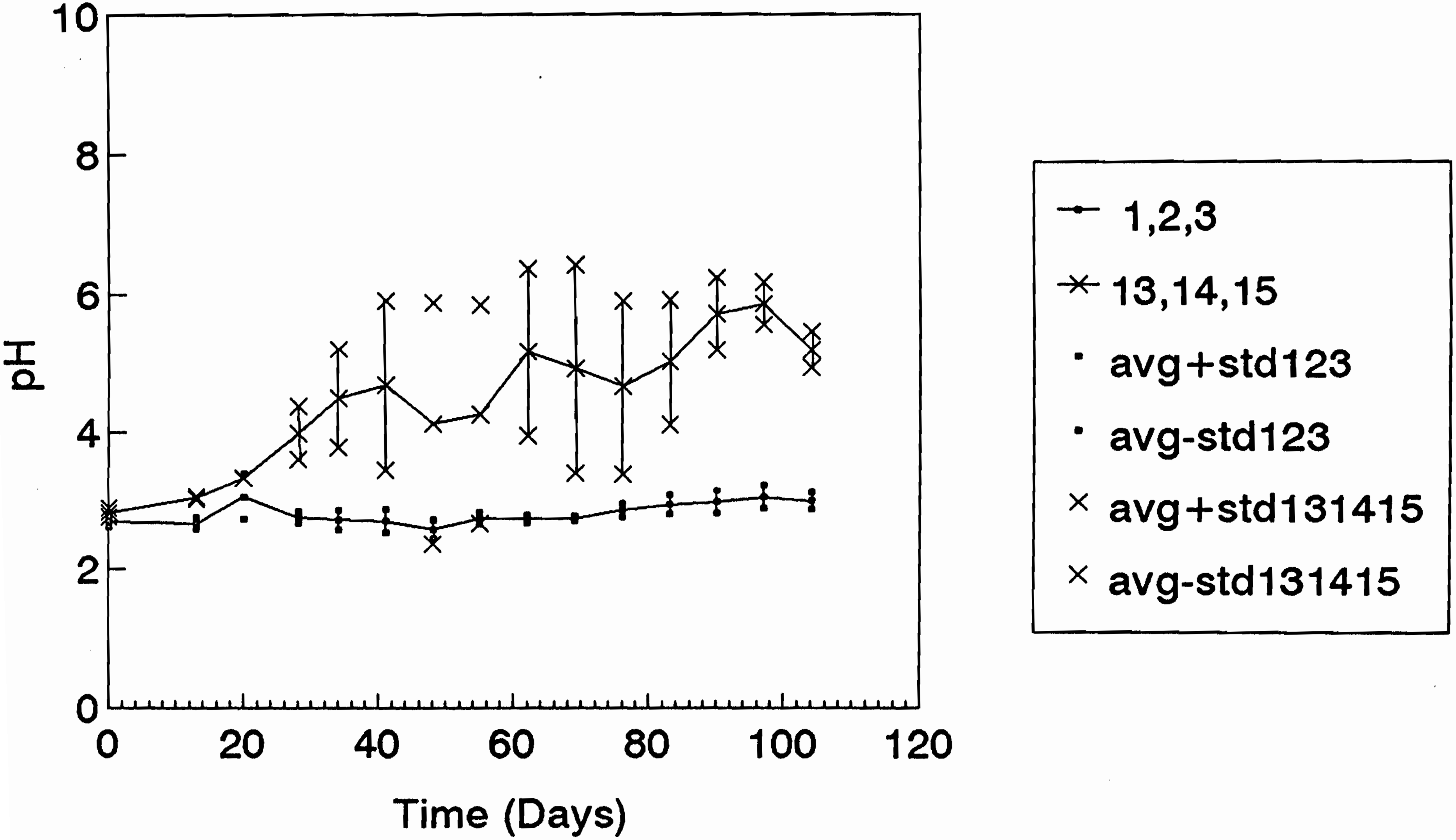

Figure 4. Control pH compared to columns 13, 14, 15

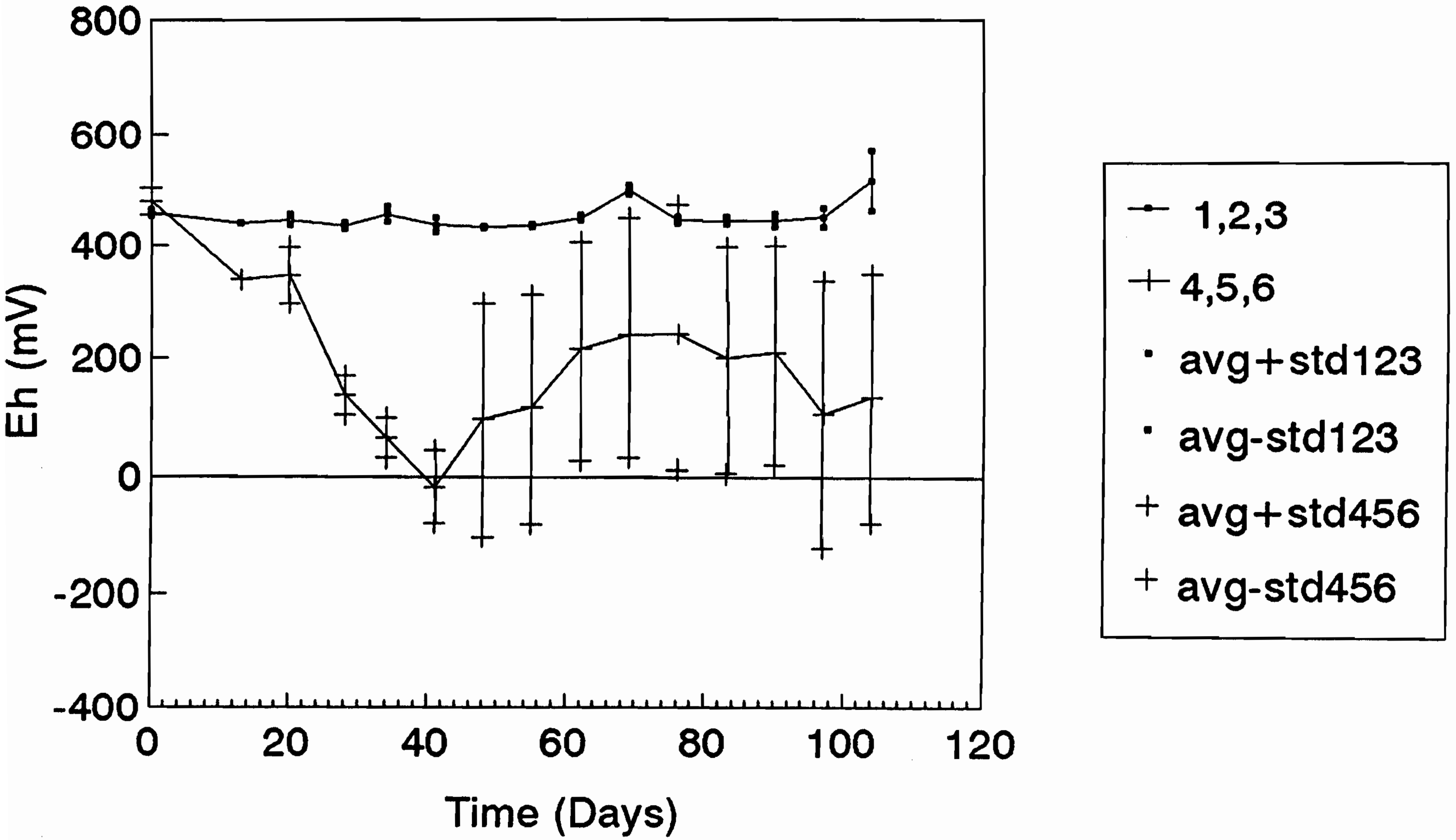

Figure 5. Control Eh average compared to columns 4, 5, 6

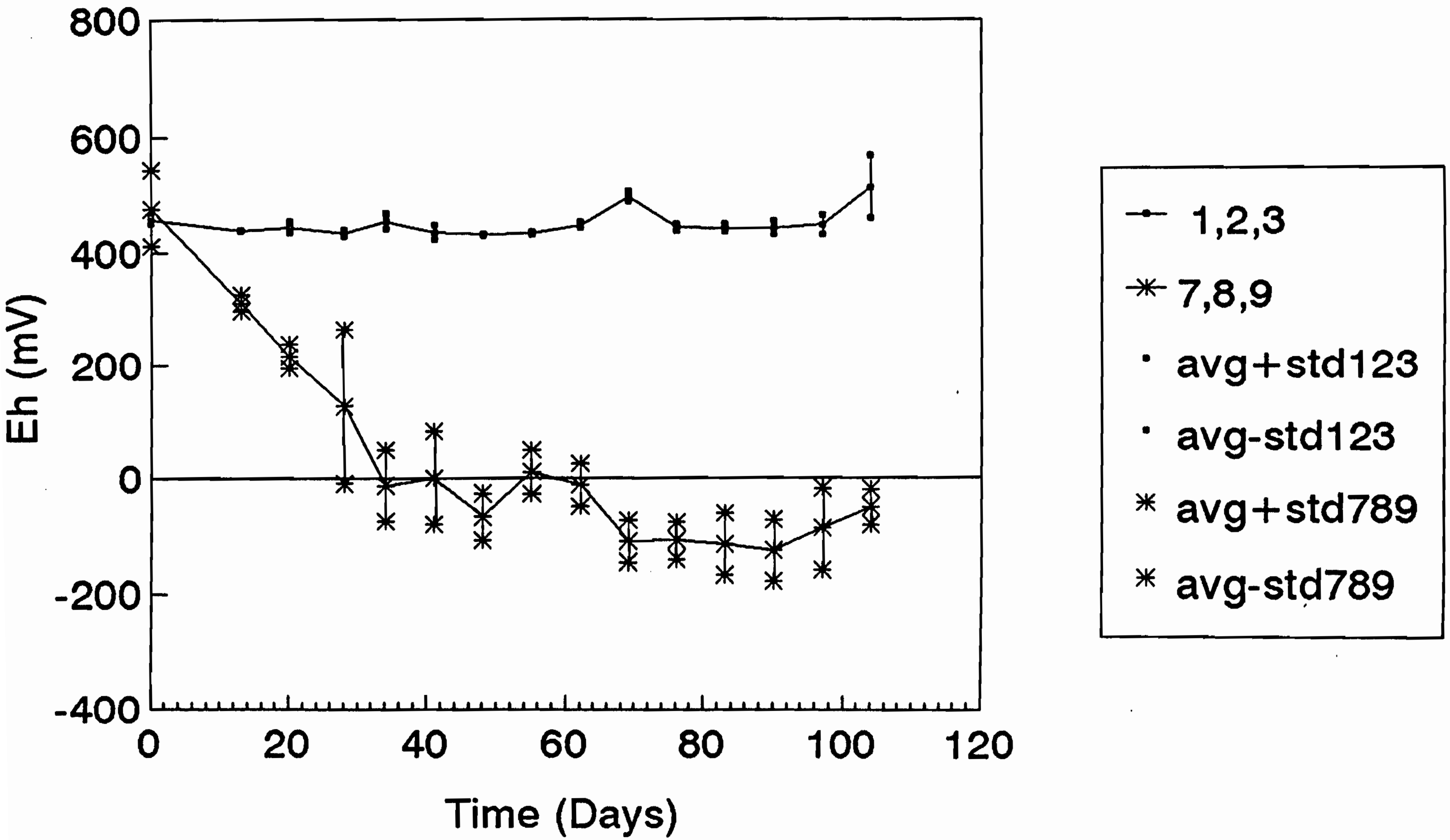

Figure 6. Control Eh average compared to columns 7, 8, 9

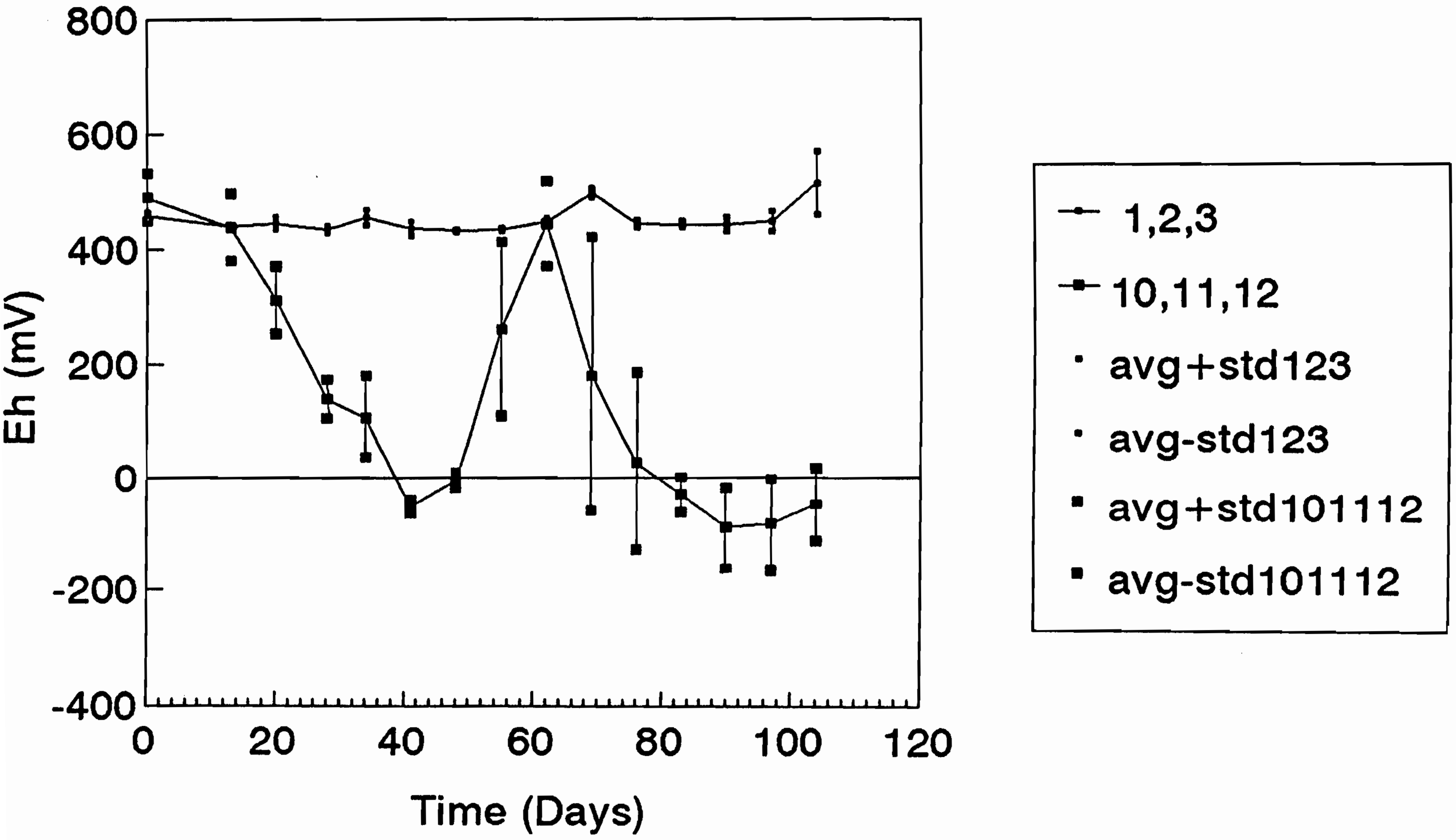

Figure 7. Control Eh average compared to columns 10, 11, 12

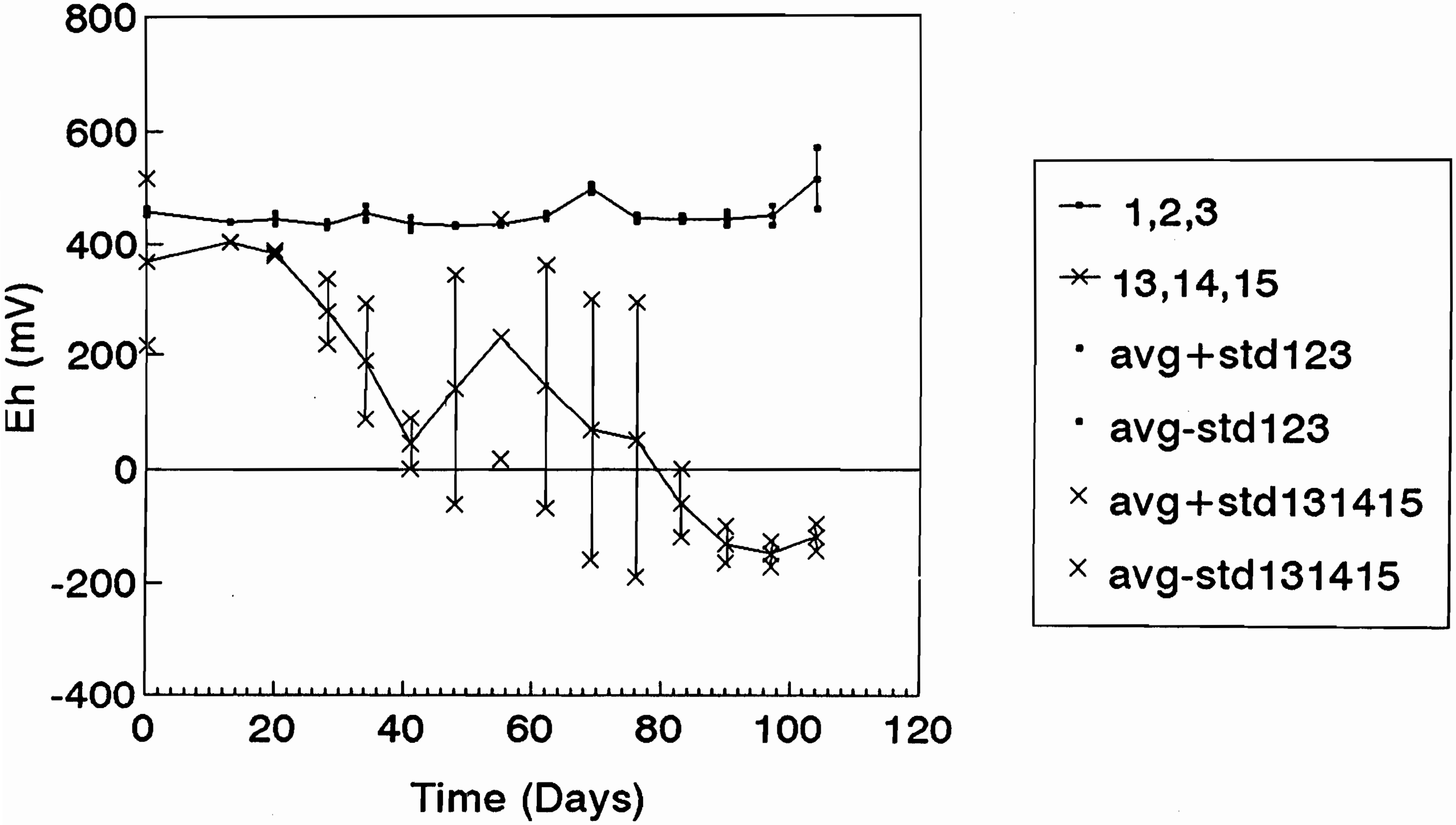

Figure 8. Control Eh average compared to columns 13, 14, 15

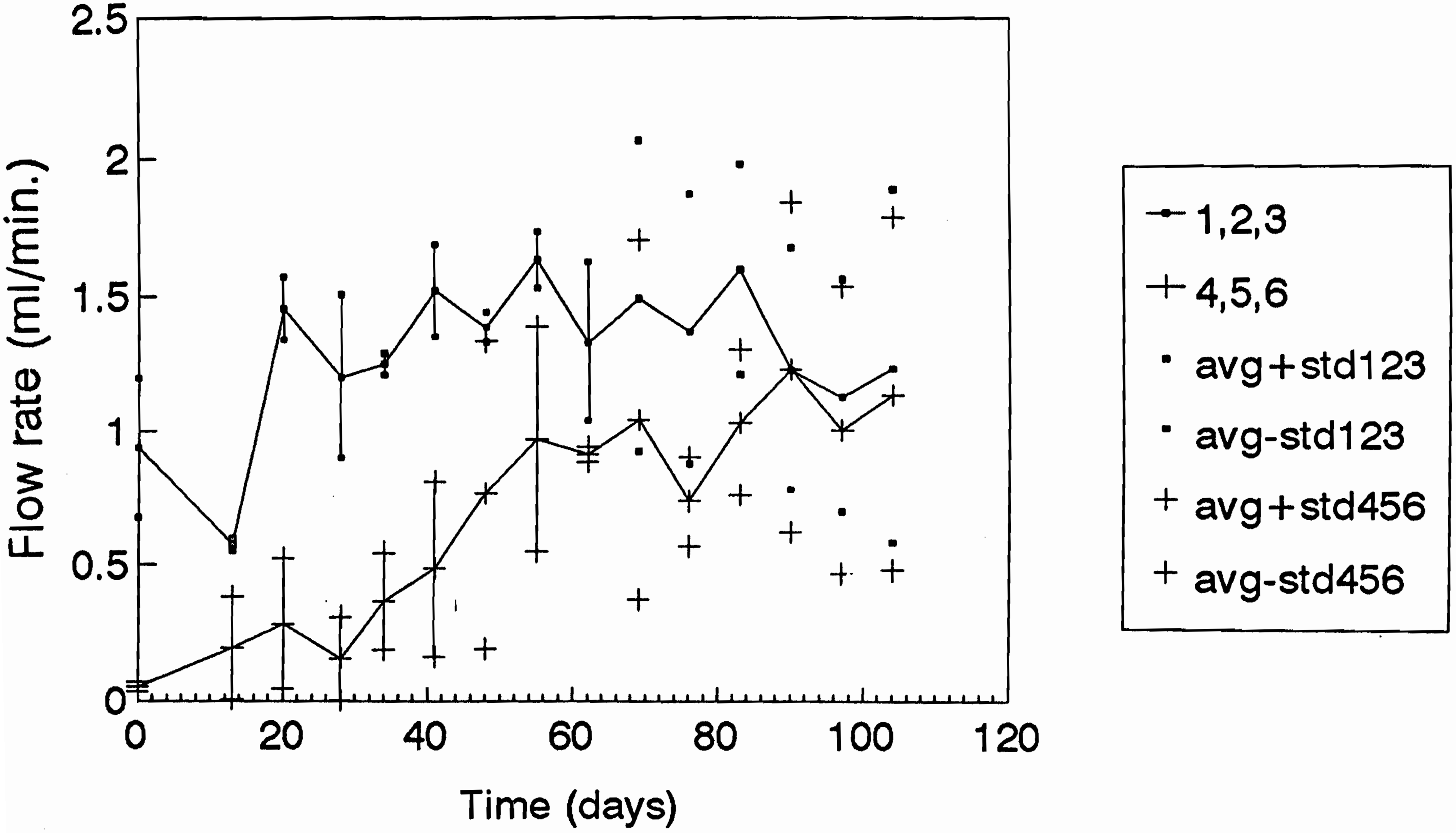

Figure 9. Control flow rate average compared to columns 4, 5, 6

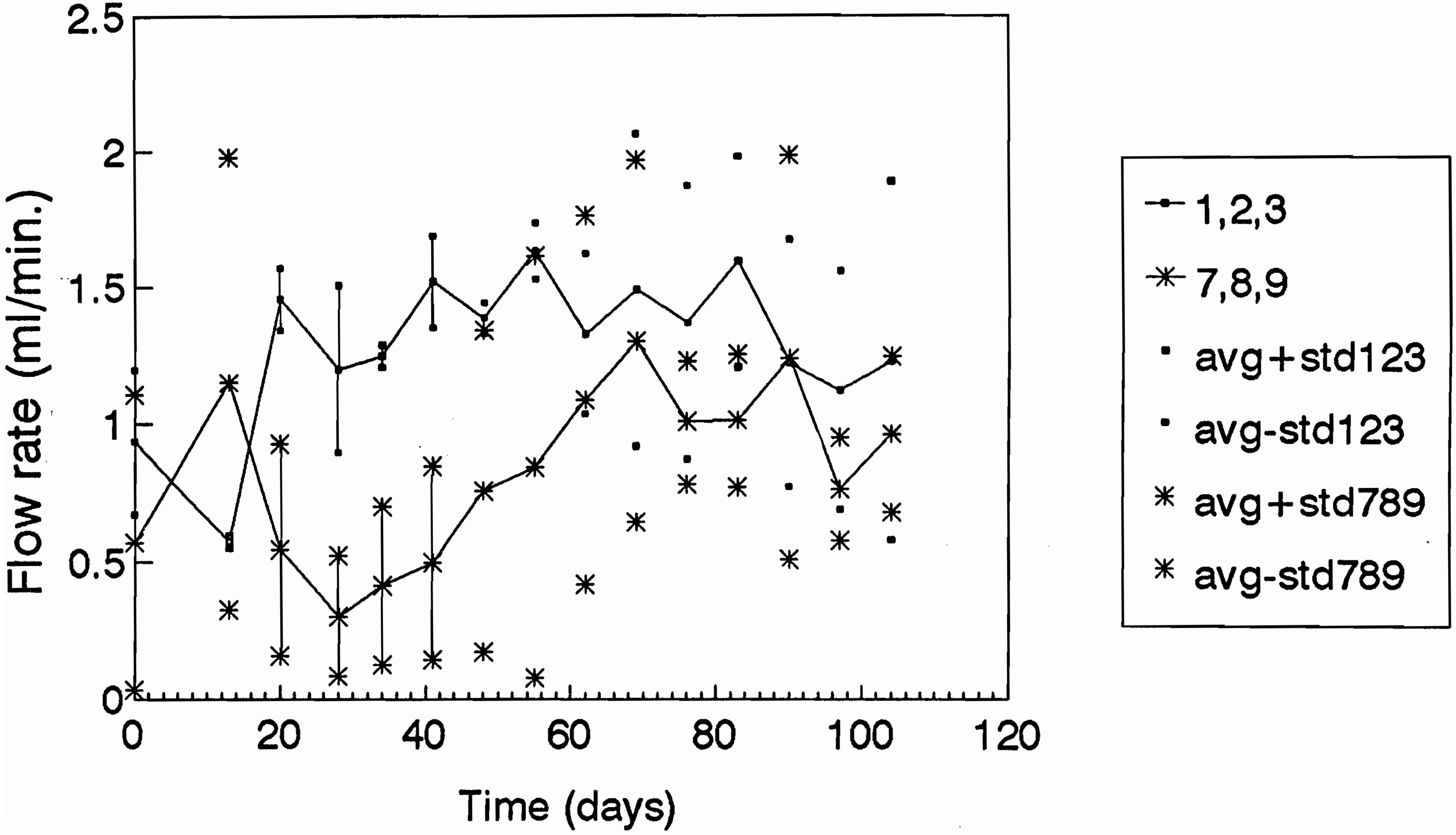

Figure 10. Control flow rate average compared to columns 7, 8, 9

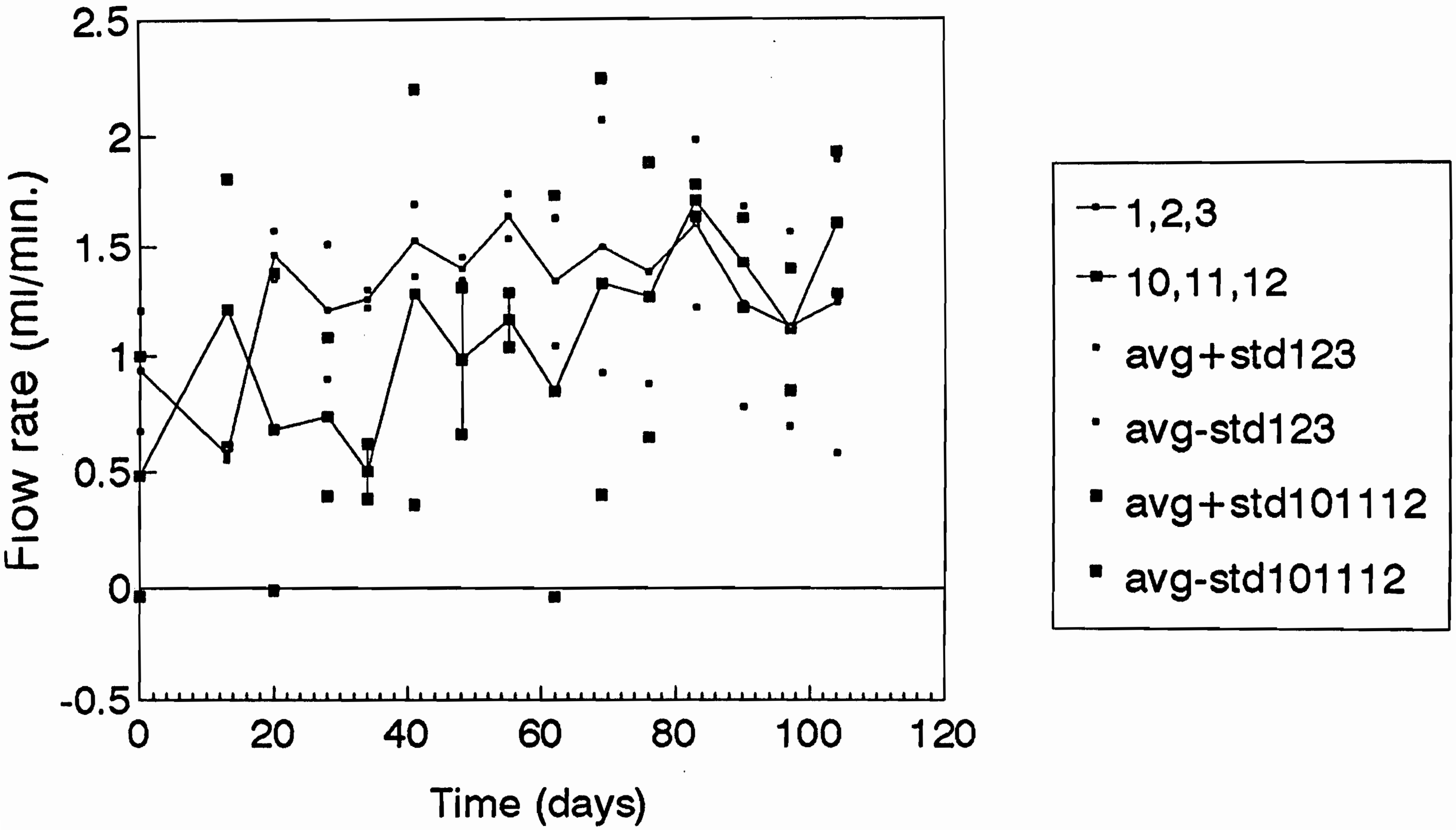

Figure 11. Control flow rate average compared to columns 10, 11, 12

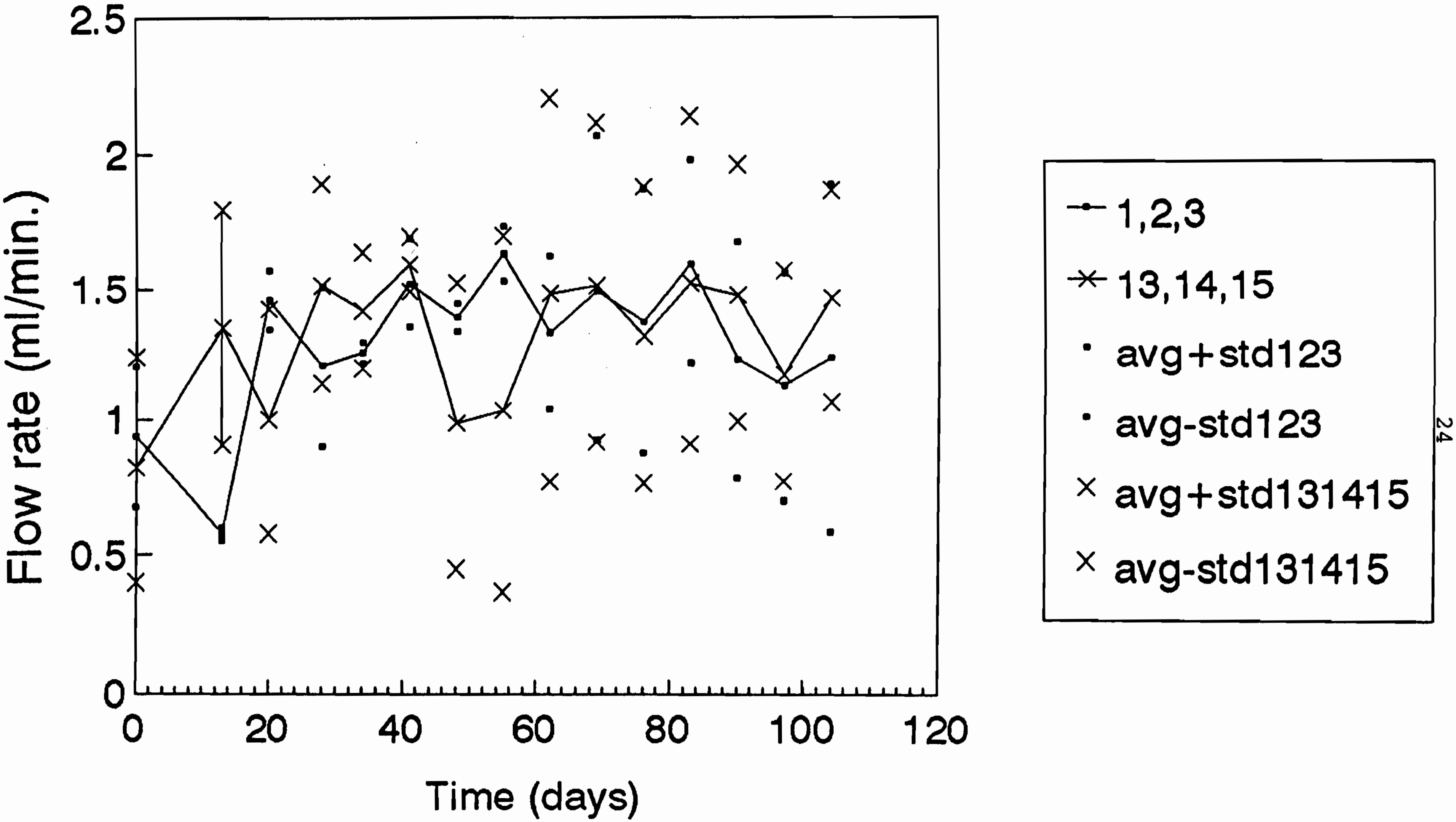

Figure 12. Control flow rate average compared to columns 13, 14, 15

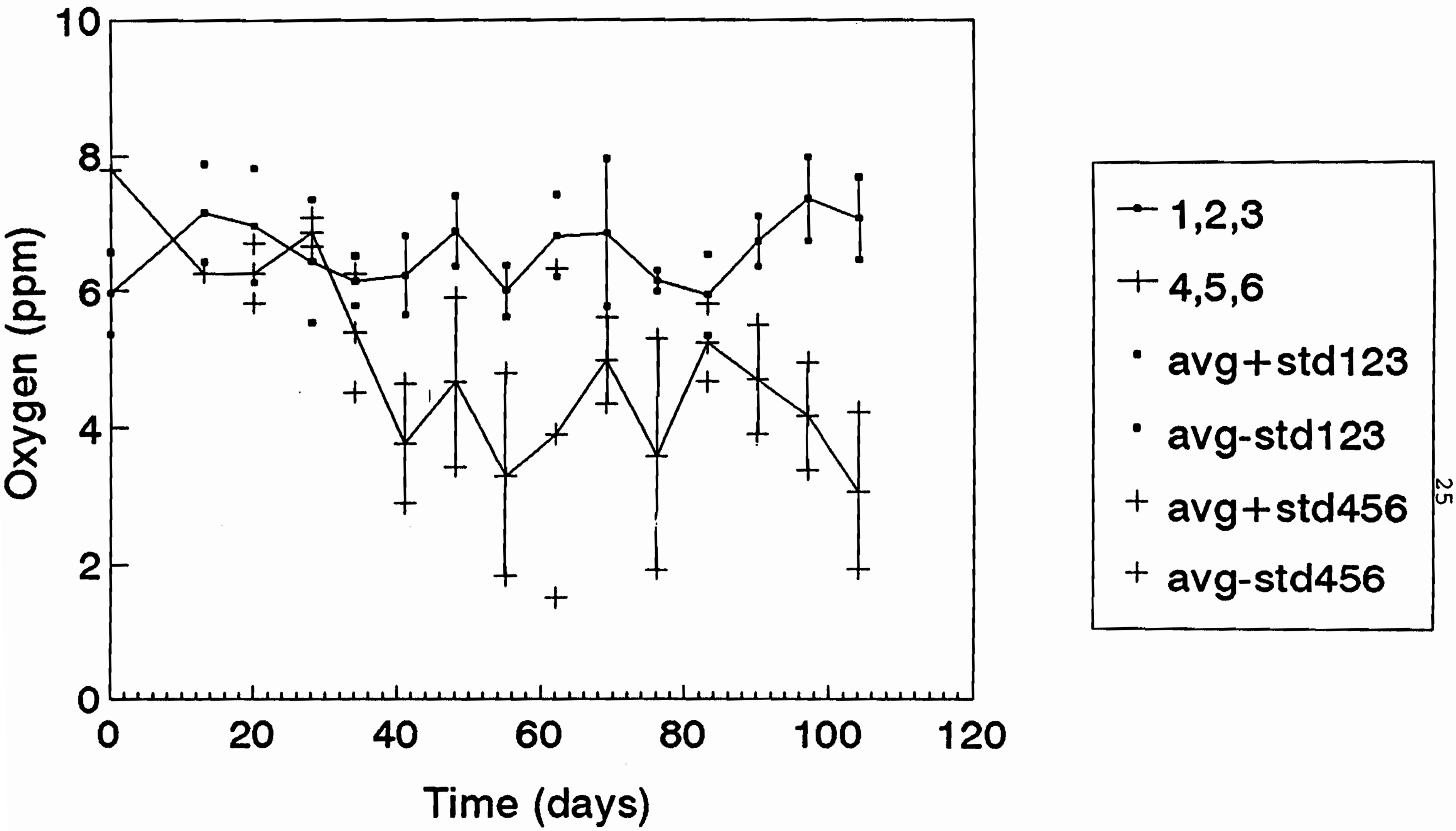

Figure 13. Control dissolved oxygen average compared to columns 4, 5, 6

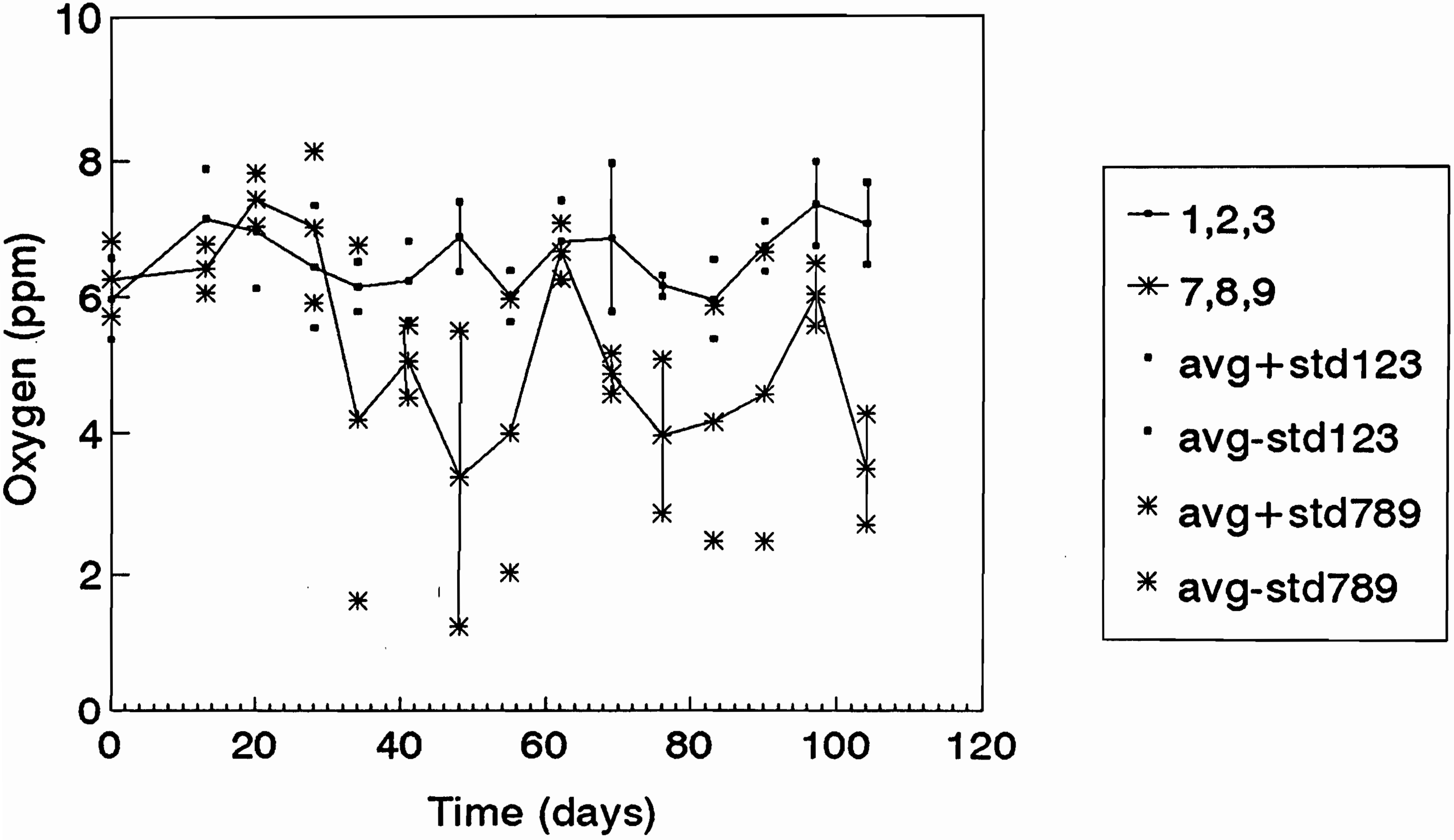

Figure 14. Control dissolved oxygen average compared to columns 7, 8, 9

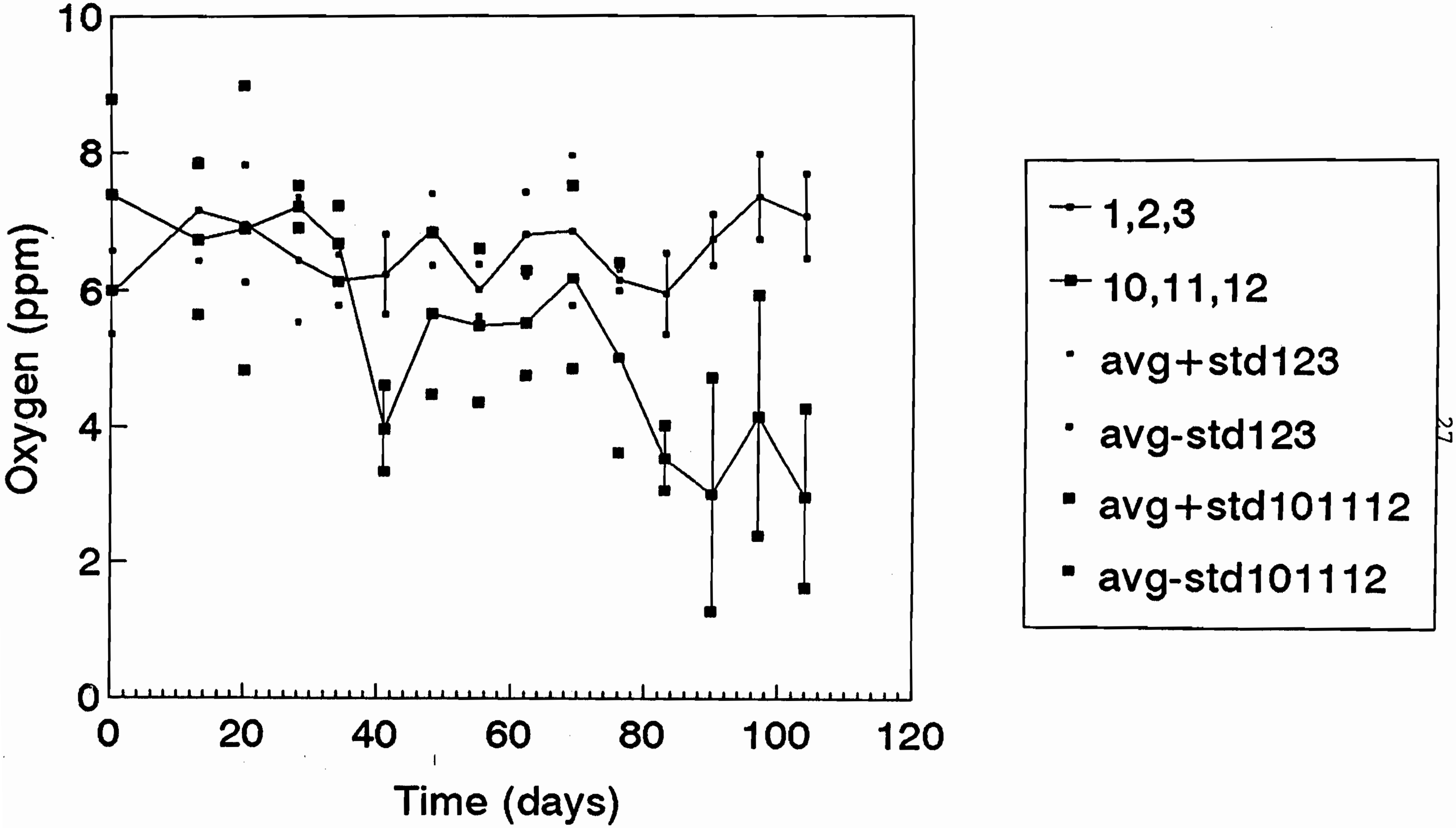

Figure 15. Control dissolved oxygen average compared to columns 10, 11, 12

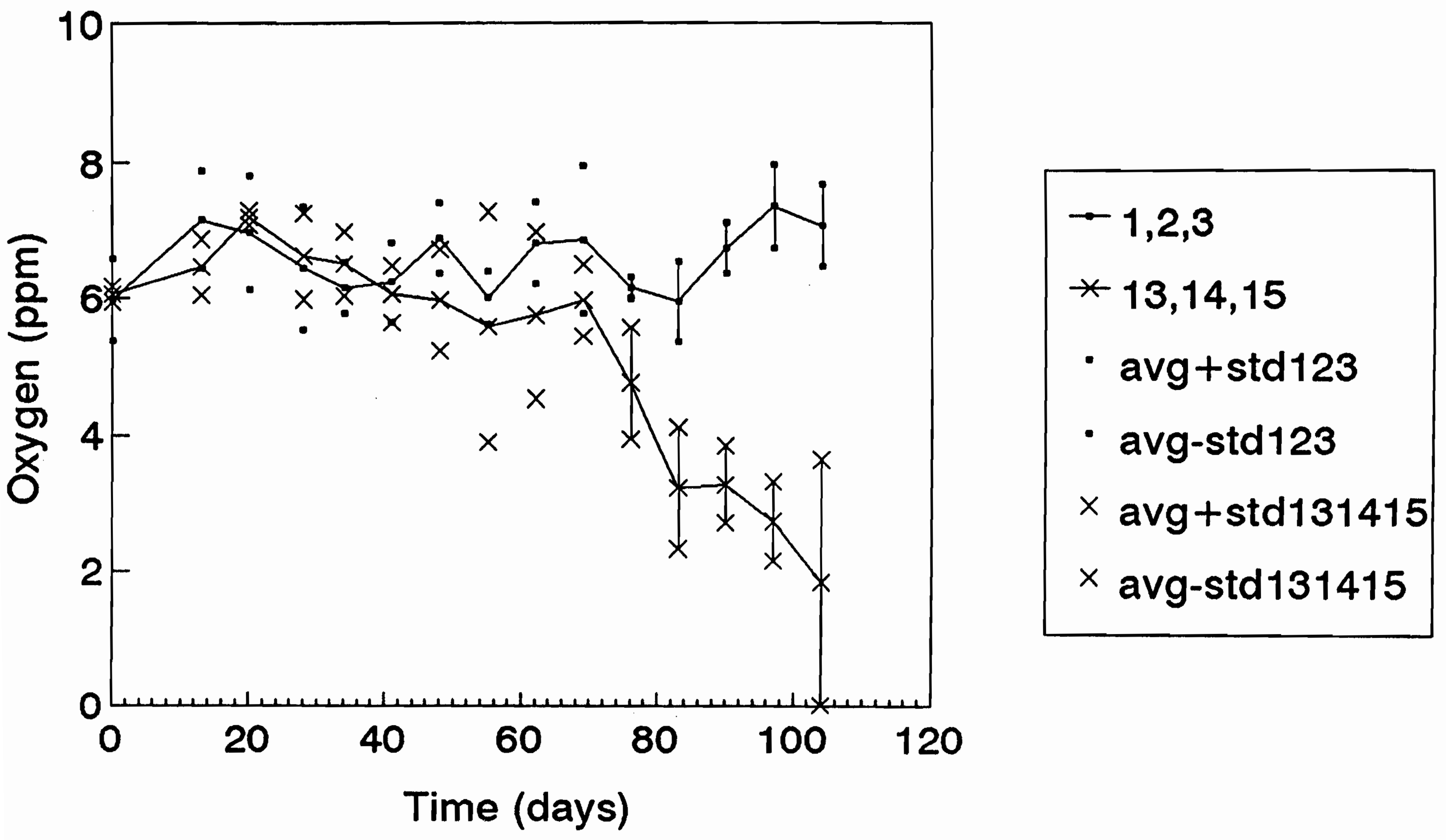

Figure 16. Control dissolved oxygen average compared to columns 13, 14, 15

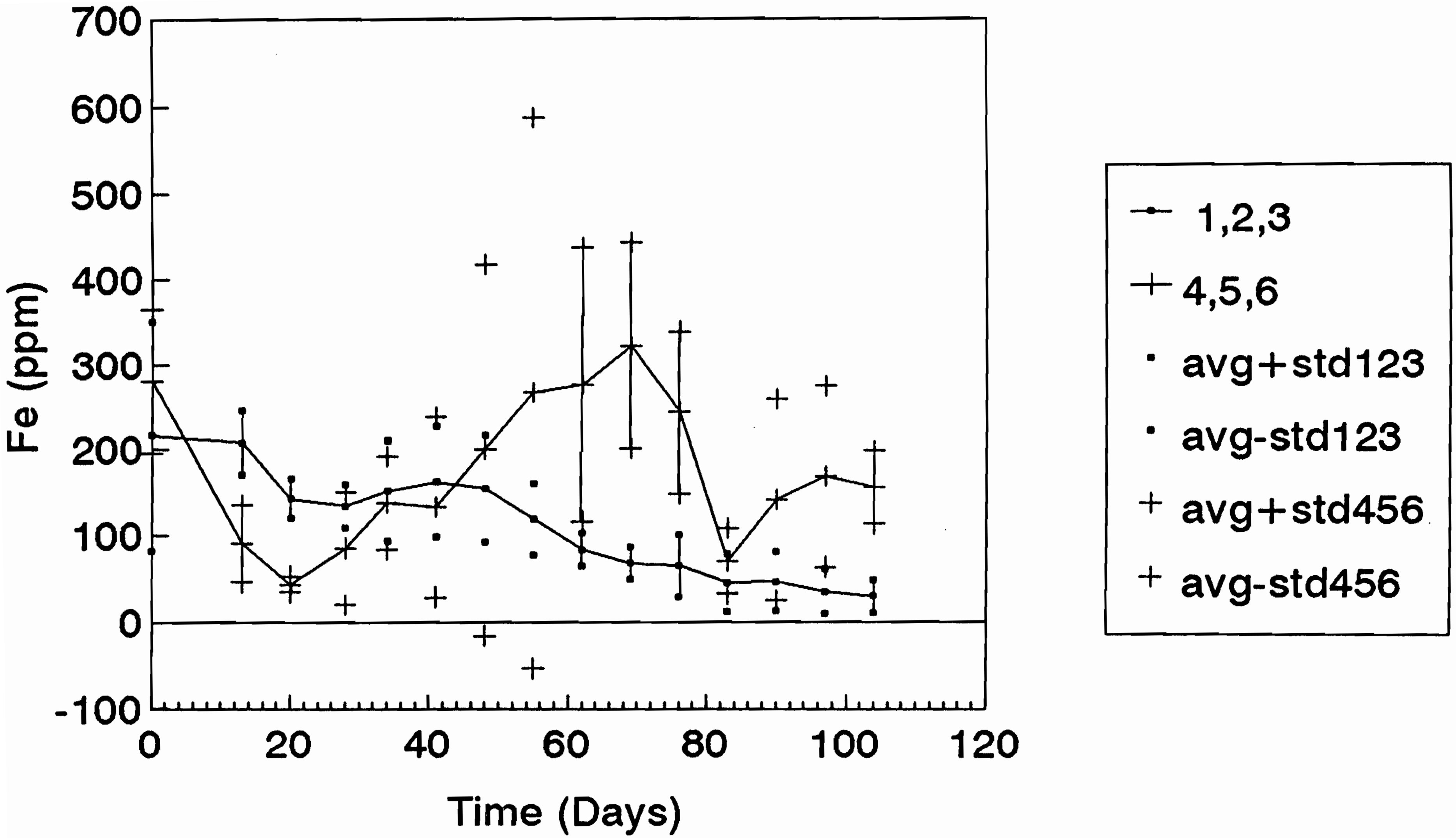

Figure 17. Control total iron average compared to columns 4, 5, 6

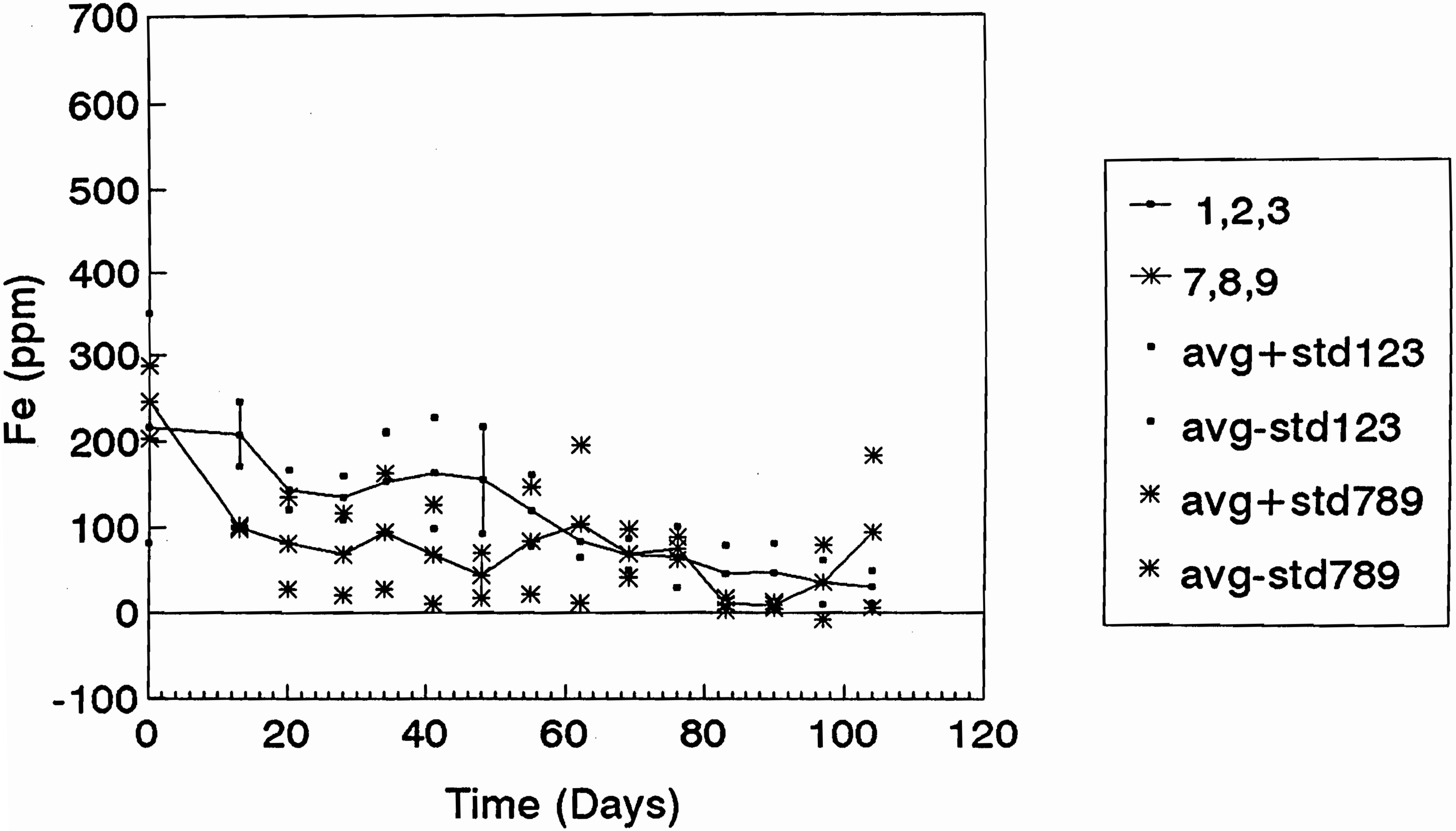

Figure 18. Control total iron average compared to columns 7, 8, 9

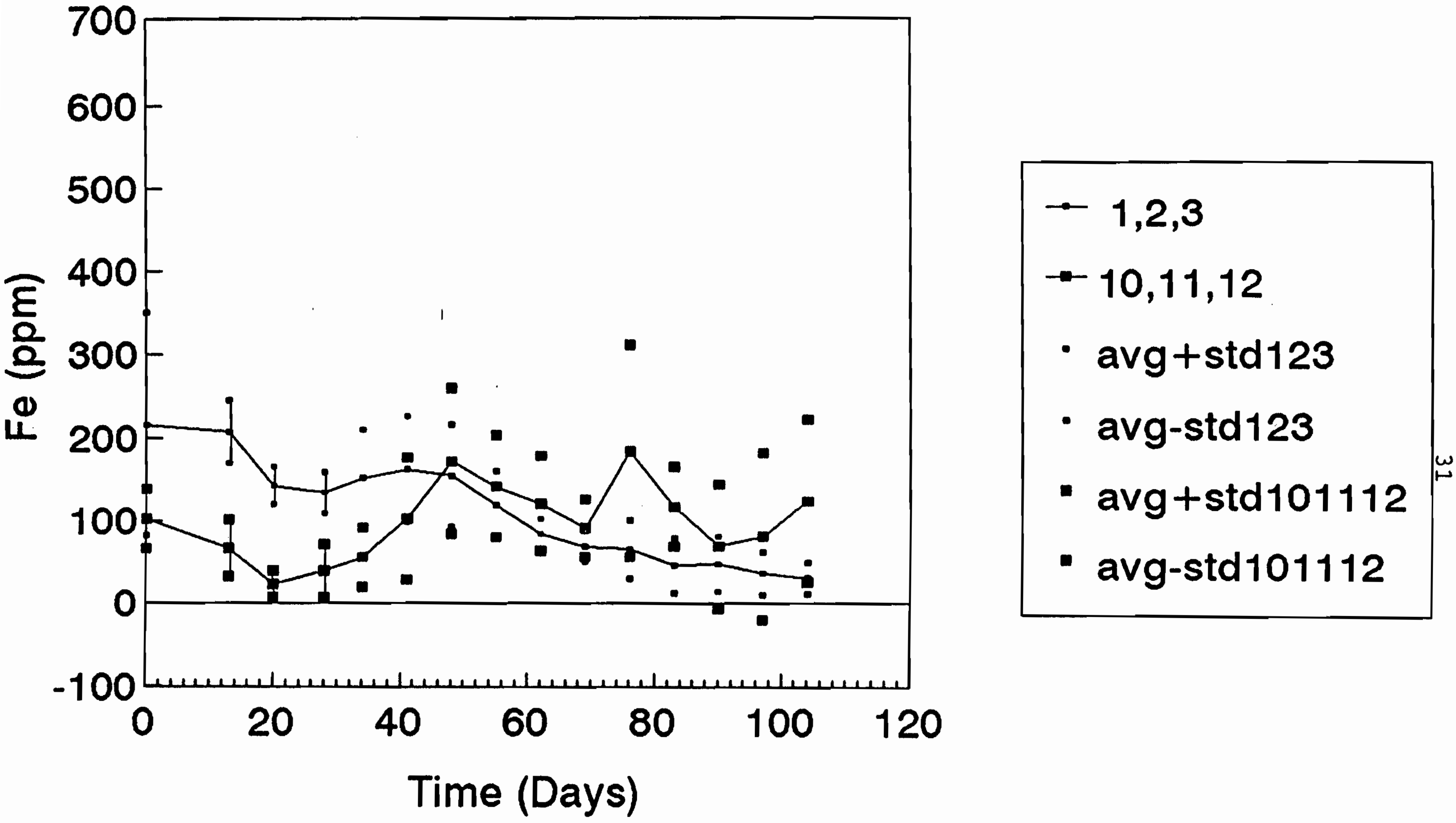

Figure 19. Control total iron average compared to columns 10, 11, 12

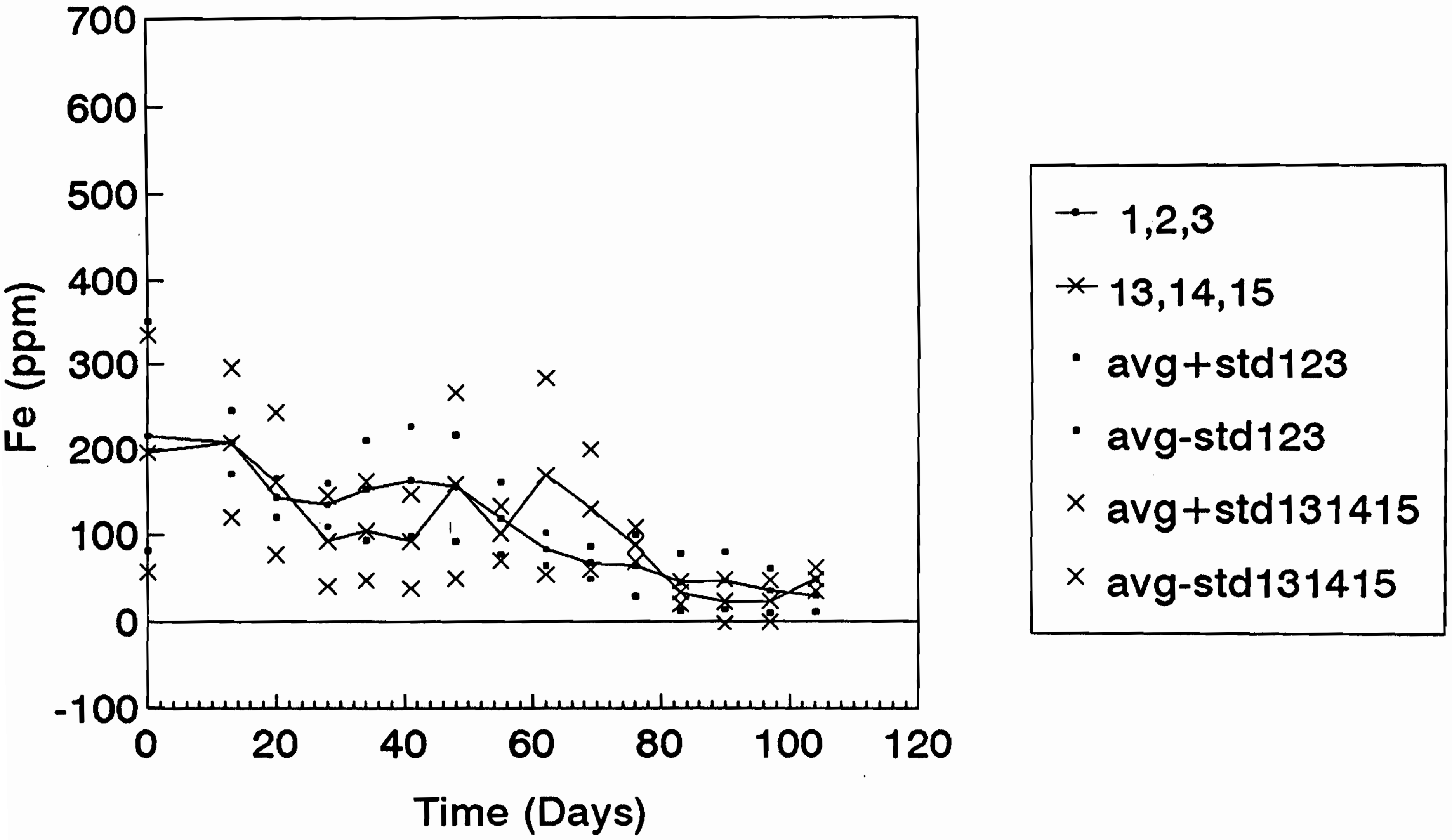

Figure 20. Control total iron average compared to columns 13, 14, 15

APPENDIX - A

Minutes of the Technical Review Meeting on MEND PROJECT 2.44.1: MICROBIAL PLUGGING

September 30, 1992

555 Booth Street
Ottawa, Ontario

Attendance:	K. Wheeland, Noranda D. Gould, CANMET M. Skaff, CANMET	A. Oliver, CANMET L. Lortie, CANMET G. Tremblay, MEND
Absent:	G. Hope, Lac Minerals P. Dauphin, CANMET	T. Hynes, Inco R. McCready, C.A.R.E.

A meeting to discuss the results to date on the microbial plugging of tailings was held at CANMET on Wednesday, September 30, 1992. A draft report was tabled and Ms. L. Lortie, Project Leader, presented the results. The conclusions of the study were that:

(1) It was not demonstrated that a microbial cap could significantly reduce the permeability of the tailings over long periods of time;
(2) A decrease of the oxygen penetration was observed for the columns that received nutrients;
(3) An increase in pH was observed for all of the permeates from the columns that received nutrients; and
(4) Addition of ultramicrobacteria's (UMB's) to the tailings is not necessary because native strains are present in the tailings.

It was noted that although a reduction in permeability was not observed in the experiments, it is possible that in fine textural tailings a significant reduction in water permeability would be expected.

Ms. Lortie then presented the work needed to complete this study. It includes:

(1) Microbial counts;
(2) Identification of strains to verify the presence of UMB's (*Klebsiella oxytoca*);
(3) Measure uronic acid concentrations; and

(4) Determining the economics of the process.

The samples needed to complete the first three tasks are scheduled to be taken at the end of the study because the coring procedure used will prevent any further laboratory experimental work. G. Tremblay, who visited R. McCready of C.A.R.E. in Calgary in early September reported that C.A.R.E. had agreed to produce a one-page summary on the economics of the process to be included in the final report.

The recommendations made by CANMET at this stage of the project followed and included:

(1) No further studies be undertaken by CANMET (other than complete the present study and issue a final report);

(2) Continue project and complete additional test work:
    a) Using humidity cells;
    b) Trying different acid generating tailings;
    c) Running the experiments for a longer period of time;
    d) Adding nutrients more often; and
    e) Analyzing for $S0_4$.

It was agreed by those present that CANMET will have completed their portion of the experimental work when the final report is submitted and accepted by MEND (i.e. recommendation (1)). Although only one of the two objectives was accomplished, it appears that the technique of microbial plugging has promise and further evaluation should be continued by other organizations.

Gilles Tremblay
MEND - Prevention and Control

APPENDIX - B

ECONOMICS OF BACTERIAL CAPPING OF TAILINGS

The current study has indicated that the tailings need not be inoculated with vegetative or ultramicrobial cells in order to produce an oxygen scavenging layer in the upper surface of the tailings. There are sufficient indigenous heterotrophs present in the surface layers of the tailings. When stimulated with rich carbohydrate medium buffered to pH 7.0, the indigenous organisms multiply and produce sufficient exopolysaccharides to reduce the percolation of precipitation and to remove the dissolved oxygen from the interstitial solution within the tailings resulting in a decrease in the Eh, and a concurrent increase in the pH of the effluents which have permeated through the tailings.

The use of a food industry waste product as the microbial nutrient, which will have to be applied at monthly intervals has resulted in a substantial reduction in the cost of the technology. Considering the cost of the waste product, the shipping costs and the application costs over a three to four month period, the cost is estimated to be approximately $25, 000 per hectare. Once the cap has been established the surface of the tailings would be re-vegetated. By judiciously selecting a revegetation cover which exudes root exudates, the microbial oxygen scavenging layer should become self-sustaining. The revegetation aspect requires further research to prove that the concept is correct and economically feasible.

In some tailings, where an indigenous population of aciduric heterotrophs has not become established, microbial inoculation may be required. In such cases, this would result in a substantial increase in the cost of the technology, increasing the estimated cost to approximately $50,000 per hectare.

Dr. Ron McCready
C.A.R.E.

APPENDIX - C

Table 7. Summary of all data used for graphics

CONTROLS

DAYS	RATE (mL / min.)						
	avg	std	avg+std	avg-std	1	2	3
0	0.936966	0.263894	1.20086	0.673072	1.1	0.6	1.1
13	0.572549	0.022184	0.594733	0.550365	0.6	0.6	0.5
20	1.457367	0.113784	1.571151	1.343584	1.3	1.6	1.5
28	1.202694	0.304515	1.507209	0.898178	1.0	1.0	1.6
34	1.251948	0.040551	1.292499	1.211398	1.2	1.3	1.3
41	1.521168	0.167414	1.688581	1.353754	1.6	1.7	1.3
48	1.390159	0.054324	1.444482	1.335835	1.4	1.4	1.3
56	1.633333	0.10274	1.736074	1.530593	1.7	1.8	1.5
62	1.331667	0.292584	1.624251	1.039082	1.7	1.0	1.4
69	1.493333	0.571625	2.064958	0.921708	2.2	0.8	1.5
76	1.373333	0.49862	1.871954	0.874713	2.0	0.8	1.3
83	1.596667	0.384043	1.980709	1.212624	2.0	1.1	1.7
90	1.226667	0.450284	1.676951	0.776383	1.8	0.7	1.2
97	1.126667	0.434844	1.56151	0.691823	1.6	0.6	1.2
104	1.233333	0.654896	1.888229	0.578437	2.0	0.4	1.3

DAYS	OXYGEN (ppm)						
	avg	std	avg+std	avg-std	1	2	3
0	5.976667	0.605824	6.58249	5.370843	5.17	6.63	6.13
13	7.16	0.721249	7.881249	6.438751	7.67	7.67	6.14
20	6.97	0.844077	7.814077	6.125923	7.76	5.80	7.35
28	6.446667	0.909444	7.356111	5.537222	7.69	5.54	6.11
34	6.153333	0.371154	6.524488	5.782179	6.45	5.63	6.38
41	6.24	0.583838	6.823838	5.656162	5.53	6.96	6.23
48	6.886667	0.516484	7.403151	6.370183	6.18	7.40	7.08
56	6.01	0.383232	6.393232	5.626768	5.70	6.56	5.78
62	6.816667	0.603453	7.42012	6.213214	6.40	7.67	6.38
69	6.863333	1.087208	7.950542	5.776125	6.14	8.40	6.05
76	6.16	0.155778	6.315778	6.004222	6.28	6.26	5.94
83	5.956667	0.59219	6.548857	5.364477	5.35	6.76	5.76
90	6.743333	0.370615	7.113948	6.372718	7.24	6.64	6.35
97	7.36	0.608112	7.968112	6.751888	7.14	8.19	6.75
104	7.076667	0.60135	7.678017	6.475316	6.56	7.92	6.75

DAYS	Eh (mV)						
	avg	std	avg+std	avg-std	1	2	3
0	458.3333	6.342099	464.6754	451.9912	452	456	467
13	439	1.414214	440.4142	437.5858	438	438	441
20	444.6667	10.40299	455.0697	434.2637	430	451	453
28	433.6667	6.599663	440.2663	427.067	425	435	441
34	455	13.36663	468.3666	441.6334	437	459	469
41	435	12.75408	447.7541	422.2459	445	417	443
48	431.6667	2.054805	433.7215	429.6119	434	429	432
56	434	2.44949	436.4495	431.5505	437	434	431
62	448.3333	4.784233	453.1176	443.5491	444	446	455
69	498	8.524475	506.5245	489.4755	486	503	505
76	444.3333	5.734884	450.0682	438.5984	437	445	451
83	443.3333	6.128259	449.4616	437.2051	436	443	451
90	443.3333	11.95361	455.2869	431.3797	430	441	459
97	448.6667	17.91337	466.58	430.7533	424	456	466
104	514.6667	54.23611	568.9028	460.4306	441	533	570

DAYS	pH						
	avg	std	avg+std	avg-std	1	2	3
0	2.693333	0.081786	2.775119	2.611548	2.73	2.58	2.77
13	2.666667	0.085765	2.752431	2.580902	2.77	2.56	2.67
20	3.063333	0.338264	3.401597	2.72507	2.79	2.86	3.54
28	2.753333	0.087305	2.840639	2.666028	2.82	2.63	2.81
34	2.713333	0.140554	2.853888	2.572779	2.77	2.52	2.85
41	2.696667	0.171529	2.868196	2.525138	2.49	2.69	2.91
48	2.573333	0.135236	2.70857	2.438097	2.40	2.59	2.73
56	2.74	0.082865	2.822865	2.657135	2.65	2.72	2.85
62	2.726667	0.052493	2.77916	2.674173	2.70	2.80	2.68
69	2.733333	0.041899	2.775233	2.691434	2.79	2.72	2.69
76	2.856667	0.097411	2.954078	2.759256	2.94	2.91	2.72
83	2.94	0.147196	3.087196	2.792804	2.99	3.09	2.74
90	2.983333	0.167796	3.15113	2.815537	3.00	3.18	2.77
97	3.056667	0.175942	3.232609	2.880725	3.04	3.28	2.85
104	3	0.131403	3.131403	2.868597	3.02	3.15	2.83

DAYS	Fe (ppm)						
	avg	std	avg+std	avg-std	1	2	3
0	216.3333	134.0804	350.4137	82.25293	182.0	395.0	72.0
13	208	37.74476	245.7448	170.2552	176.0	261.0	187.0
20	142.6667	22.95406	165.6207	119.7126	124.0	175.0	129.0
28	134.3333	25.22345	159.5568	109.1099	117.0	170.0	116.0
34	152	58.48647	210.4865	93.51353	126.0	233.0	97.0
41	162.3333	64.32383	226.6572	98.0095	246.0	146.0	95.0
48	154.6667	62.30213	216.9688	92.36454	131.0	240.0	93.0
56	119	41.04469	160.0447	77.95531	177.0	92.0	88.0
62	83.63333	18.58321	102.2165	65.05013	84.4	60.5	106.0
69	67.83333	18.56418	86.39752	49.26915	52.9	56.6	94.0
76	64.8	35.6396	100.4396	29.1607	35.8	43.6	115.0
83	45.2	33.43651	78.63651	11.76349	26.2	17.2	92.2
90	46.86667	33.50187	80.36854	13.36479	30.8	16.3	93.5
97	35.26667	25.66636	60.93303	9.600303	28.6	7.7	69.5
104	30.03333	19.01444	49.04777	11.01889	26.2	8.9	56.0

UMB + LIQUID NUTRIENTS

DAYS	RATE (mL / min.)						
	Avg	STD	avg+std	avg-std	4	5	6
0	0.052632	0.018639	0.071271	0.033993	0.0	0.1	0.1
13	0.194351	0.18843	0.38278	0.005921	0.5	0.1	0.1
20	0.283569	0.239831	0.5234	0.043738	0.2	0.0	0.6
28	0.155778	0.152965	0.308743	0.002813	0.1	0.0	0.4
34	0.365081	0.177193	0.542274	0.187887	0.2	0.2	0.6
41	0.485995	0.322601	0.808596	0.163394	0.0	0.8	0.6
48	0.764584	0.572279	1.336863	0.192305	0.0	0.8	1.4
56	0.97	0.421663	1.391663	0.548337	0.4	1.2	1.3
62	0.91	0.028284	0.938284	0.881716	1.0	0.9	0.9
69	1.039333	0.666894	1.706227	0.372439	0.5	0.6	2.0
76	0.733333	0.1666	0.899933	0.566733	0.8	0.5	0.9
83	1.03	0.274348	1.304348	0.755652	0.7	1.1	1.4
90	1.23	0.613025	1.843025	0.616975	1.2	0.5	2.0
97	1	0.535413	1.535413	0.464587	1.1	0.3	1.6
104	1.133333	0.654896	1.788229	0.478437	1.2	0.3	1.9

DAYS	OXYGEN (ppm)						
	Avg	STD	avg+std	avg-std	4	5	6
0	7.8	4.3E-19	7.8	7.8	7.80	7.80	7.80
13	6.27	0	6.27	6.27	6.27		
20	6.266667	0.442895	6.709561	5.823772	5.67	6.40	6.73
28	6.876667	0.213125	7.089792	6.663542	6.63	6.85	7.15
34	5.396667	0.86984	6.266507	4.526826	4.49	5.13	6.57
41	3.79	0.869081	4.659081	2.920919	4.38	2.56	4.43
48	4.686667	1.221402	5.908068	3.465265	6.40	4.02	3.64
56	3.326667	1.484528	4.811194	1.842139	4.04	4.68	1.26
62	3.923333	2.409832	6.333165	1.513502	5.19	6.03	0.56
69	4.996667	0.627606	5.624272	4.369061	5.86	4.63	4.48
76	3.623333	1.688398	5.311732	1.934935	5.32	1.32	4.23
83	5.256667	0.562396	5.819062	4.694271	5.13	4.64	6.00
90	4.726667	0.790373	5.517039	3.936294	4.02	4.33	5.83
97	4.196667	0.777103	4.97377	3.419564	3.28	5.18	4.13
104	3.096667	1.155345	4.252012	1.941322	3.70	1.48	4.11

DAYS	Eh (mV)						
	Avg	STD	avg+std	avg-std	4	5	6
0	479	24.65766	503.6577	454.3423	475	511	451
13	338	0	338	338	338		
20	346	50.6162	396.6162	295.3838	355	403	280
28	136.6667	32.16969	168.8364	104.497	127	180	103
34	65.66667	33.50953	99.1762	32.15713	44	113	40
41	-17.3333	62.18431	44.85098	-79.5176	-46	-75	69
48	96.66667	199.7904	296.4571	-103.124	-35	-54	379
56	115.3333	196.123	311.4563	-80.7896	-49	391	4
62	216.6667	188.6466	405.3133	28.02002	-26	242	434
69	240.6667	207.6541	448.3208	33.01257	-53	386	387
76	242.3333	229.5304	471.8638	12.80289	-82	416	393
83	201	194.6398	395.6398	6.360162	-72	368	307
90	208.6667	188.3372	397.0038	20.3295	-60	393	293
97	106.3333	229.1438	335.4772	-122.81	-121	420	20
104	134	212.8865	346.8865	-78.8865	-46	433	15

DAYS	pH						
	Avg	STD	avg+std	avg-std	4	5	6
0	2.49	0.195107	2.685107	2.294893	2.41	2.57	2.88
13	2.9	0	2.9	2.9	2.90		
20	3.185	0.300703	3.485703	2.884297	3.52	2.85	3.45
28	4.45	0.156915	4.606915	4.293085	4.57	4.33	4.71
34	5.13	0.104987	5.234987	5.025013	5.11	6.15	5.35
41	6.145	0.620054	6.765054	5.524946	6.05	6.24	4.84
48	6.63	2.055324	8.685324	4.574676	7.11	6.15	2.35
56	5.935	1.68191	7.61691	4.25309	6.32	5.56	2.43
62	4.72	1.580745	6.300745	3.139256	6.22	3.22	2.60
69	4.315	1.433093	5.748093	2.881907	5.83	2.80	2.78
76	3.96	1.180574	5.140574	2.779426	5.27	2.65	2.90
83	4.105	1.328566	5.433566	2.776434	5.64	2.57	3.17
90	4.305	1.610362	5.915362	2.694638	6.19	2.42	3.30
97	4.12	1.321893	5.441893	2.798107	5.68	2.56	4.87
104	3.91	1.08423	4.99423	2.82577	5.06	2.76	5.06

DAYS	Fe (ppm)						
	Avg	STD	avg+std	avg-std	4	5	6
0	290.3333	94.63779	384.9711	195.6956	393.0	289.0	189.0
13	91	44.59447	135.5945	46.40553	154.0	62.0	57.0
20	44	9.092121	53.09212	34.90788	56.0	42.0	34.0
28	85.33333	64.92218	150.2555	20.41116	177.0	44.0	35.0
34	137.6667	54.10073	191.7674	83.56594	214.0	104.0	95.0
41	133.3333	104.4743	237.8077	28.85899	87.0	35.0	278.0
48	200.1667	216.1829	416.3496	-16.0163	27.5	68.0	505.0
56	266.6667	320.5717	587.2384	-53.905	36.0	44.0	720.0
62	276.4667	159.9005	436.3672	116.5662	51.4	370.0	408.0
69	322	120.3993	442.3993	201.6007	214.0	490.0	262.0
76	243.6667	95.22721	338.8939	148.4395	312.0	310.0	109.0
83	70.3	37.67395	107.974	32.62605	33.3	122.0	55.6
90	141.5	117.0605	258.5605	24.43947	16.5	298.0	110.0
97	169	105.5683	274.5683	63.4317	28.0	282.0	197.0
104	156	42.76291	198.7629	113.2371	99.0	202.0	167.0

UMB + LIQUID & SOLID NUTRIENTS

DAYS	RATE (mL / min.)						
	avg	std	avg+std	avg-std	7	8	9
0	0.57118	0.538298	1.109478	0.032881	0.4	1.3	0.0
13	1.153598	0.824768	1.978367	0.32883	1.9	1.5	0.0
20	0.543152	0.384255	0.927407	0.158897	0.8	0.8	0.0
28	0.303944	0.219814	0.523758	0.08413	0.4	0.5	0.0
34	0.413766	0.287417	0.701183	0.12635	0.6	0.6	0.0
41	0.497663	0.352994	0.850656	0.144669	0.7	0.8	0.0
48	0.759921	0.584453	1.344374	0.175467	1.4	0.9	0.0
55	0.846667	0.768433	1.615099	0.078234	1.9	0.7	0.0
62	1.09	0.672756	1.762756	0.417244	2.0	0.6	0.7
69	1.306667	0.660168	1.966835	0.646498	2.2	0.9	0.8
76	1.01	0.225536	1.235536	0.784464	1.3	0.8	0.9
83	1.016667	0.242258	1.258925	0.774409	1.2	0.7	1.1
90	1.246667	0.738708	1.985374	0.507959	2.2	1.1	0.4
97	0.766667	0.188562	0.955228	0.578105	0.9	0.9	0.5
104	0.966667	0.286744	1.253411	0.679922	1.3	1.0	0.6

DAYS	OXYGEN (ppm)						
	avg	std	avg+std	avg-std	7	8	9
0	6.273333	0.558231	6.831565	5.715102	6.09	5.70	7.03
13	6.42	0.36	6.78	6.06	6.06	6.78	
20	7.435	0.385	7.82	7.05	7.05	7.82	
28	7.023333	1.114431	8.137764	5.908903	7.73	7.89	5.45
34	4.196667	2.573575	6.770242	1.623092	4.97	6.89	0.73
41	5.043333	0.526709	5.570042	4.516624	4.95	4.45	5.73
48	3.373333	2.118999	5.492332	1.254335	4.62	5.11	0.39
55	3.996667	1.966289	5.962956	2.030379	4.49	6.12	1.38
62	6.67	0.412149	7.082149	6.257851	6.53	7.23	6.25
69	4.86	0.293909	5.153909	4.566091	4.86	4.50	5.22
76	3.966667	1.102008	5.068675	2.864658	2.41	4.81	4.68
83	4.163333	1.696473	5.859807	2.46686	2.87	3.06	6.56
90	4.56	2.09501	6.65501	2.46499	4.36	2.10	7.22
97	6.03	0.46483	6.49483	5.56517	5.84	5.58	6.67
104	3.49	0.787951	4.277951	2.702049	4.13	3.96	2.38

DAYS	Eh (mV)						
	avg	std	avg+std	avg-std	7	8	9
0	477.6667	66.41964	544.0862	411.2471	451	413	569
13	312	15	327	297	327	297	
20	216.5	21.5	238	195	238	195	
28	127.3333	136.6488	263.9821	-9.31545	18	44	320
34	-13	63.35614	50.35614	-76.3561	2	56	-97
41	0.666667	82.28541	82.95208	-81.6187	-60	-56	117
48	-68	41.21488	-26.7851	-109.215	-44	-34	-126
55	11.33333	39.26265	50.59598	-27.9293	-35	8	61
62	-11.6667	37.95026	26.28359	-49.6169	42	-39	-38
69	-110	36.00478	-73.9952	-146.005	-135	-136	-59
76	-109	31.82242	-77.1776	-140.822	-142	-119	-66
83	-115.333	32.75309	-82.5802	-148.086	-158	-147	-41
90	-125.667	52.13018	-73.5365	-177.797	-160	-165	-52
97	-88.6667	70.45291	-18.2142	-159.119	-150	-126	10
104	-51	31.12341	-19.8766	-82.1234	-72	-74	-7

DAYS	pH						
	avg	std	avg+std	avg-std	7	8	9
0	2.686667	0.093927	2.780593	2.59274	2.69	2.80	2.57
13	2.94	0.09	3.03	2.85	2.85	3.03	
20	3.356667	0.649991	4.006658	2.706675	3.59	4.01	2.47
28	4.106667	0.811186	4.917852	3.295481	4.65	4.71	2.96
34	5.7	0.705266	6.405266	4.994734	5.31	5.10	6.69
41	6.483333	0.763952	7.247285	5.719382	6.15	5.76	7.54
48	4.57	2.150364	6.720364	2.419636	6.16	6.02	1.53
55	5.936667	0.804253	6.740919	5.132414	4.95	5.94	6.92
62	5.493333	0.995802	6.489136	4.497531	4.12	5.91	6.45
69	5.58	0.592002	6.172002	4.987998	4.86	5.57	6.31
76	5.296667	0.441236	5.737902	4.855431	4.96	5.01	5.92
83	6.093333	0.83914	6.932473	5.254194	5.49	5.51	7.28
90	6.076667	0.575171	6.651838	5.501495	5.66	5.68	6.89
97	5.726667	0.10873	5.835397	5.617937	5.84	5.58	5.76
104	5.076667	0.148174	5.224841	4.928493	5.05	4.91	5.27

DAYS	Fe (ppm)						
	avg	std	avg+std	avg-std	7	8	9
0	246	42.05562	288.0556	203.9445	269.0	282.0	187.0
13	100	2	102	98	98.0	102.0	
20	81	53.98295	134.983	27.01705	37.0	49.0	157.0
28	68.23333	47.76026	115.9936	20.47308	103.0	101.0	0.7
34	94.43333	67.30658	161.7399	27.12675	113.0	166.0	4.3
41	67.7	57.52721	125.2272	10.17279	54.0	144.0	5.1
48	43.33333	26.77167	70.105	16.56167	36.5	79.0	14.5
55	83.5	62.28296	145.783	21.21704	161.0	81.0	8.5
62	103.1333	92.07433	195.2077	11.059	230.0	65.1	14.3
69	69	28.33137	97.33137	40.66863	109.0	47.0	51.0
76	75	13.44123	88.44123	61.55877	66.0	65.0	94.0
83	9.866667	7.269266	17.13593	2.597401	3.3	20.0	6.3
90	8.366667	4.164399	12.53107	4.202267	3.3	8.3	13.5
97	35.46667	43.90614	79.3728	-8.43947	2.1	6.8	97.5
104	94.5	88.75618	183.2562	5.743817	29.8	33.7	220.0

UMB + LIQUID & SOLID NUTRIENTS + CALCIUM

DAYS	RATE (mL / min.)						
	avg	std	avg+std	avg-std	10	11	12
0	0.480038	0.519445	0.999483	-0.03941	0.2	1.2	0.1
13	1.206295	0.60072	1.807015	0.605575	0.4	1.6	1.7
20	0.679136	0.692754	1.37189	-0.01362	0.3	1.7	0.1
28	0.736667	0.344513	1.081179	0.392154	1.0	1.0	0.3
34	0.498519	0.118536	0.617054	0.379983	0.5	0.6	0.3
41	1.275413	0.921198	2.19661	0.354217	2.2	1.6	0.0
48	0.979802	0.321792	1.301594	0.65801	1.4	0.8	0.7
56	1.156667	0.121198	1.277864	1.035469	1.3	1.1	1.0
62	0.843333	0.884772	1.728106	-0.04144	2.1	0.4	0.1
69	1.32	0.922063	2.242063	0.397937	1.6	2.3	0.1
76	1.26	0.615955	1.875955	0.644045	1.5	1.9	0.4
83	1.703333	0.074087	1.77742	1.629246	1.8	1.7	1.6
90	1.416667	0.206774	1.623441	1.209893	1.6	1.5	1.1
97	1.116667	0.271825	1.388492	0.844842	1.4	1.2	0.8
104	1.6	0.326599	1.926599	1.273401	1.6	1.2	2.0

DAYS	OXYGEN (ppm)						
	avg	std	avg+std	avg-std	10	11	12
0	7.383333	1.383048	8.766381	6.000285	7.80	5.52	8.83
13	6.746667	1.094359	7.841026	5.652307	7.73	5.22	7.29
20	6.9	2.071827	8.971827	4.828173	8.37	3.97	8.36
28	7.213333	0.30576	7.519093	6.907574	7.53	7.31	6.80
34	6.683333	0.54756	7.230894	6.135773	7.37	6.03	6.65
41	3.973333	0.635418	4.608751	3.337916	4.83	3.78	3.31
48	5.66	1.178672	6.838672	4.481328	4.41	5.33	7.24
56	5.49	1.124663	6.614663	4.365337	6.25	6.32	3.90
62	5.53	0.772054	6.302054	4.757946	5.04	4.93	6.62
69	6.186667	1.326206	7.512873	4.860461	5.44	5.07	8.05
76	5.02	1.395517	6.415517	3.624483	3.84	4.24	6.98
83	3.543333	0.488831	4.032164	3.054503	3.62	2.91	4.10
90	3.003333	1.716612	4.719945	1.286722	1.73	1.86	5.43
97	4.163333	1.775788	5.939121	2.387546	2.15	3.87	6.47
104	2.953333	1.32957	4.282903	1.623764	1.08	4.03	3.75

DAYS	Eh (mV)						
	avg	std	avg+std	avg-std	10	11	12
0	489.6667	41.58798	531.2546	448.0787	467	454	548
13	437.6667	58.67614	496.3428	378.9905	446	505	362
20	312.3333	57.87534	370.2087	254.458	260	284	393
28	140.6667	32.71425	173.3809	107.9524	186	126	110
34	109.3333	71.48116	180.8145	37.85218	210	51	67
41	-54	12.32883	-41.6712	-66.3288	-56	-38	-68
48	-5	14.4453	9.445299	-19.4453	-21	14	-8
56	262.3333	149.9252	412.2585	112.4082	75	270	442
62	444.3333	73.14977	517.4831	371.1836	382	404	547
69	180.3333	240.6551	420.9885	-60.3218	-8	29	520
76	28	159.1037	187.1037	-131.104	-86	-83	253
83	-31.3333	32.52008	1.186746	-63.8534	-22	-75	3
90	-91.6667	73.07682	-18.5898	-164.743	-181	-92	-2
97	-85	82.56311	-2.43689	-167.563	-160	-125	30
104	-49	66.81816	17.81816	-115.818	-138	-32	23

DAYS	pH						
	avg	std	avg+std	avg-std	10	11	12
0	2.793333	0.024944	2.818278	2.768389	2.80	2.82	2.76
13	2.726667	0.143372	2.870039	2.583295	2.71	2.56	2.91
20	3.183333	0.121198	3.304531	3.062135	3.02	3.22	3.31
28	4.433333	0.270842	4.704176	4.162491	4.07	4.51	4.72
34	5.16	0.221058	5.381058	4.938942	4.85	5.35	5.28
41	6.223333	0.945034	7.168367	5.2783	5.42	5.70	7.56
48	5.573333	0.228668	5.802001	5.344666	5.58	5.29	5.85
56	3.523333	0.755837	4.27917	2.767497	4.59	3.05	2.93
62	3.026667	0.226618	3.253284	2.800049	3.28	3.07	2.73
69	3.396667	0.509924	3.90659	2.886743	4.08	3.31	2.82
76	4.506667	0.40803	4.914697	4.098636	4.94	4.62	3.96
83	5.37	0.08641	5.45641	5.28359	5.49	5.29	5.33
90	5.903333	0.298254	6.201588	5.605079	6.26	5.92	5.53
97	5.596667	0.52468	6.121346	5.071987	6.27	5.53	4.99
104	5.073333	0.245266	5.3186	4.828067	5.42	4.91	4.89

DAYS	Fe (ppm)						
	avg	std	avg+std	avg-std	10	11	12
0	102	36.34098	138.341	65.65902	146.0	103.0	57.0
13	66.66667	34.65384	101.3205	32.01282	86.0	96.0	18.0
20	23	15.76917	38.76917	7.230832	19.0	44.0	6.0
28	38.66667	32.31443	70.98109	6.352239	21.0	84.0	11.0
34	55.33333	36.00309	91.33642	19.33025	52.0	101.0	13.0
41	102.2	74.37975	176.5797	27.82025	112.0	188.0	6.6
48	172	88.03503	260.035	83.96497	189.5	270.0	56.5
56	141.6667	61.80256	203.4692	79.86411	229.0	101.0	95.0
62	120.9	58.13851	179.0386	62.76149	135.0	184.0	43.7
69	90.56667	35.26342	125.8301	55.30325	116.0	115.0	40.7
76	183.7333	127.9693	311.7026	55.76403	346.0	172.0	33.2
83	116.7	48.6975	165.3975	68.0025	65.1	182.0	103.0
90	68.2	75.89168	144.0917	-7.69168	5.6	24.0	175.0
97	80.56667	101.5203	182.0869	-20.9536	3.4	14.3	224.0
104	123.8333	98.55314	222.3865	25.28019	30.0	81.5	260.0

LIQUID NUTRIENTS

DAYS	RATE (mL / min.)						
	avg	std	avg+std	avg-std	13	14	15
0	0.82	0.416413	1.236413	0.403587	0.3	1.3	0.8
13	1.35	0.445846	1.795846	0.904154	1.7	1.7	0.7
20	1	0.424264	1.424264	0.575736	0.7	1.6	0.7
28	1.513333	0.378183	1.891516	1.135151	1.9	1.6	1.0
34	1.416667	0.22291	1.639577	1.193757	1.7	1.3	1.2
41	1.593333	0.102089	1.695423	1.491244	1.7	1.5	1.7
48	0.986667	0.53767	1.524337	0.448997	0.2	1.3	1.4
55	1.033333	0.66705	1.700383	0.366283	0.1	1.5	1.5
62	1.483333	0.719182	2.202515	0.764152	0.5	2.2	1.8
69	1.513333	0.599185	2.112518	0.914149	0.7	2.2	1.6
76	1.32	0.561664	1.881664	0.758336	0.6	1.9	1.5
83	1.523333	0.615702	2.139035	0.907631	0.7	2.1	1.8
90	1.476667	0.485547	1.962213	0.99112	0.8	1.6	2.0
97	1.166667	0.402768	1.569435	0.763898	0.6	1.4	1.5
104	1.466667	0.402768	1.869435	1.063898	0.9	1.8	1.7

DAYS	OXYGEN (ppm)						
	avg	std	avg+std	avg-std	13	14	15
0	6.063333	0.115854	6.179188	5.947479	6.09	6.19	5.91
13	6.46	0.415291	6.875291	6.044709	6.67	6.83	5.88
20	7.196667	0.108423	7.30509	7.088244	7.12	7.35	7.12
28	6.62	0.639375	7.259375	5.980625	5.80	6.70	7.36
34	6.506667	0.478493	6.98516	6.028174	5.83	6.85	6.84
41	6.06	0.416973	6.476973	5.643027	5.94	6.62	5.62
48	5.973333	0.748881	6.722214	5.224452	7.02	5.31	5.59
55	5.59	1.688727	7.278727	3.901273	7.90	4.96	3.91
62	5.753333	1.224754	6.978087	4.528579	6.83	6.39	4.04
69	5.97	0.530729	6.500729	5.439271	6.62	5.32	5.97
76	4.796667	0.812007	5.608674	3.98466	3.78	5.60	5.01
83	3.223333	0.899642	4.122975	2.323691	2.82	2.38	4.47
90	3.273333	0.571625	3.844958	2.701708	3.98	2.58	3.26
97	2.726667	0.586307	3.312973	2.14036	2.05	3.48	2.65
104	1.823333	1.810531	3.633864	0.012802	0.32	4.37	0.78

DAYS	Eh (mV)						
	avg	std	avg+std	avg-std	13	14	15
0	367.6667	150.3803	518.0469	217.2864	473	156	475
13	403	0.816497	403.8165	402.1835	404	403	402
20	382.3333	5.18545	387.5188	377.1479	386	375	386
28	277.6667	59.2865	336.9532	218.3802	361	244	228
34	189	102.098	291.098	86.90201	325	163	79
41	45	44.1588	89.1588	0.841198	90	-15	60
48	141.3333	202.05	343.3834	-60.7167	79	-69	414
55	230.6667	213.0639	443.7306	17.60277	339	-67	420
62	146	214.1074	360.1074	-68.1074	24	-33	447
69	69	228.5301	297.5301	-159.53	-68	-116	391
76	51.33333	240.9763	292.3096	-189.643	-127	-111	392
83	-59.6667	61.07009	1.403421	-120.737	-138	-52	11
90	-132.667	32.56105	-100.106	-165.228	-117	-178	-103
97	-149.333	21.63844	-127.695	-170.972	-161	-168	-119
104	-120	24.26245	-95.7375	-144.262	-99	-107	-154

DAYS	pH						
	avg	std	avg+std	avg-std	13	14	15
0	2.826667	0.061283	2.887949	2.765384	2.87	2.74	2.87
13	3.043333	0.02357	3.066904	3.019763	3.06	3.01	3.06
20	3.336667	0.004714	3.341381	3.331953	3.34	3.33	3.34
28	3.99	0.380526	4.370526	3.609474	3.47	4.37	4.13
34	4.493333	0.70957	5.202903	3.783764	3.58	5.31	4.59
41	4.683333	1.230835	5.914168	3.452498	3.44	6.36	4.25
48	4.123333	1.758301	5.881634	2.365032	3.38	6.55	2.44
55	4.26	1.598583	5.858583	2.661417	3.88	6.38	2.52
62	5.166667	1.211537	6.378204	3.95513	5.40	6.52	3.58
69	4.923333	1.515461	6.438794	3.407872	5.49	6.43	2.85
76	4.66	1.257219	5.917219	3.402781	5.13	5.91	2.94
83	5.02	0.905428	5.925428	4.114572	5.69	5.63	3.74
90	5.726667	0.528226	6.254892	5.198441	6.08	6.12	4.98
97	5.88	0.304083	6.184083	5.575917	5.59	6.30	5.75
104	5.2	0.265456	5.465456	4.934544	4.83	5.33	5.44

DAYS	Fe (ppm)						
	avg	std	avg+std	avg-std	13	14	15
0	196.3333	138.1698	334.5031	58.16356	122.0	390.0	77.0
13	208	87.74205	295.742	120.258	150.0	332.0	142.0
20	160	82.90156	242.9015	77.09845	148.0	267.0	65.0
28	92.66667	52.0854	144.7521	40.58127	50.0	166.0	62.0
34	104	56.92686	160.9269	47.07316	43.0	180.0	89.0
41	92.66667	54.16231	146.829	38.50436	60.0	49.0	169.0
48	158	108.3728	266.3728	49.62719	99.0	65.0	310.0
55	101.3333	31.08412	132.4174	70.24922	138.0	62.0	104.0
62	168.9	114.9438	283.8438	53.95616	162.0	31.7	313.0
69	129.4667	69.63837	199.105	59.8283	140.0	39.4	209.0
76	88.93333	19.70471	108.638	69.22862	97.0	108.0	61.8
83	33.16667	13.33025	46.49692	19.83642	17.4	50.0	32.1
90	22.66667	25.69622	48.36289	-3.02956	6.1	3.9	58.0
97	23.23333	24.30286	47.53619	-1.06952	8.4	3.8	57.5
104	48.9	13.98356	62.88356	34.91644	55.8	29.4	61.5

APPENDIX - D

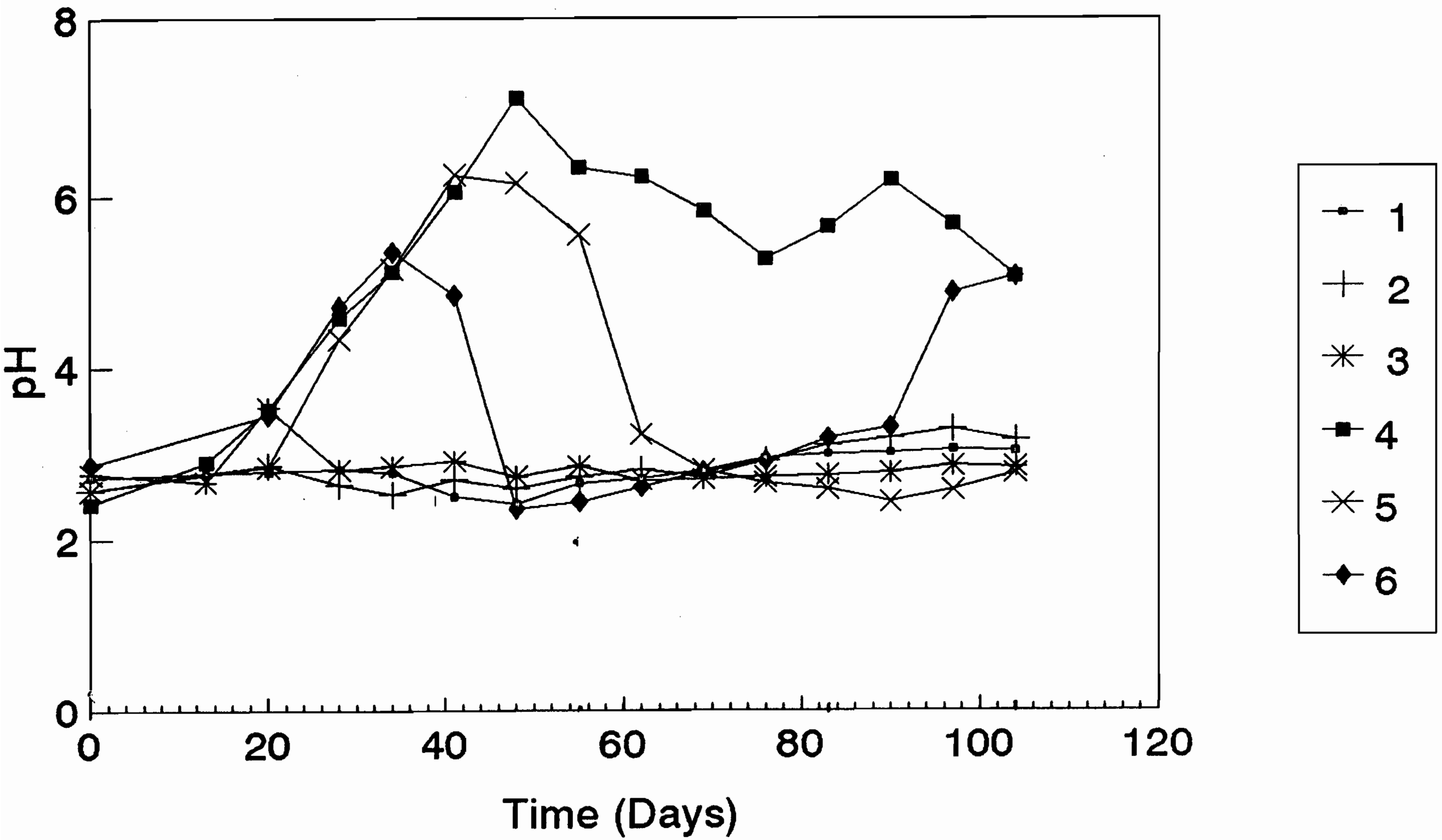

Figure 21. Controls pH compared to columns 4, 5, 6

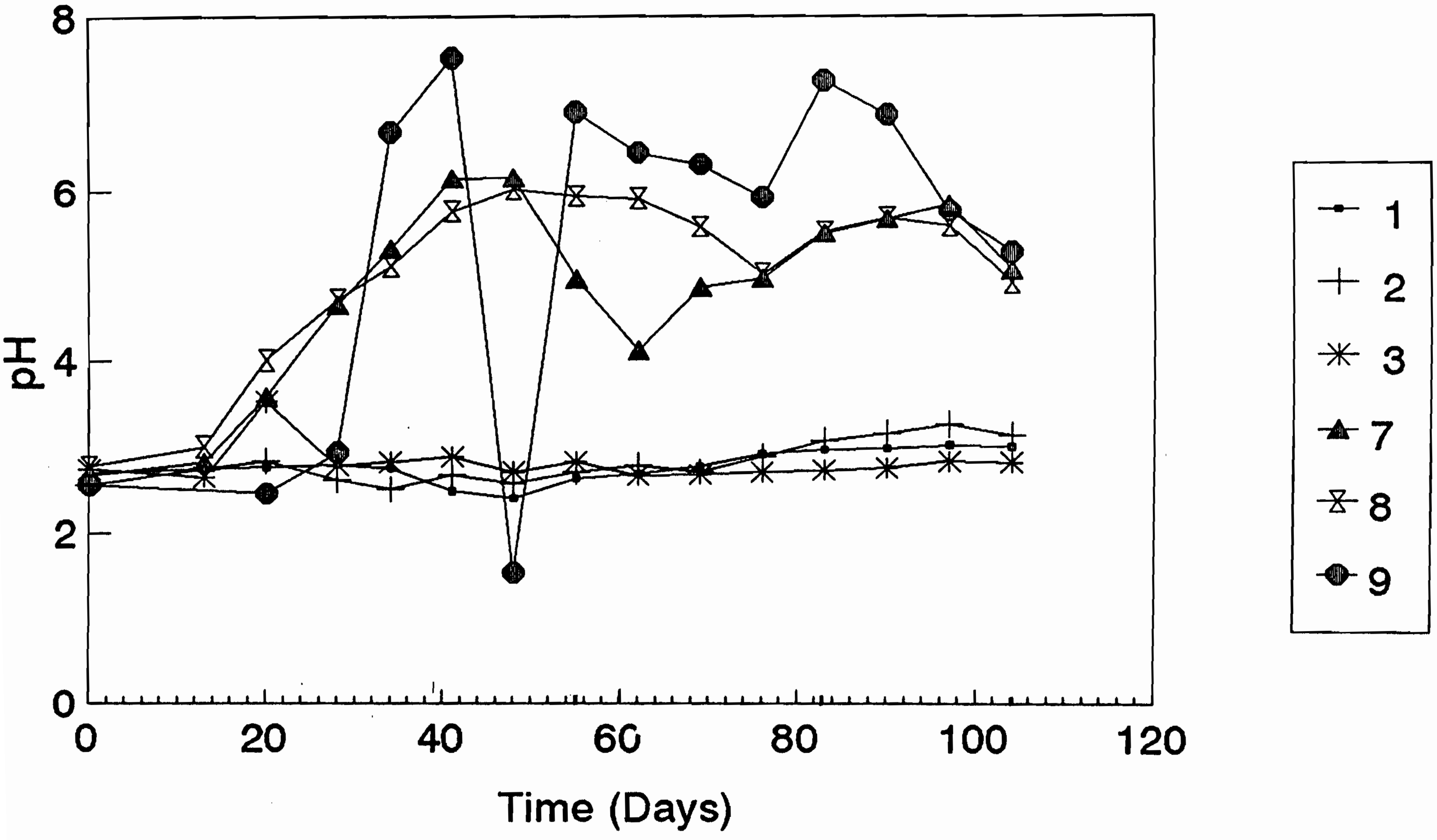

Figure 22. Controls pH compared to columns 7, 8, 9

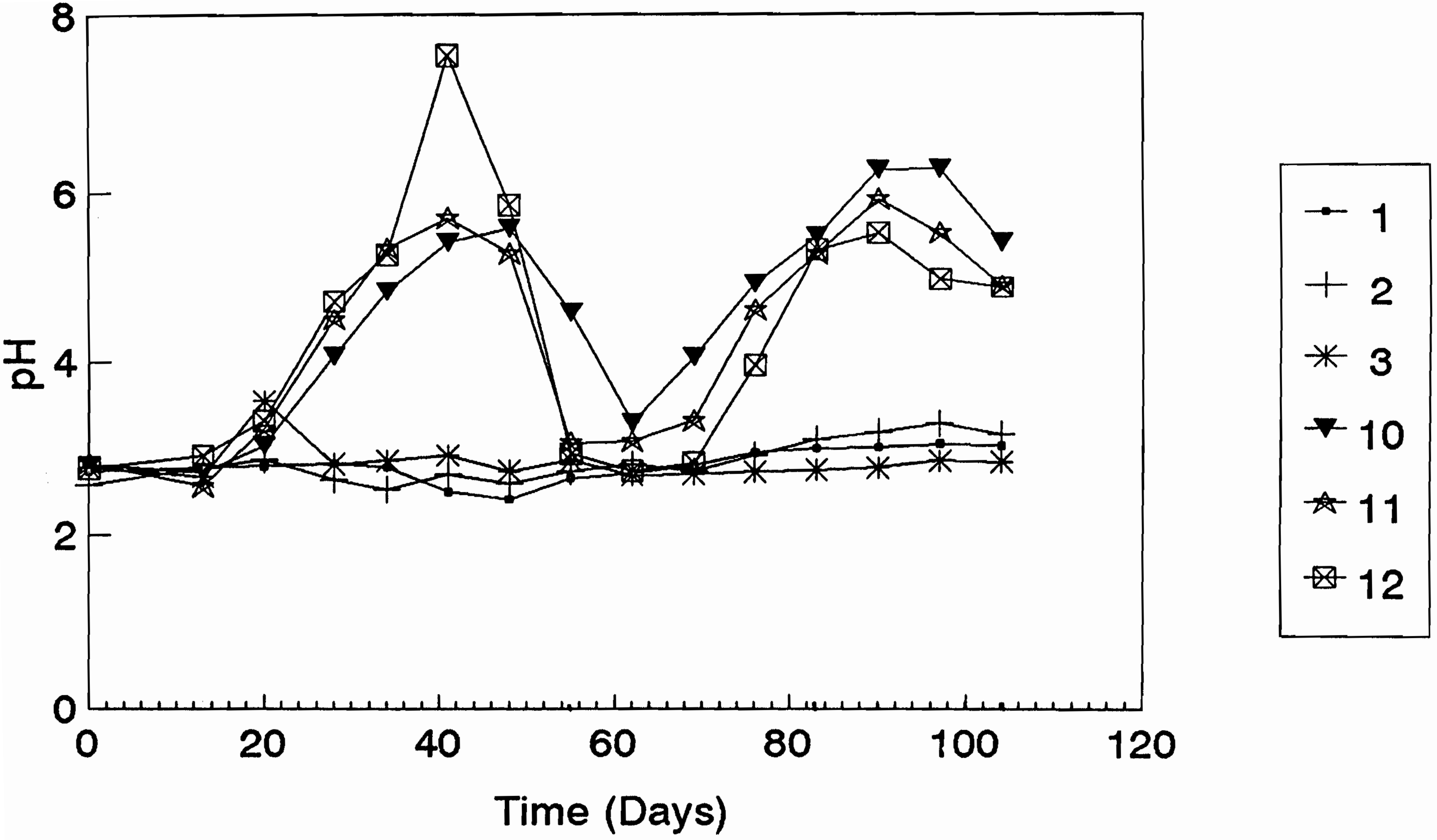

Figure 23. Controls pH compared to columns 10, 11, 12

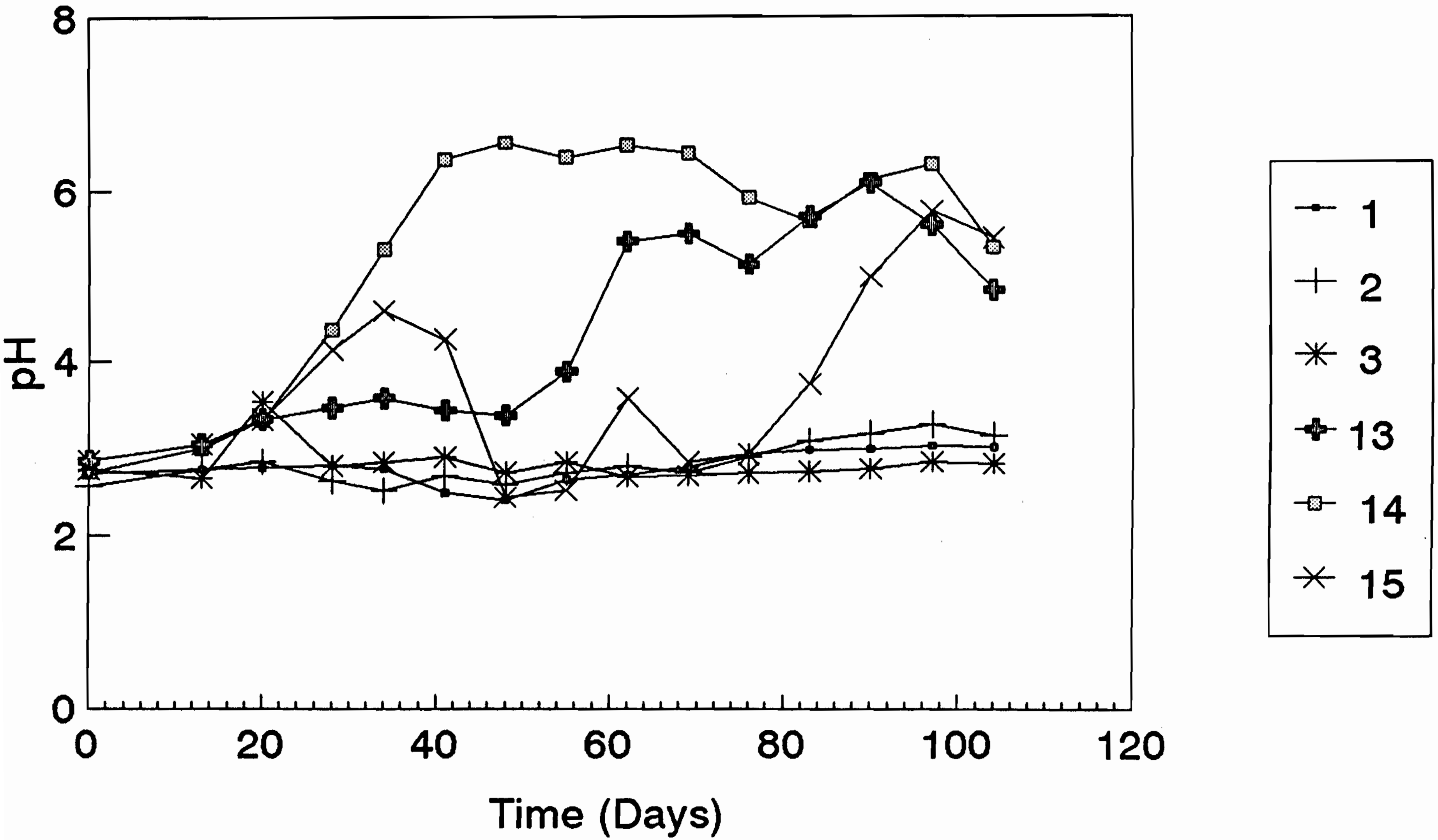

Figure 24. Controls pH compared to columns 13, 14, 15

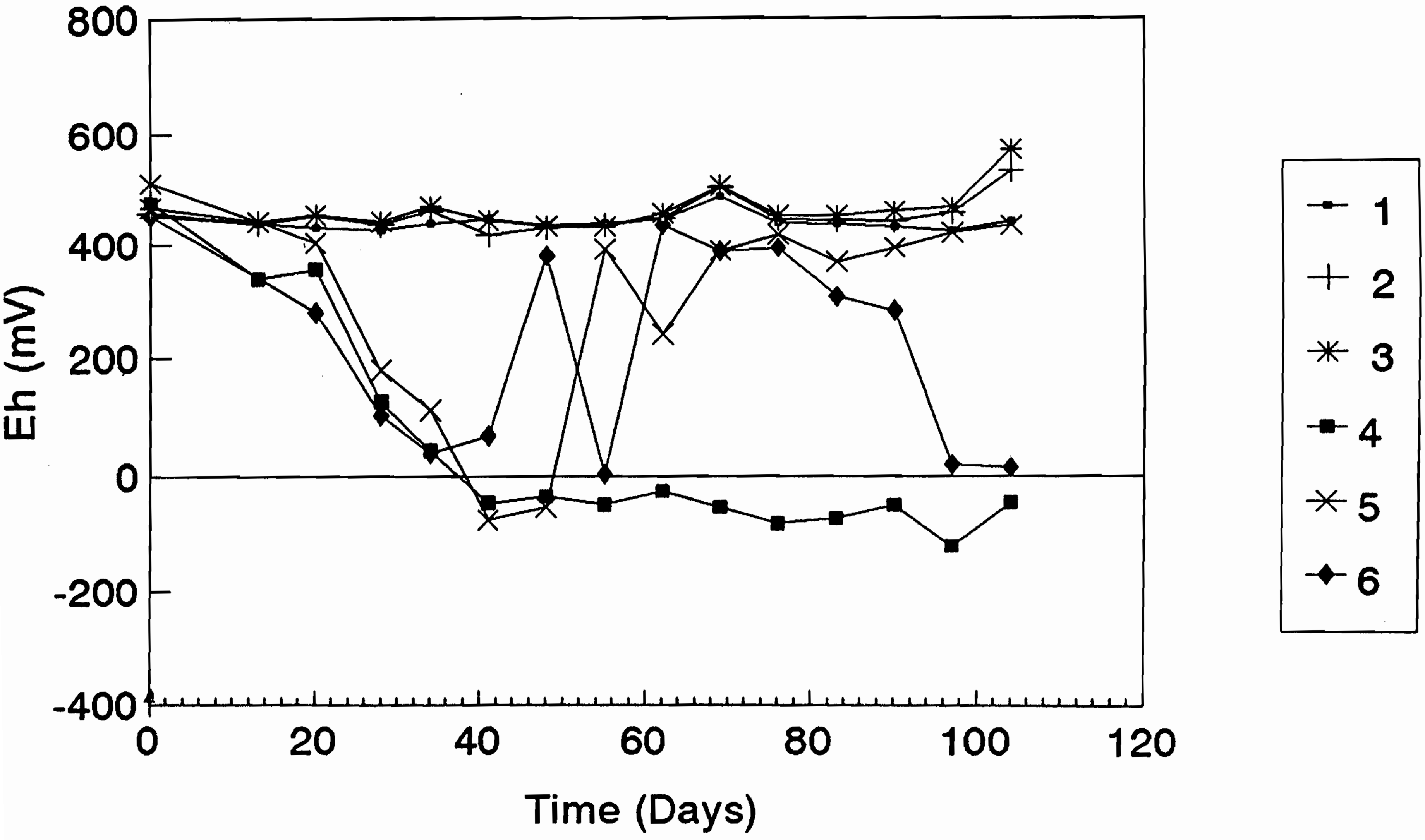

Figure 25. Controls Eh compared to columns 4, 5, 6

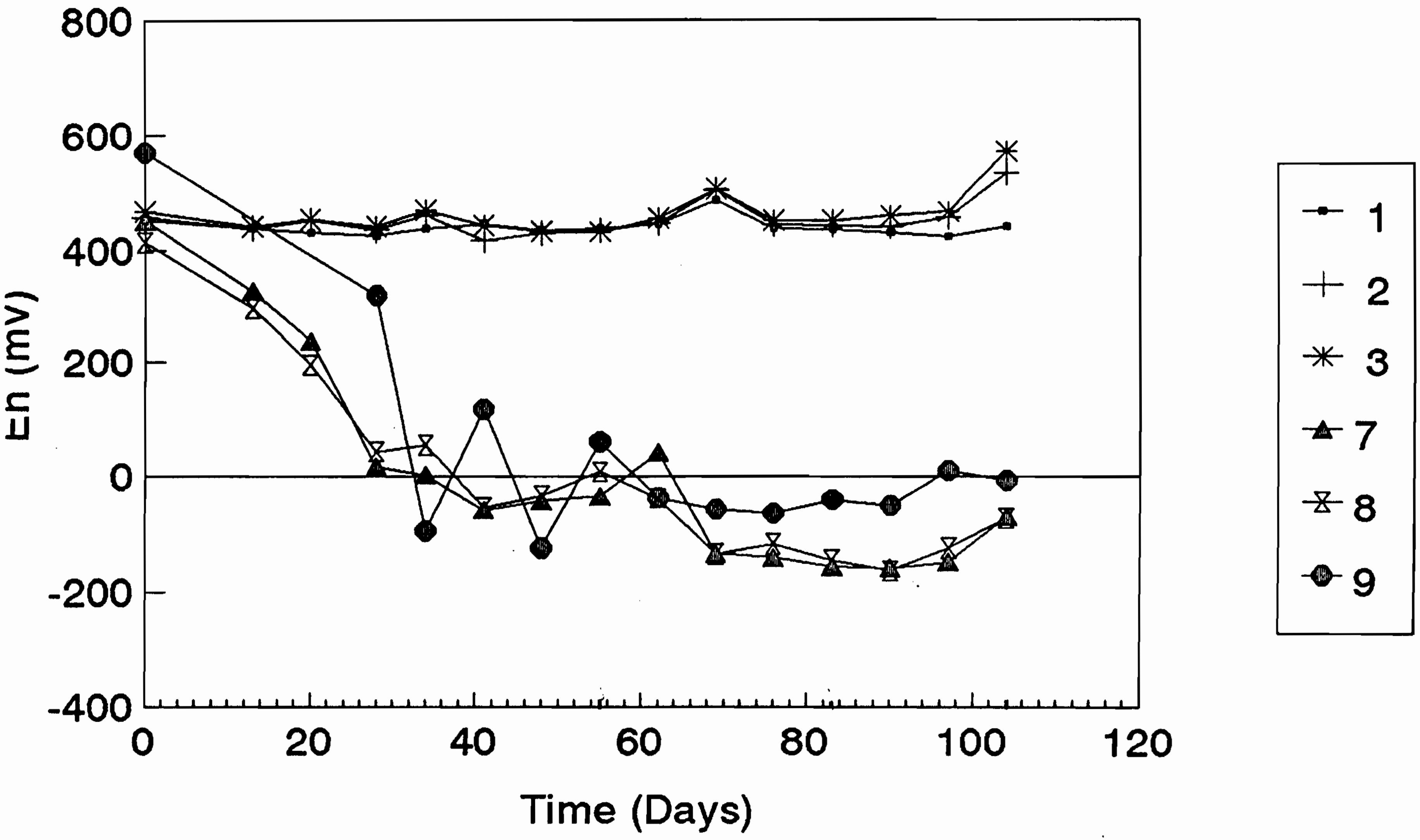

Figure 26. Controls Eh compared to columns 7, 8, 9

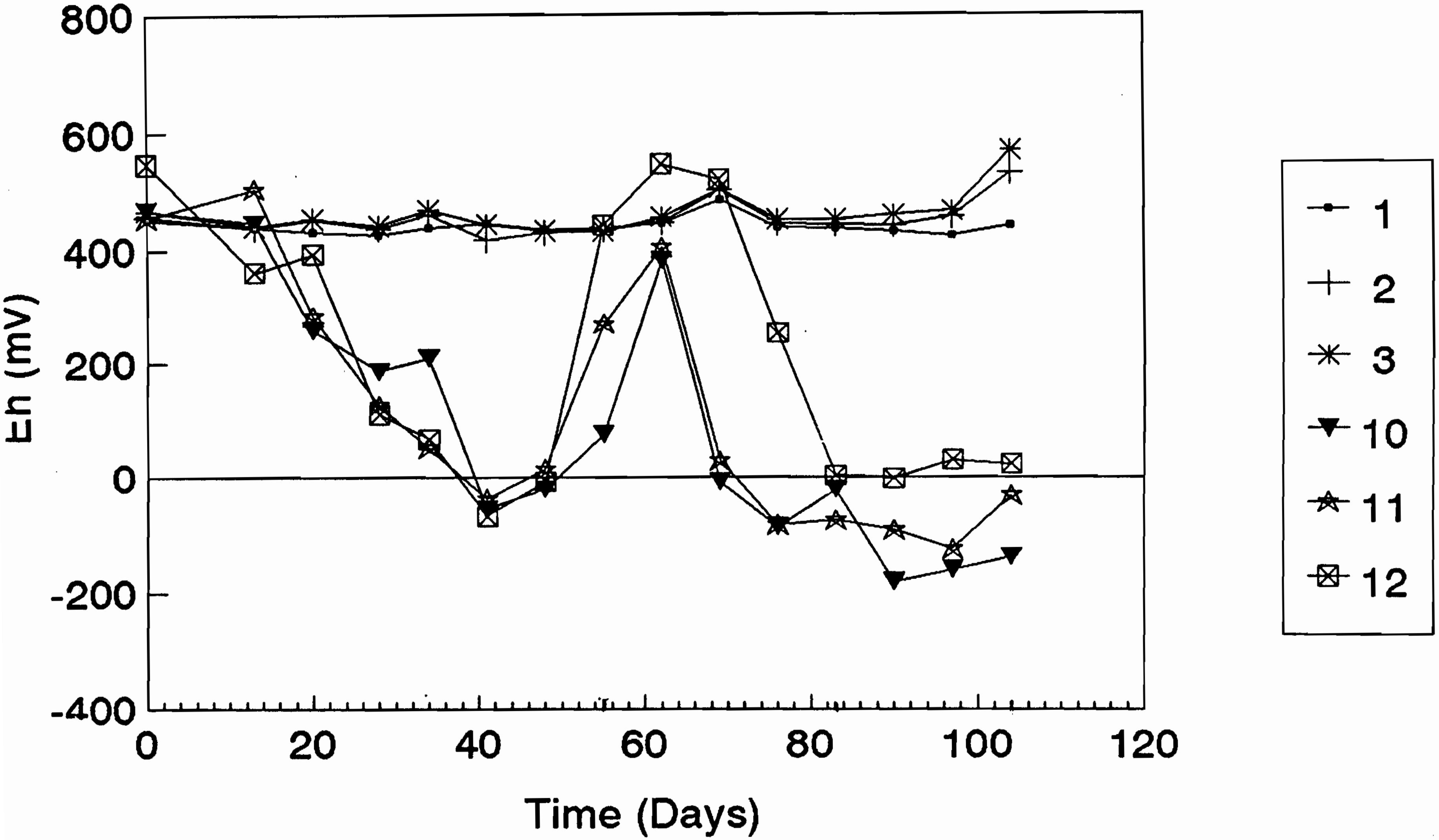

Figure 27. Controls Eh compared to columns 10, 11, 12

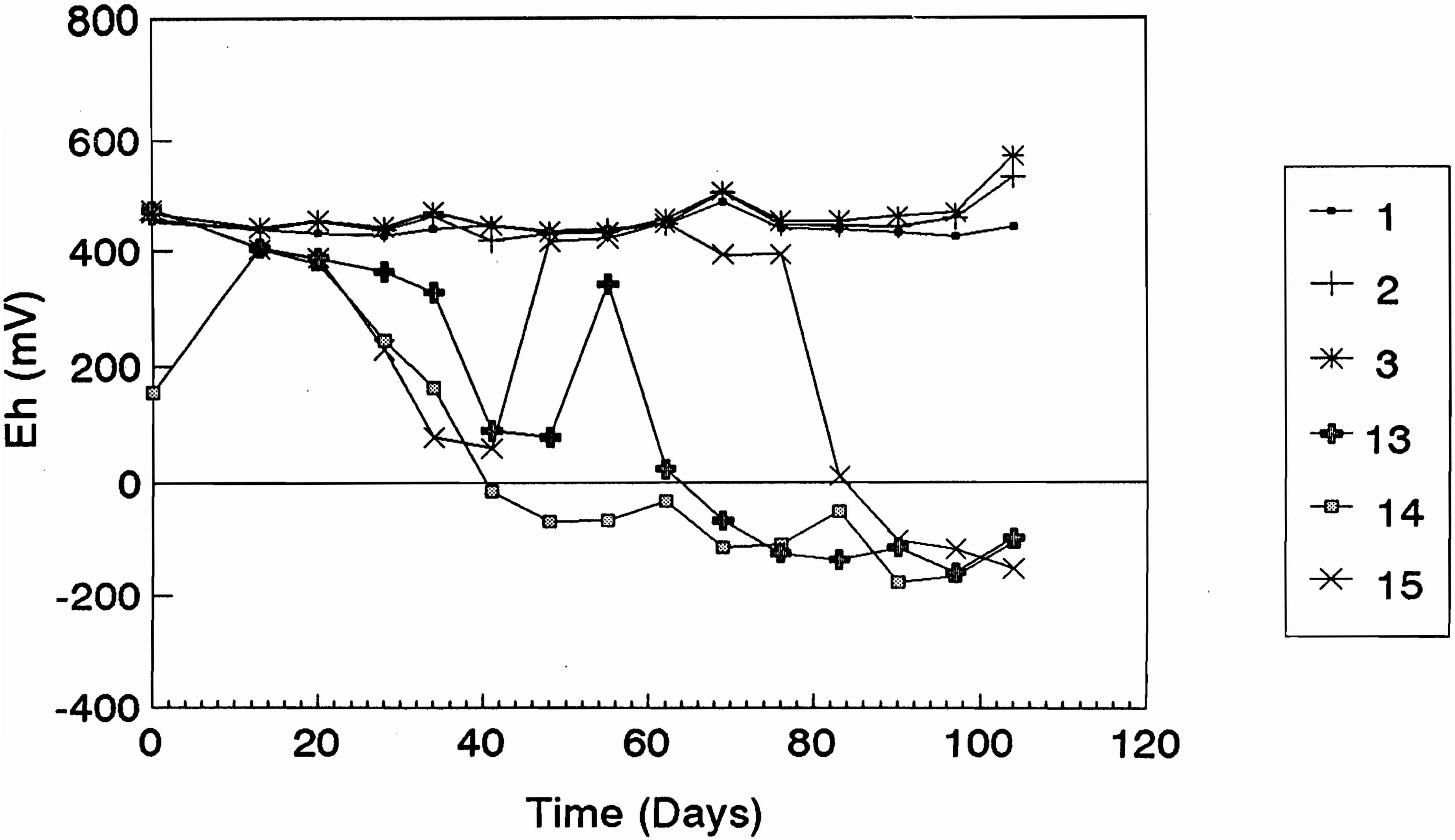

Figure 28. Controls Eh compared to columns 13, 14, 15

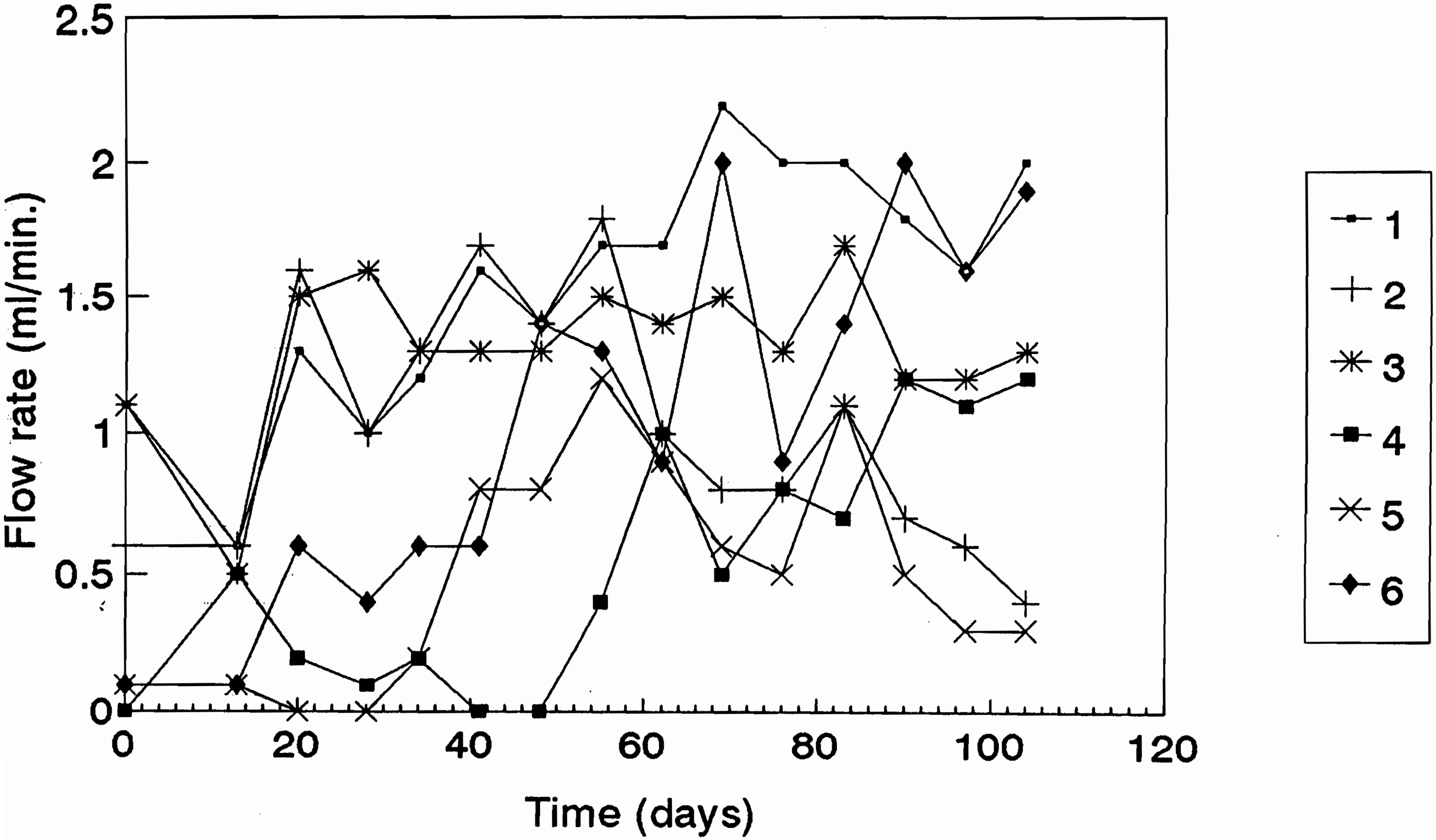

Figure 29. Controls flow rate compared to columns 4, 5, 6

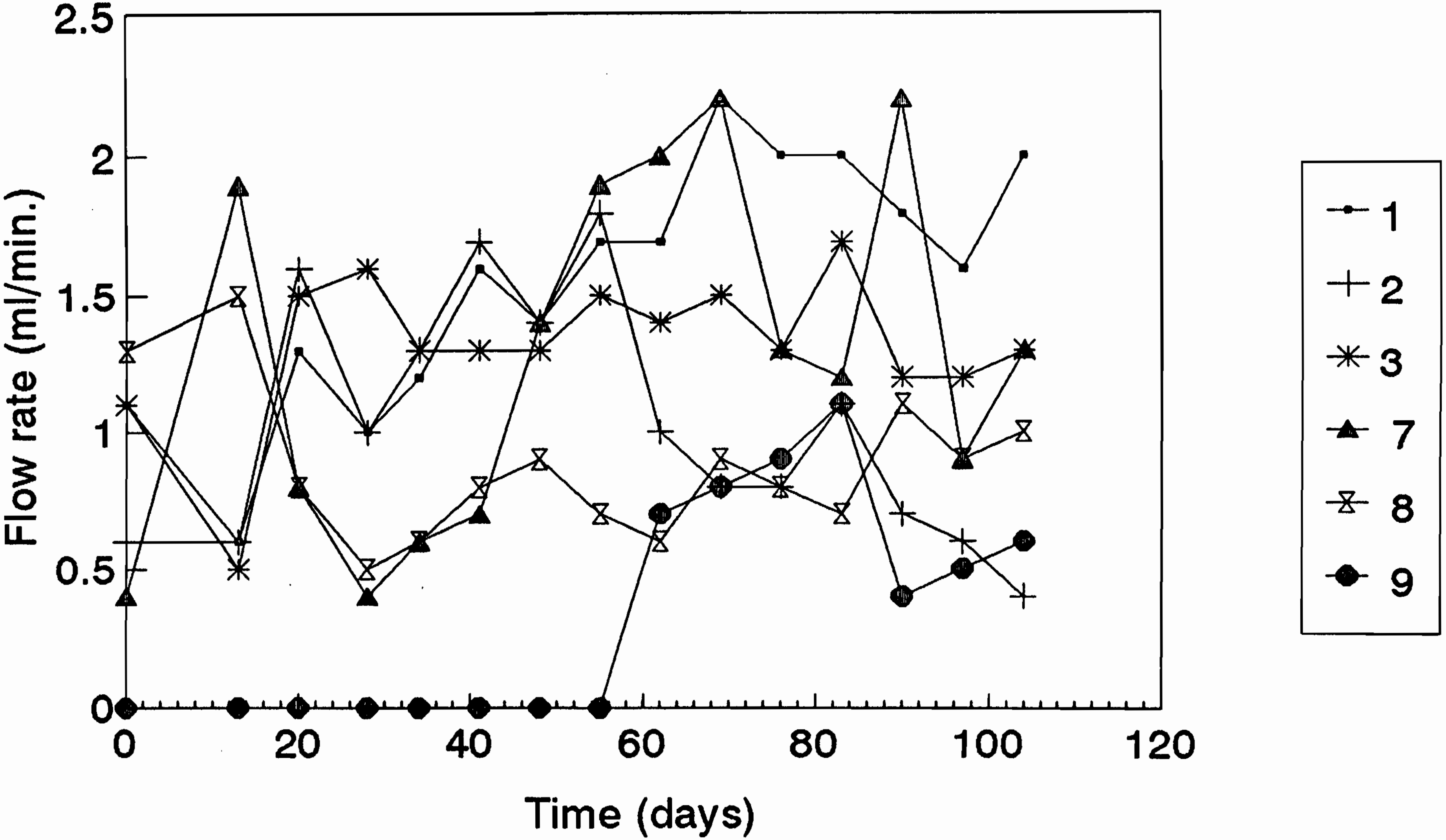

Figure 30. Controls flow rate compared to columns 7, 8, 9

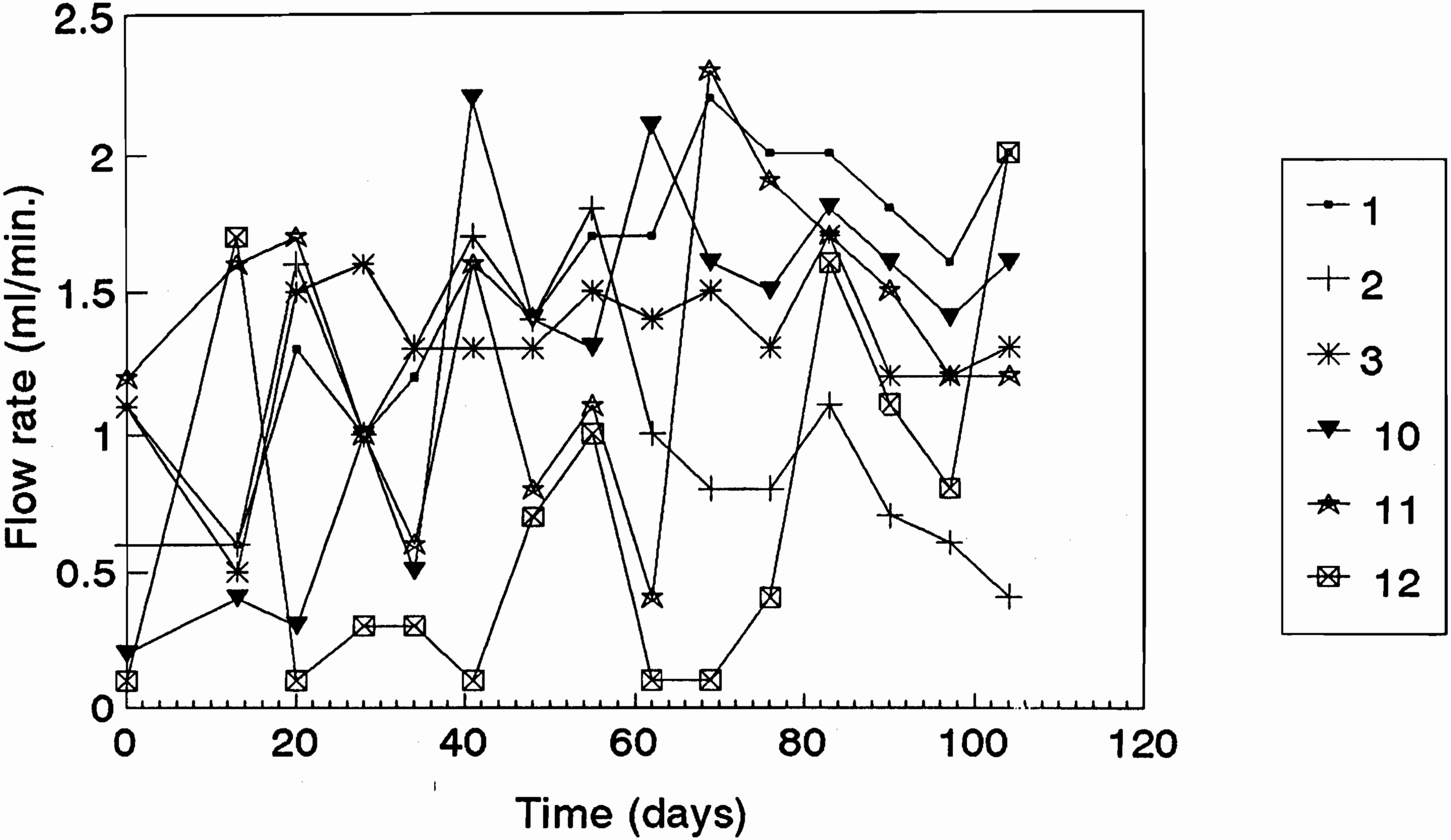

Figure 31. Controls flow rate compared to columns 10, 11, 12

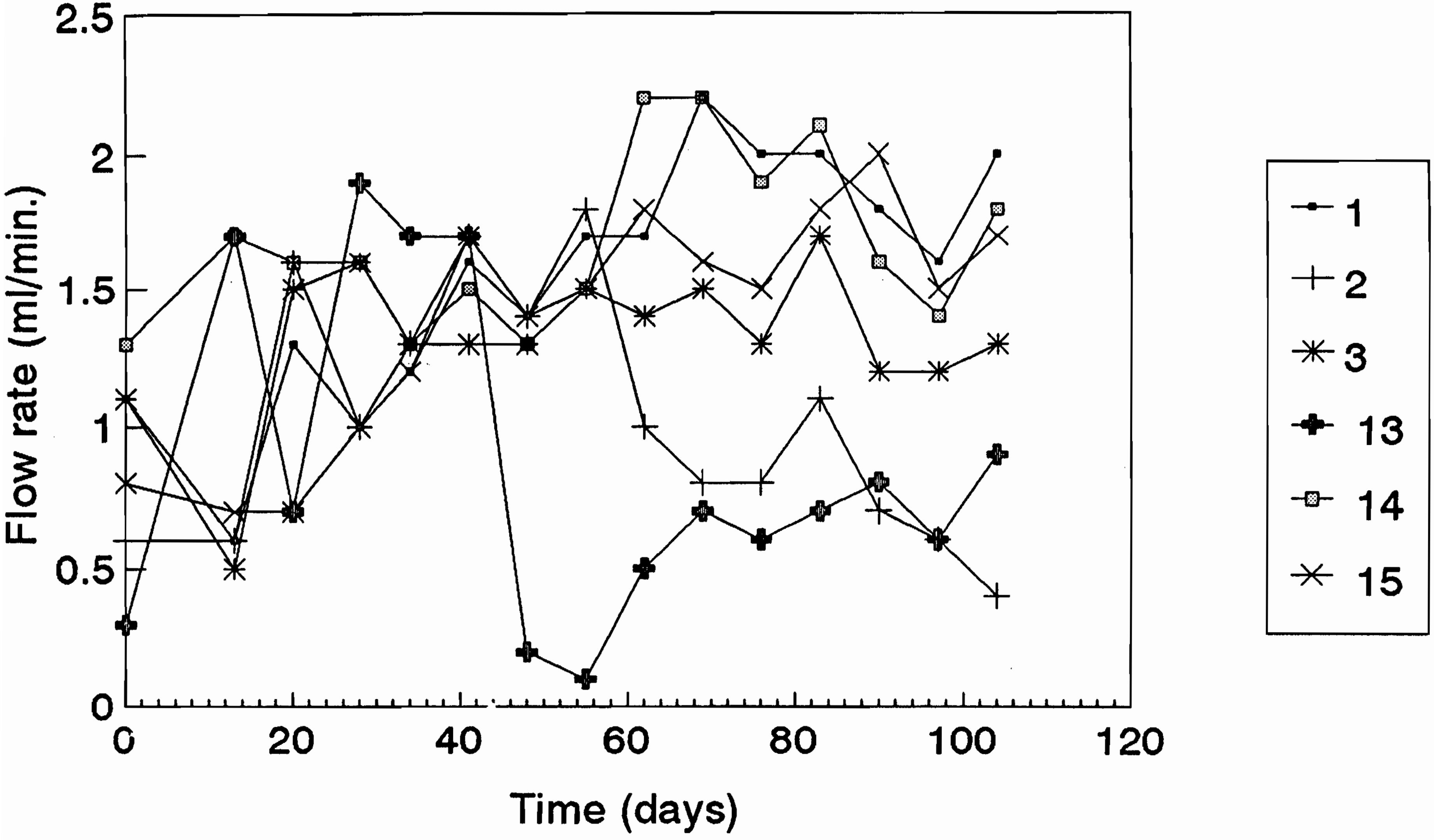

Figure 32. Controls flow rate compared to columns 13, 14, 15

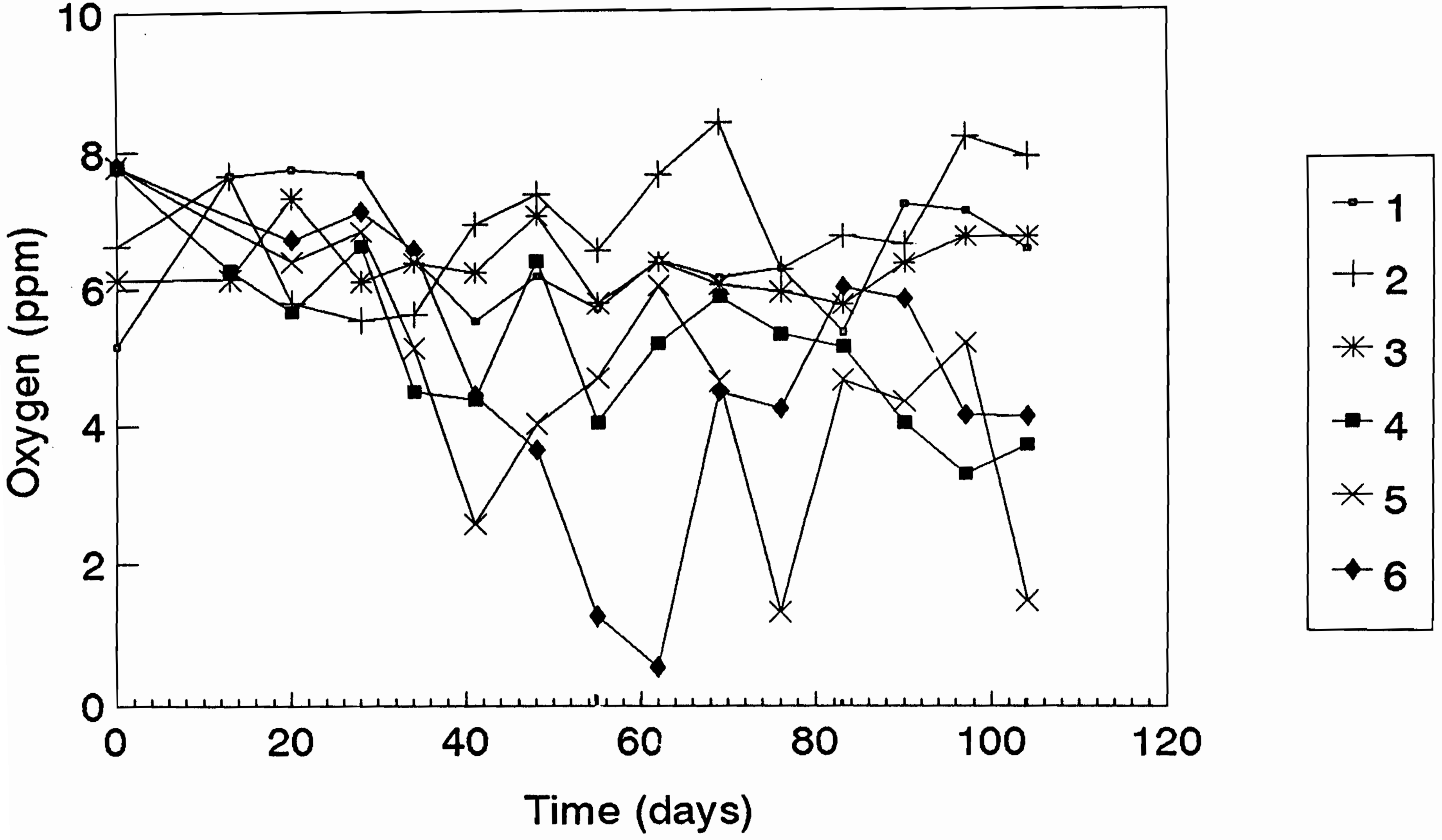

Figure 33. Controls dissolved oxygen compared to columns 4, 5, 6

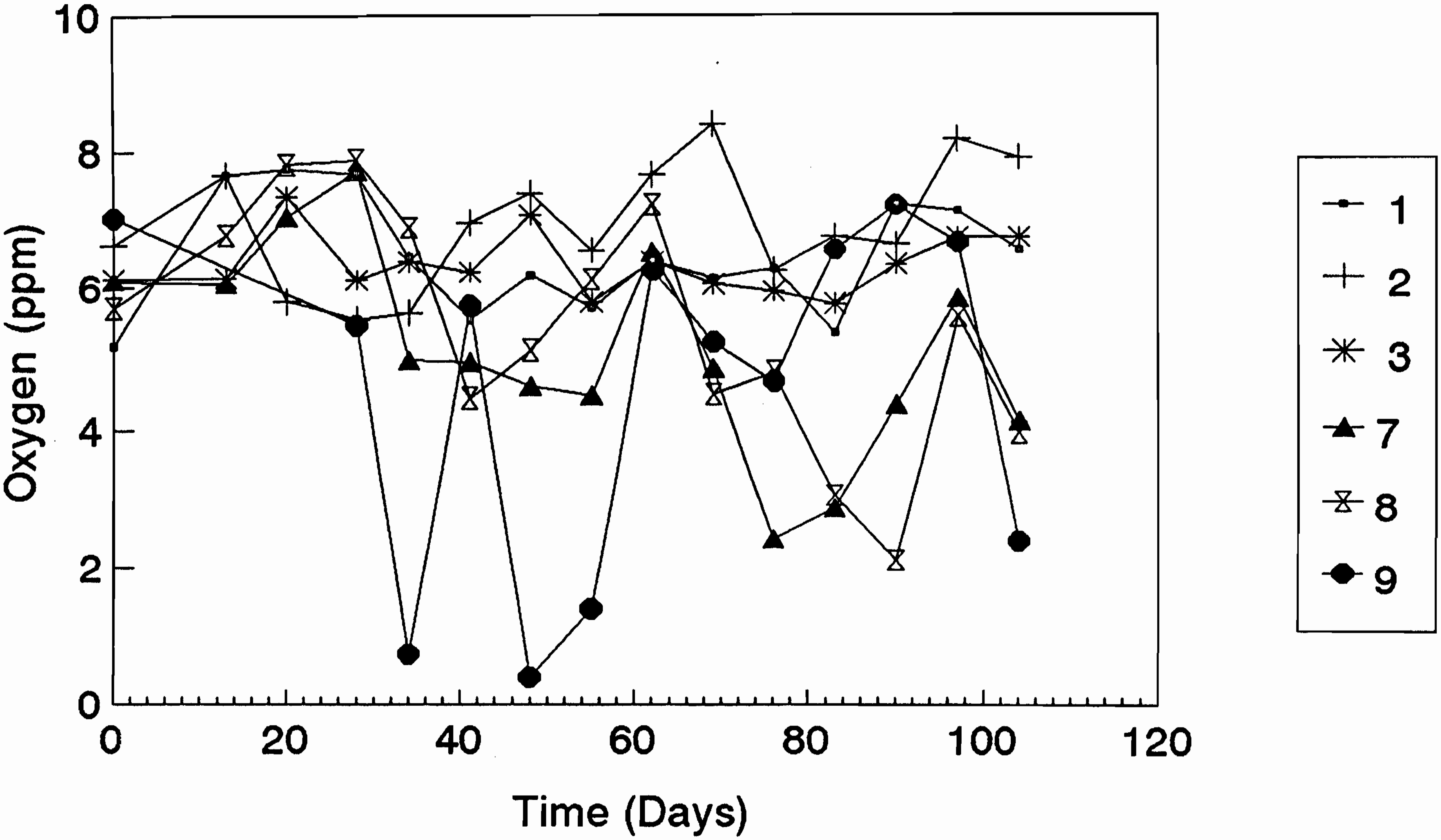

Figure 34. Controls dissolved oxygen compared to columns 7, 8, 9

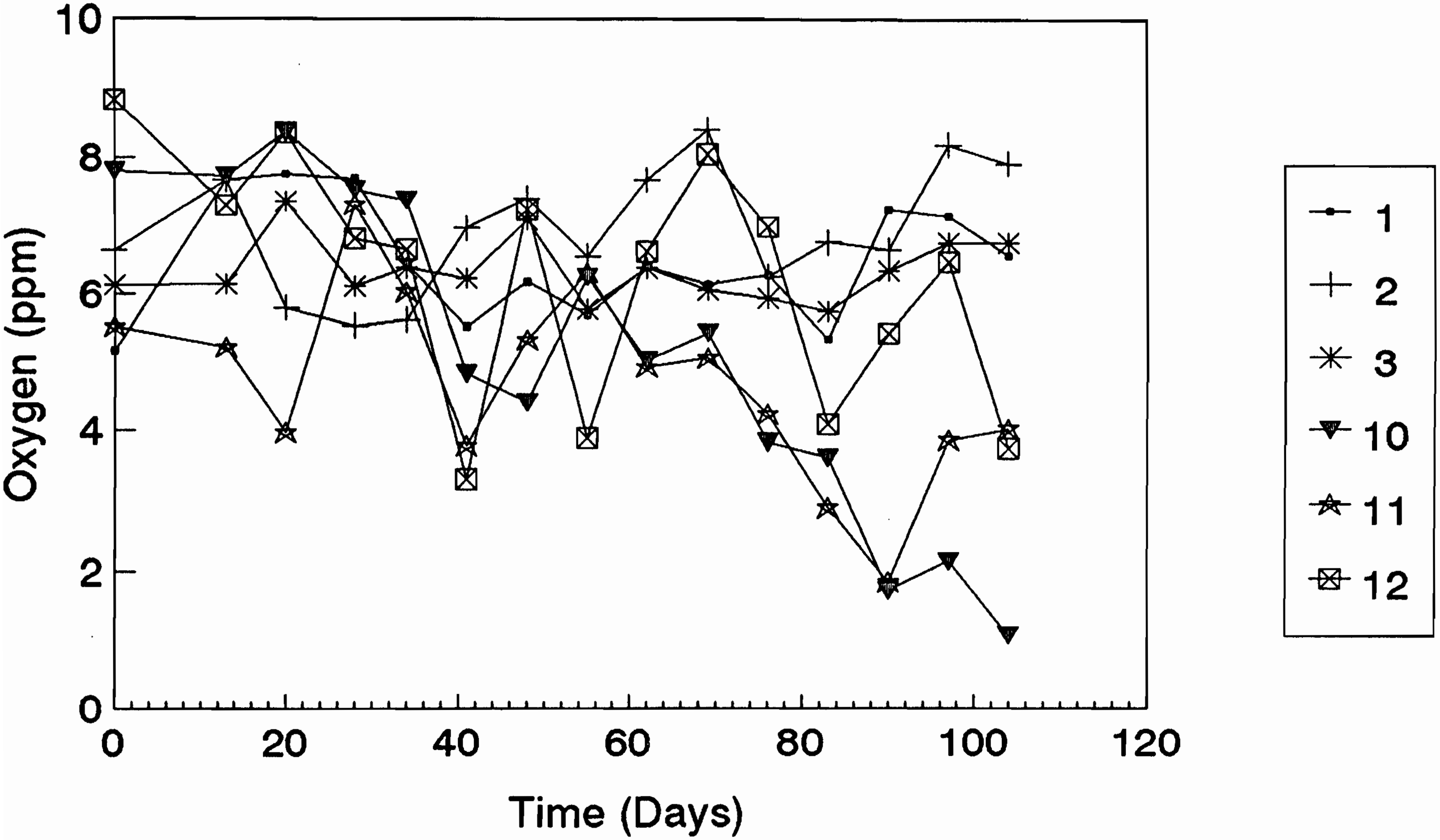

Figure 35. Controls dissolved oxygen compared to columns 10, 11, 12

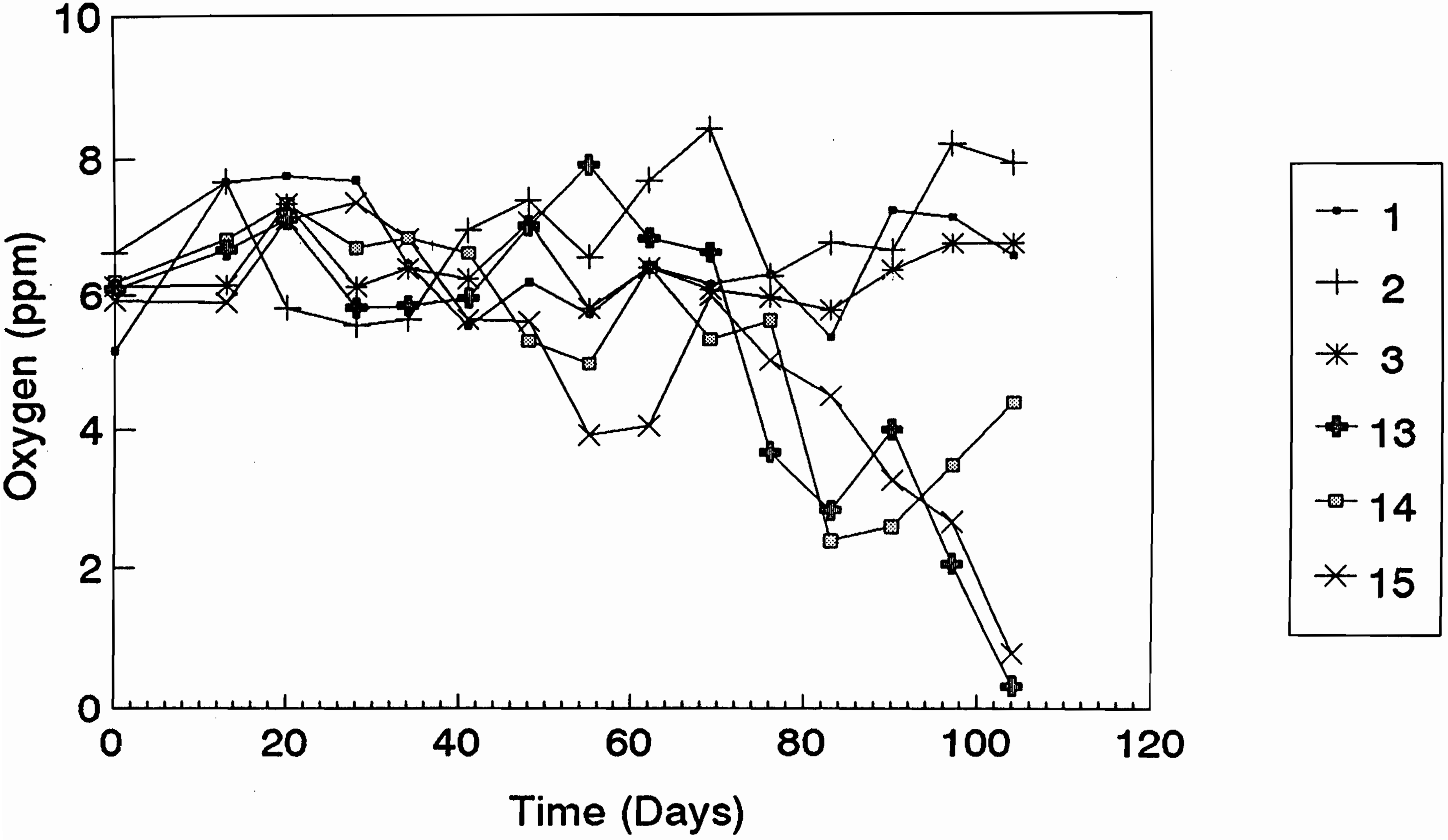

Figure 36. Controls dissolved oxygen compared to columns 13, 14, 15

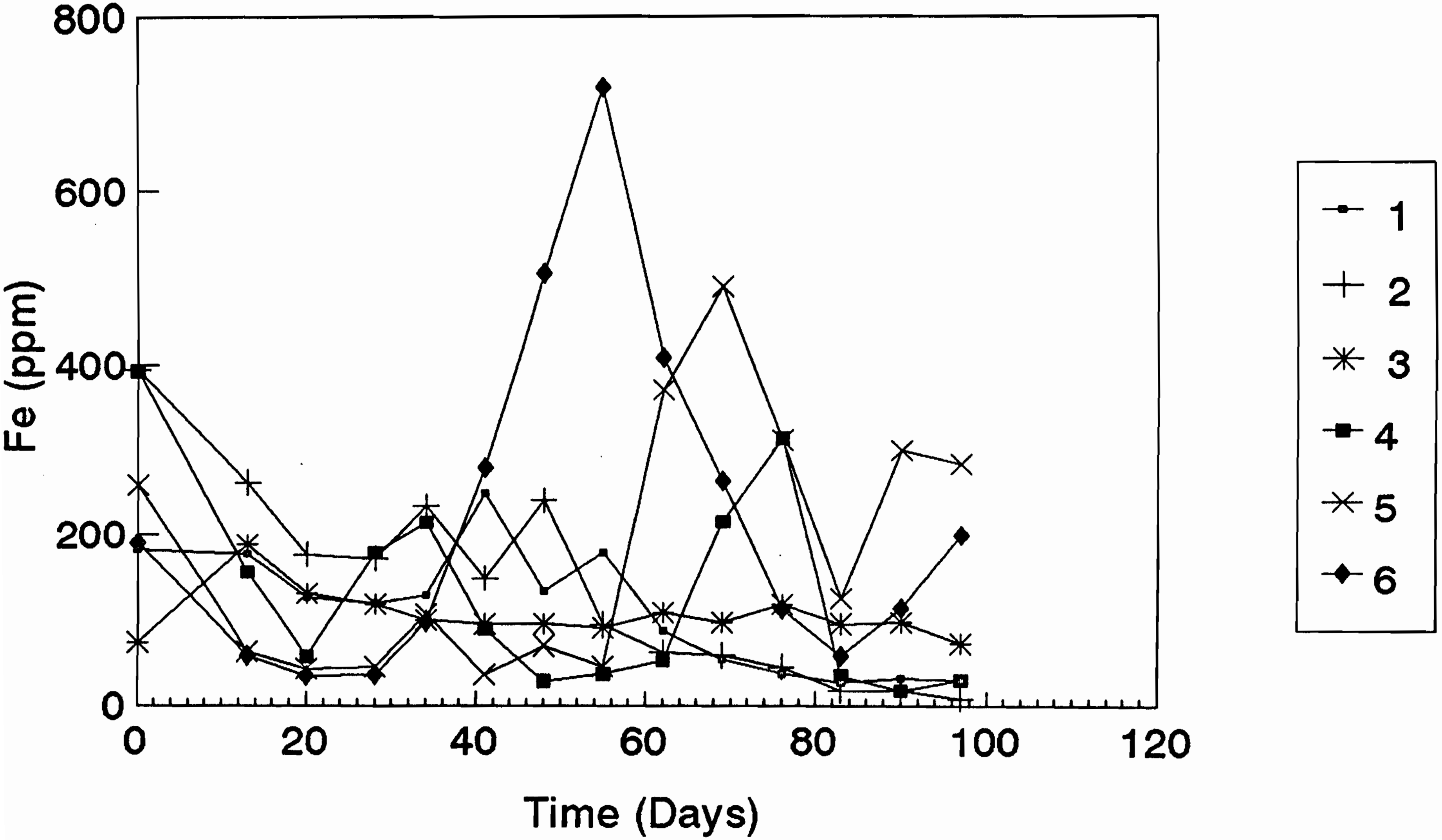

Figure 37. Controls total iron compared to columns 4, 5, 6

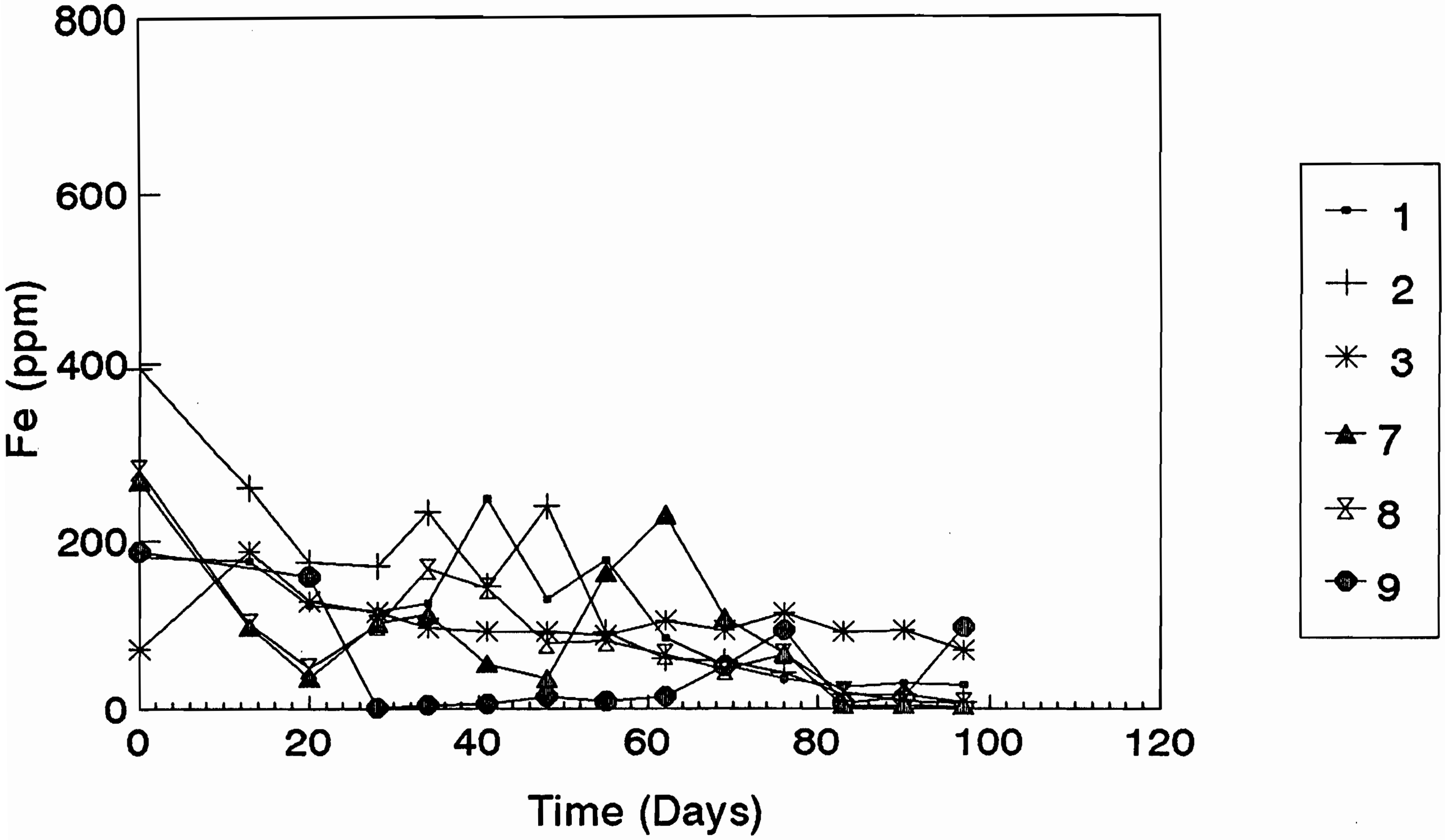

Figure 38. Controls total iron compared to columns 7, 8, 9

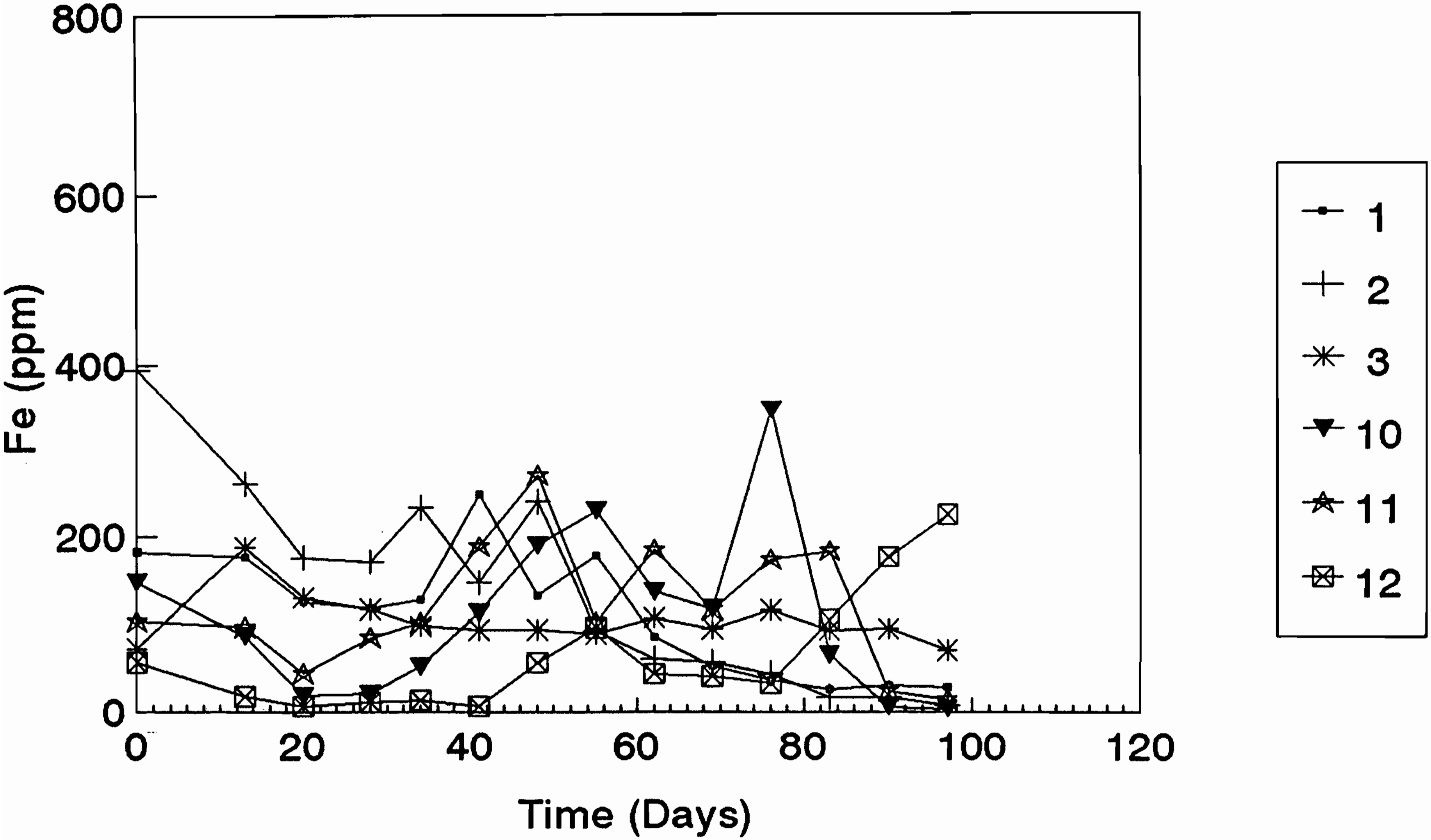

Figure 39. Controls total iron compared to columns 10, 11, 12

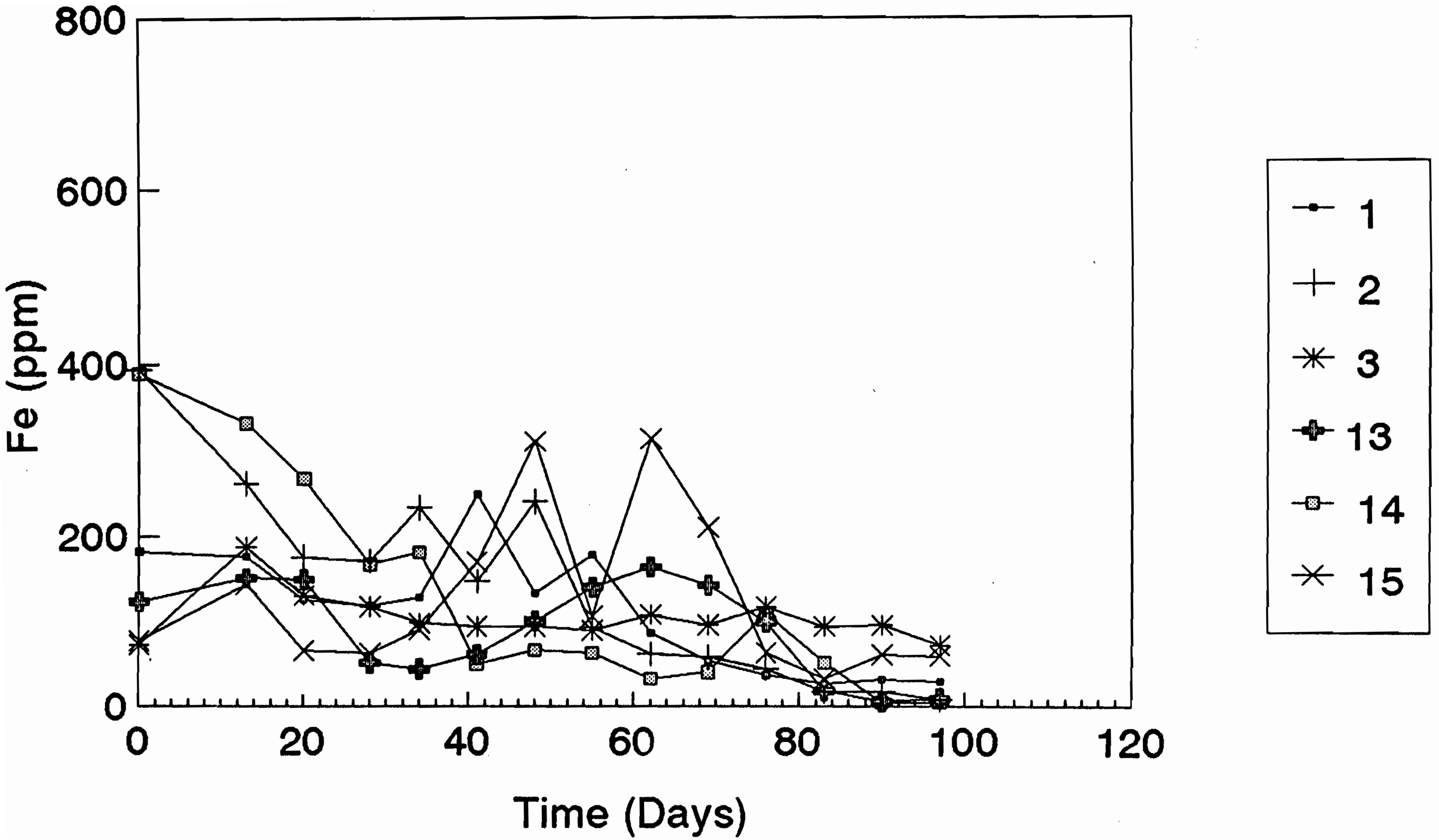

Figure 40. Controls total iron compared to columns 13, 14, 15

APPENDIX - E

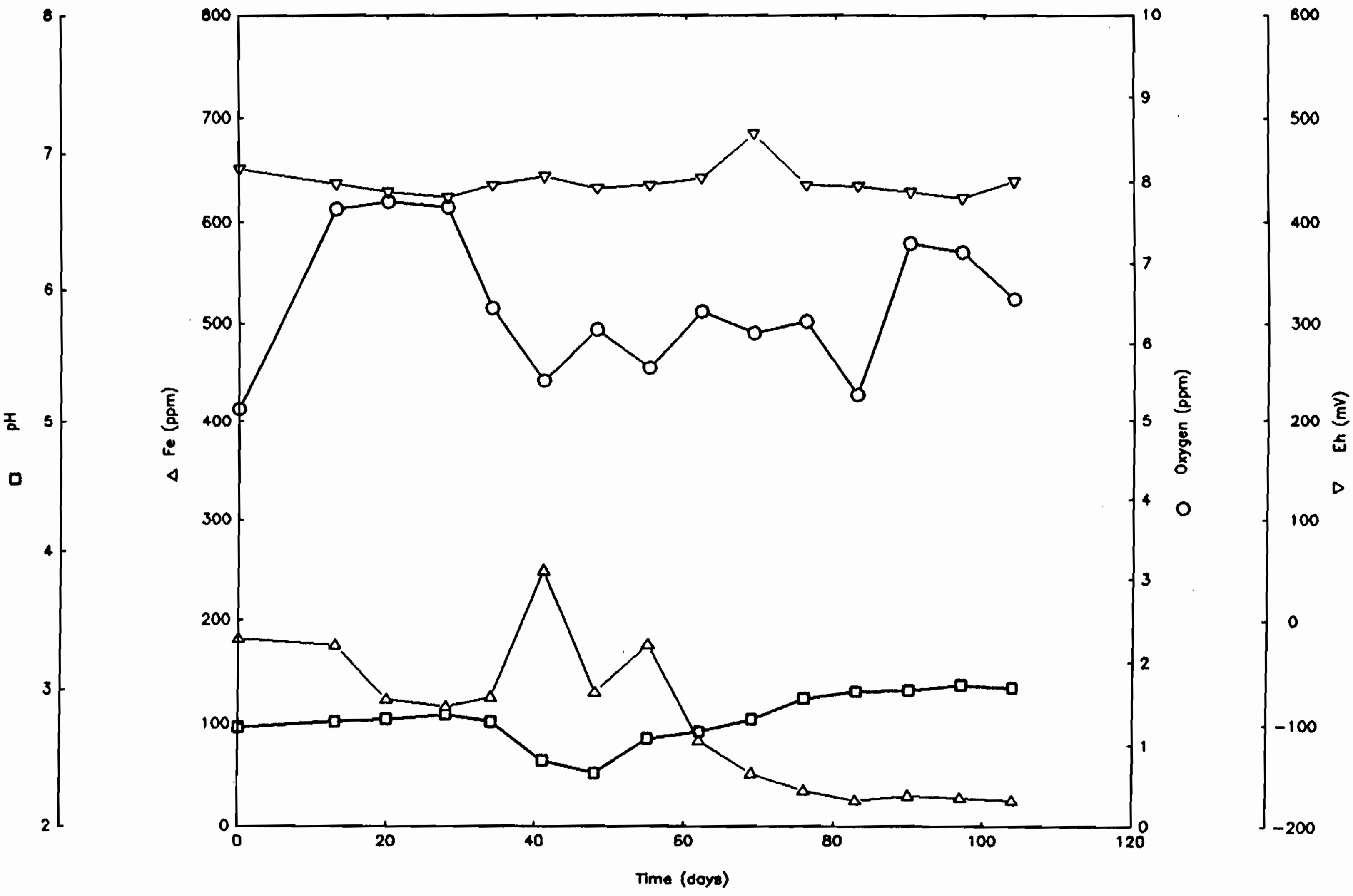

Figure 41. Column 1 pH, total iron, dissolved oxygen and Eh.

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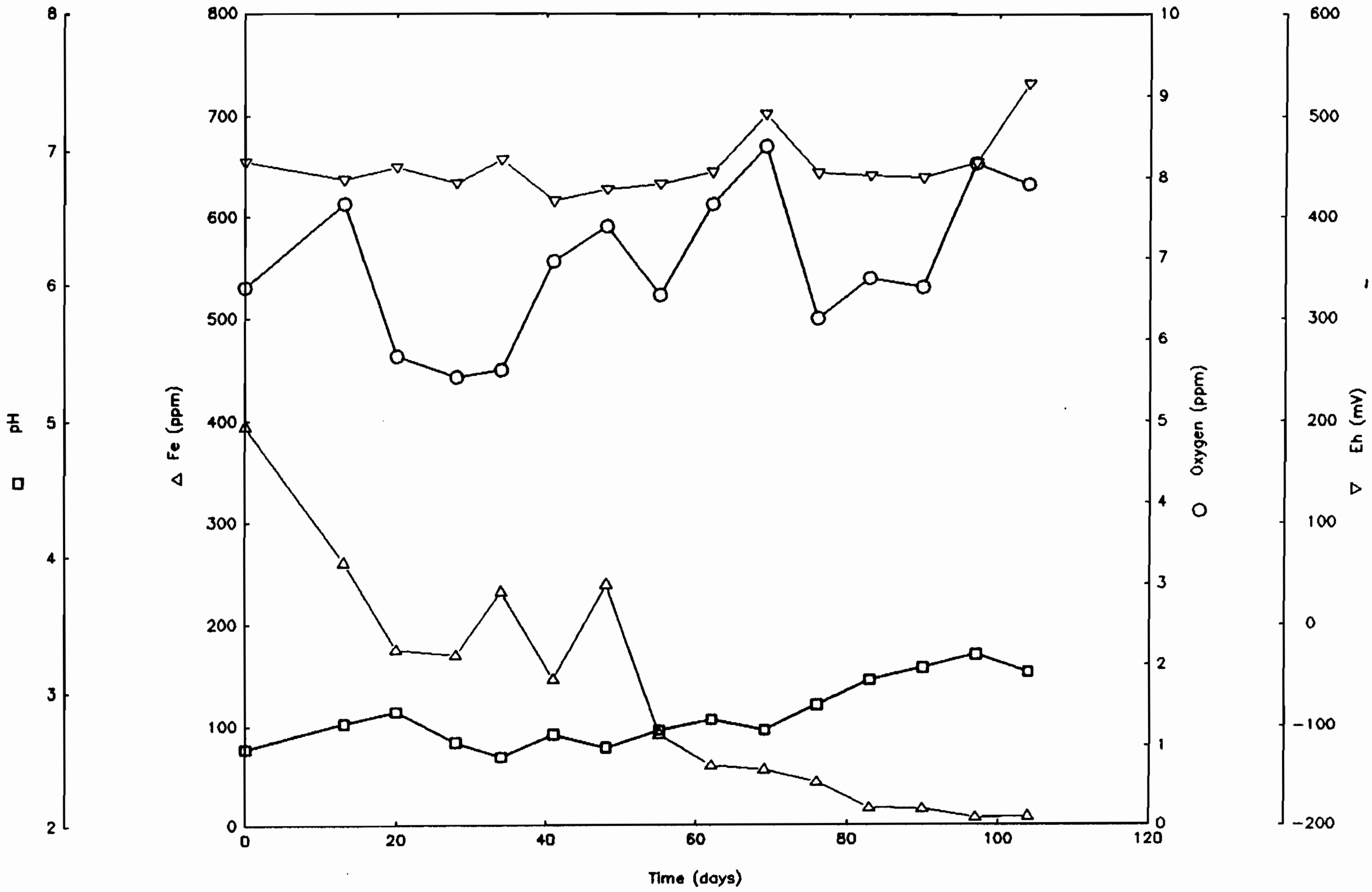

Figure 42. Column 2 pH, total iron, dissolved oxygen and Eh.

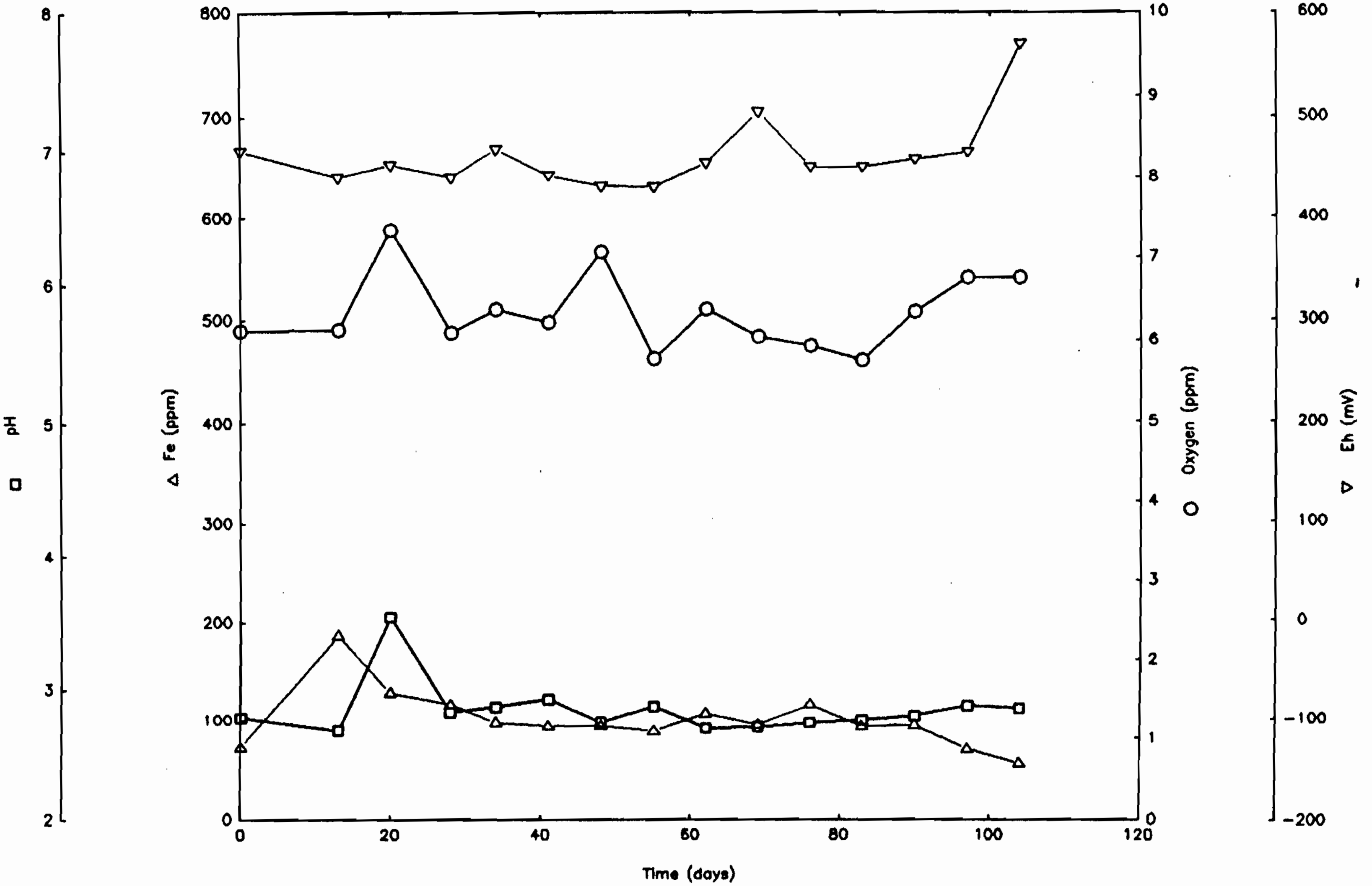

Figure 43. Column 3 pH, total iron, dissolved oxygen and Eh.

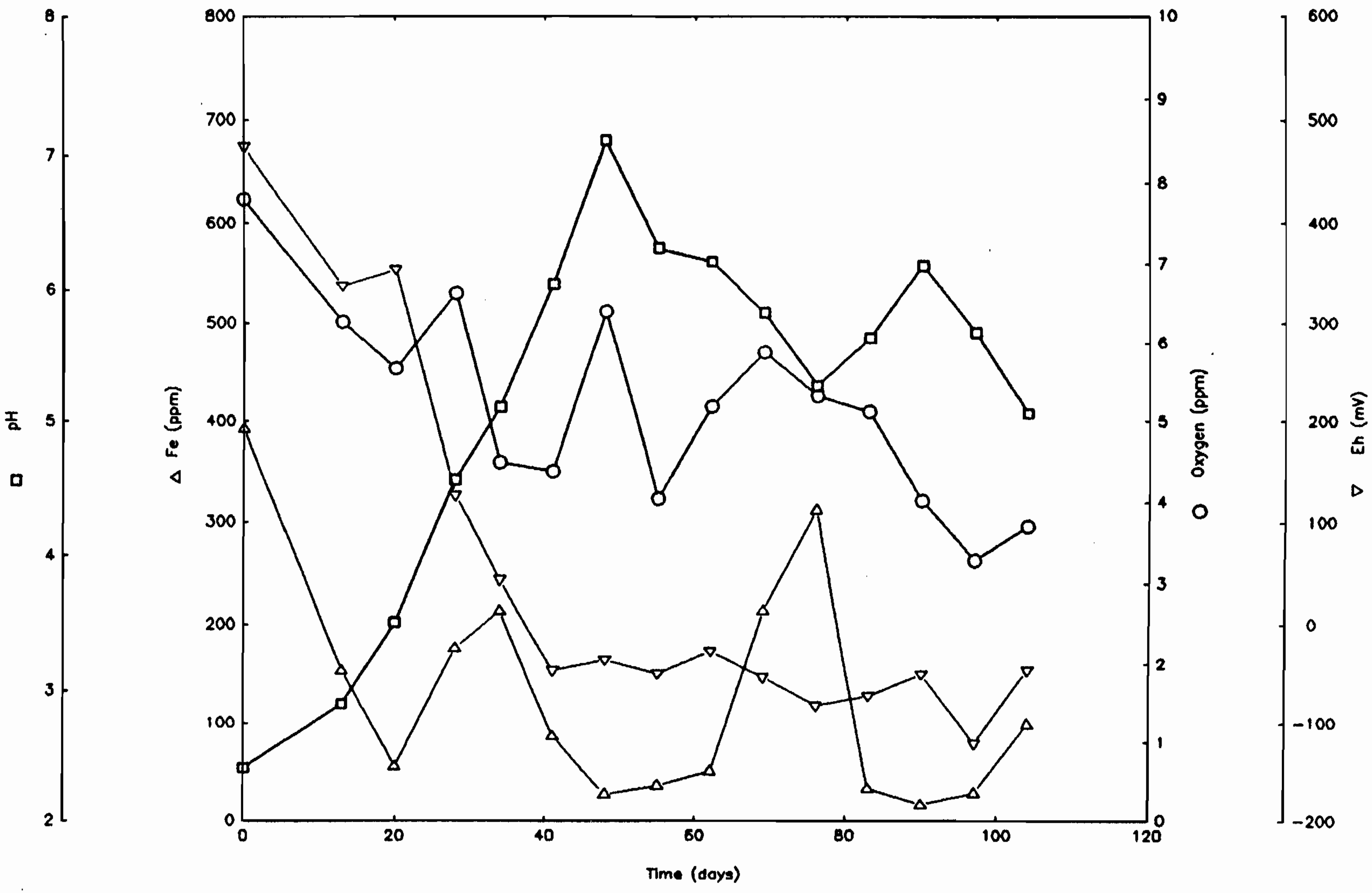

Figure 44. Column 4 pH, total iron, dissolved oxygen and Eh.

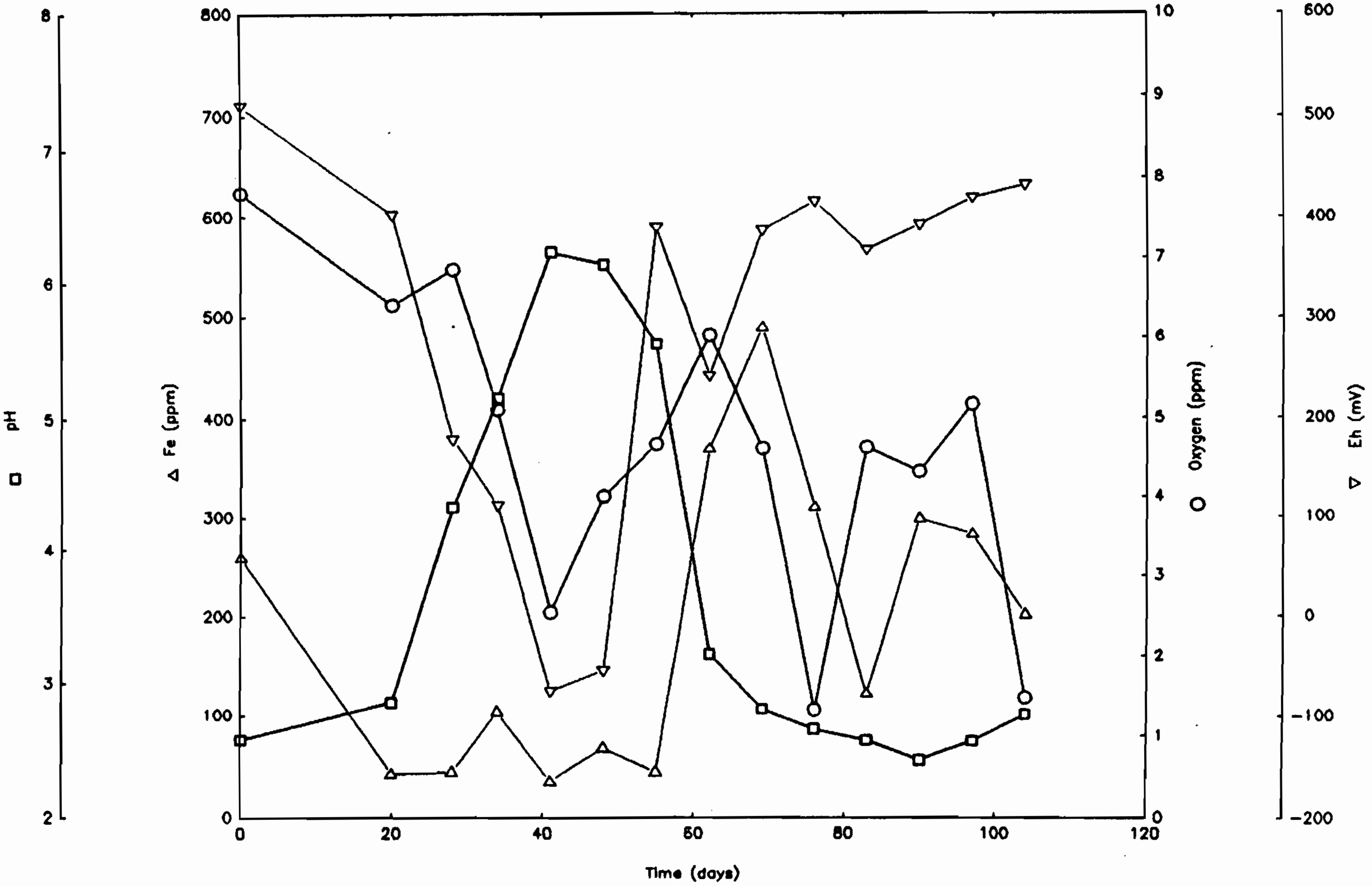

Figure 45. Column 5 pH, total iron, dissolved oxygen and Eh.

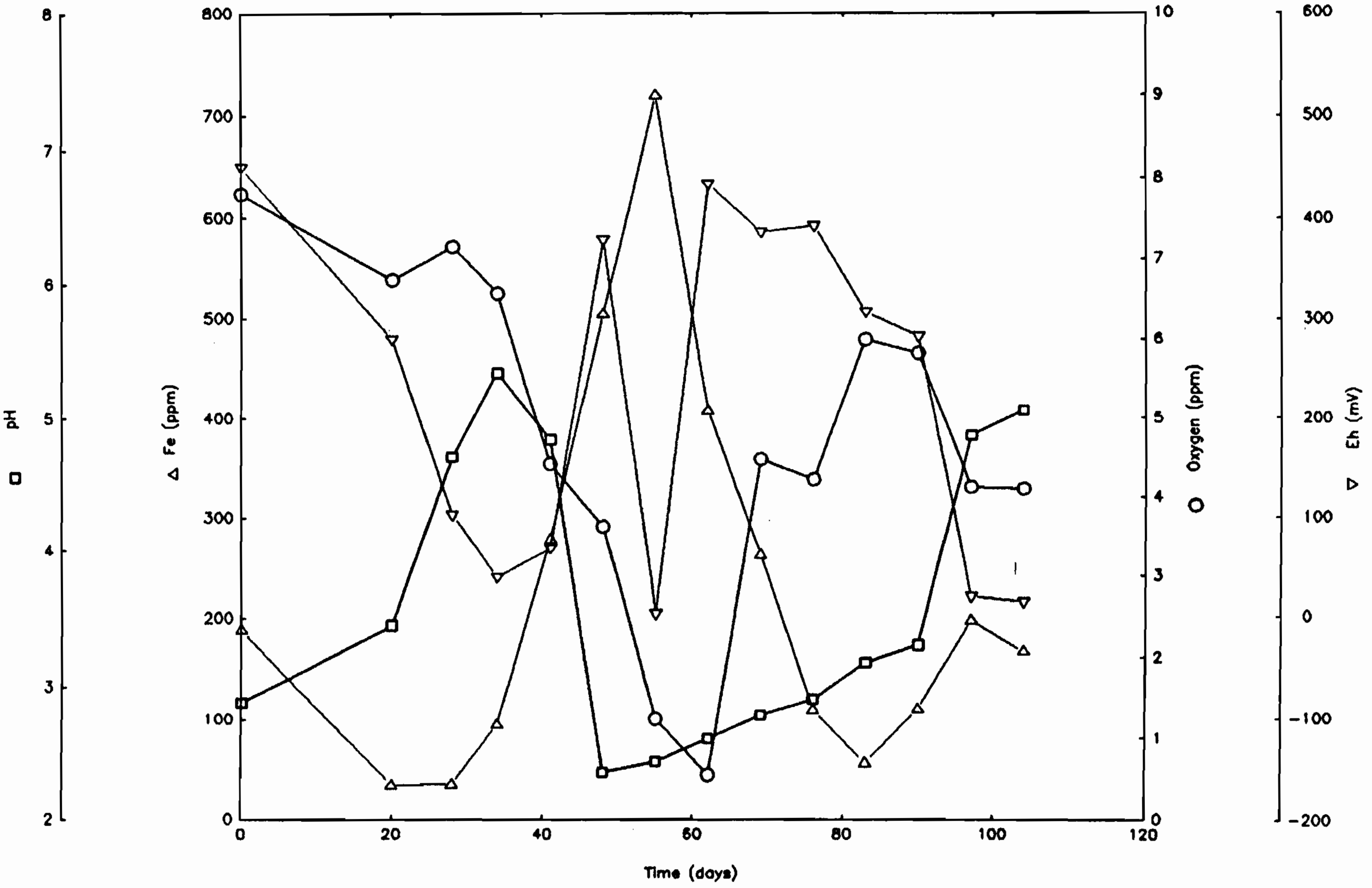

Figure 46. Column 6 pH, total iron, dissolved oxygen and Eh.

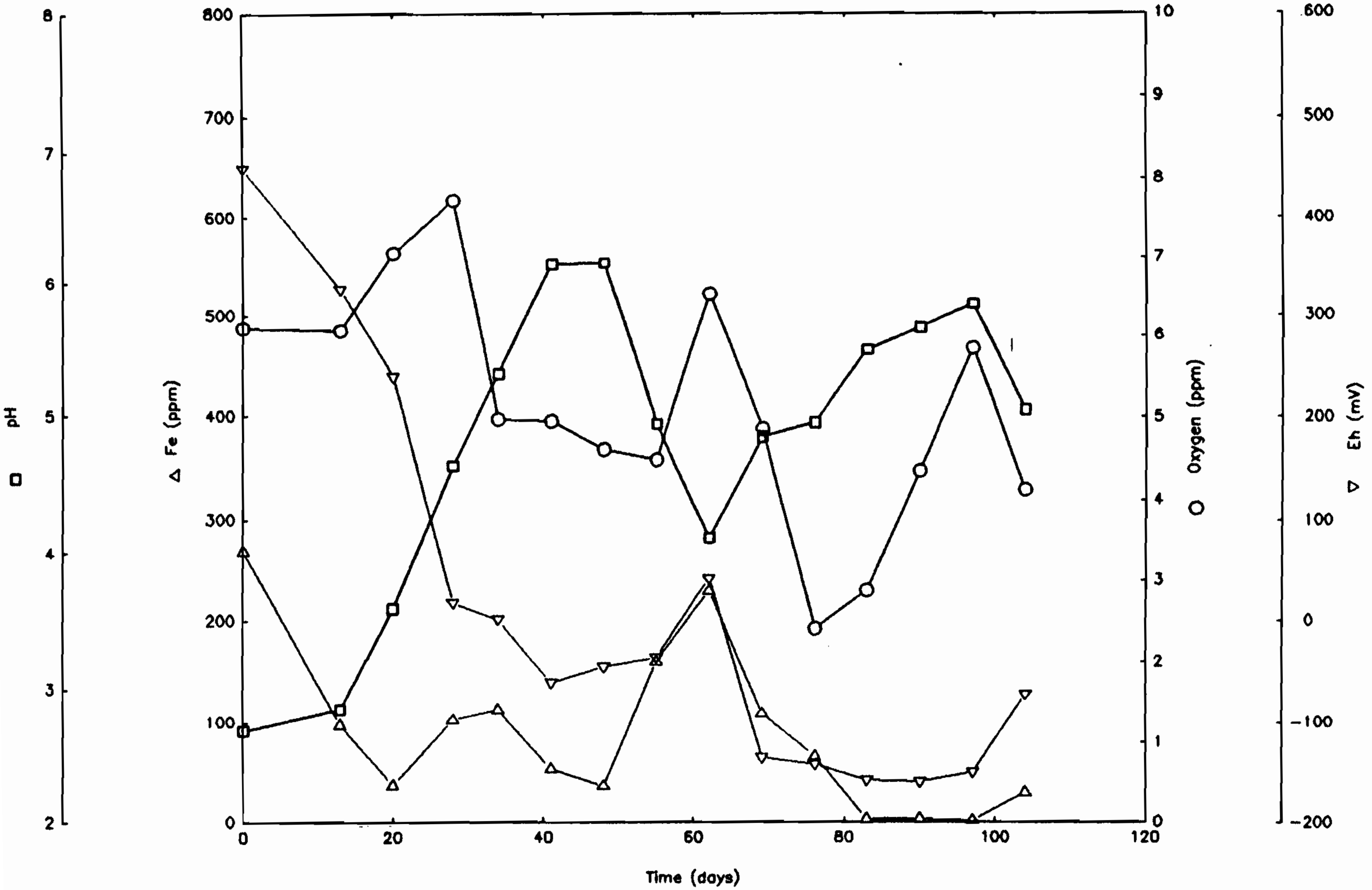

Figure 47. Column 7pH, total iron, issolved oxygen and Eh.

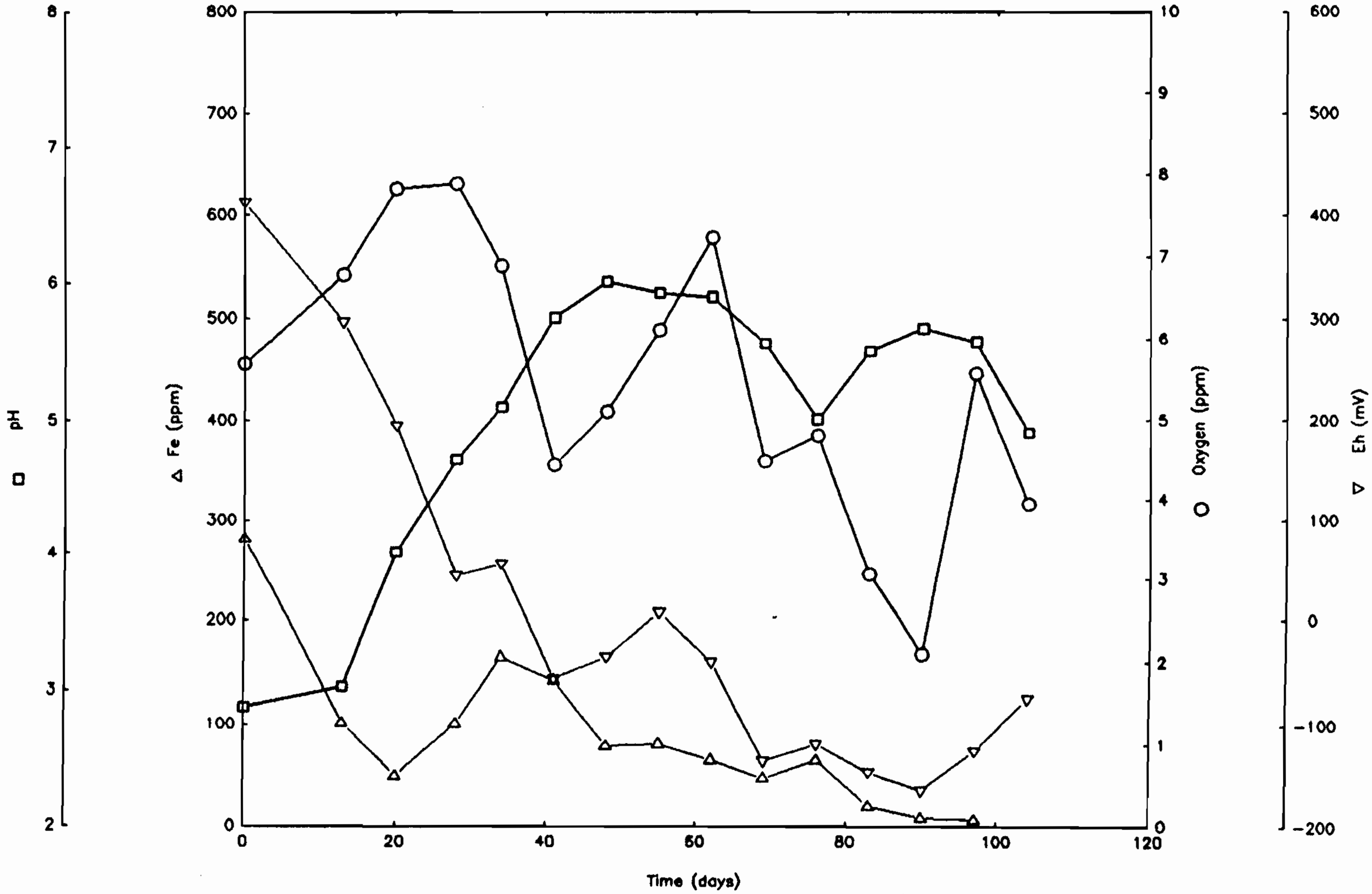

Figure 48. Column 8 pH, total iron, dissolved oxygen and Eh.

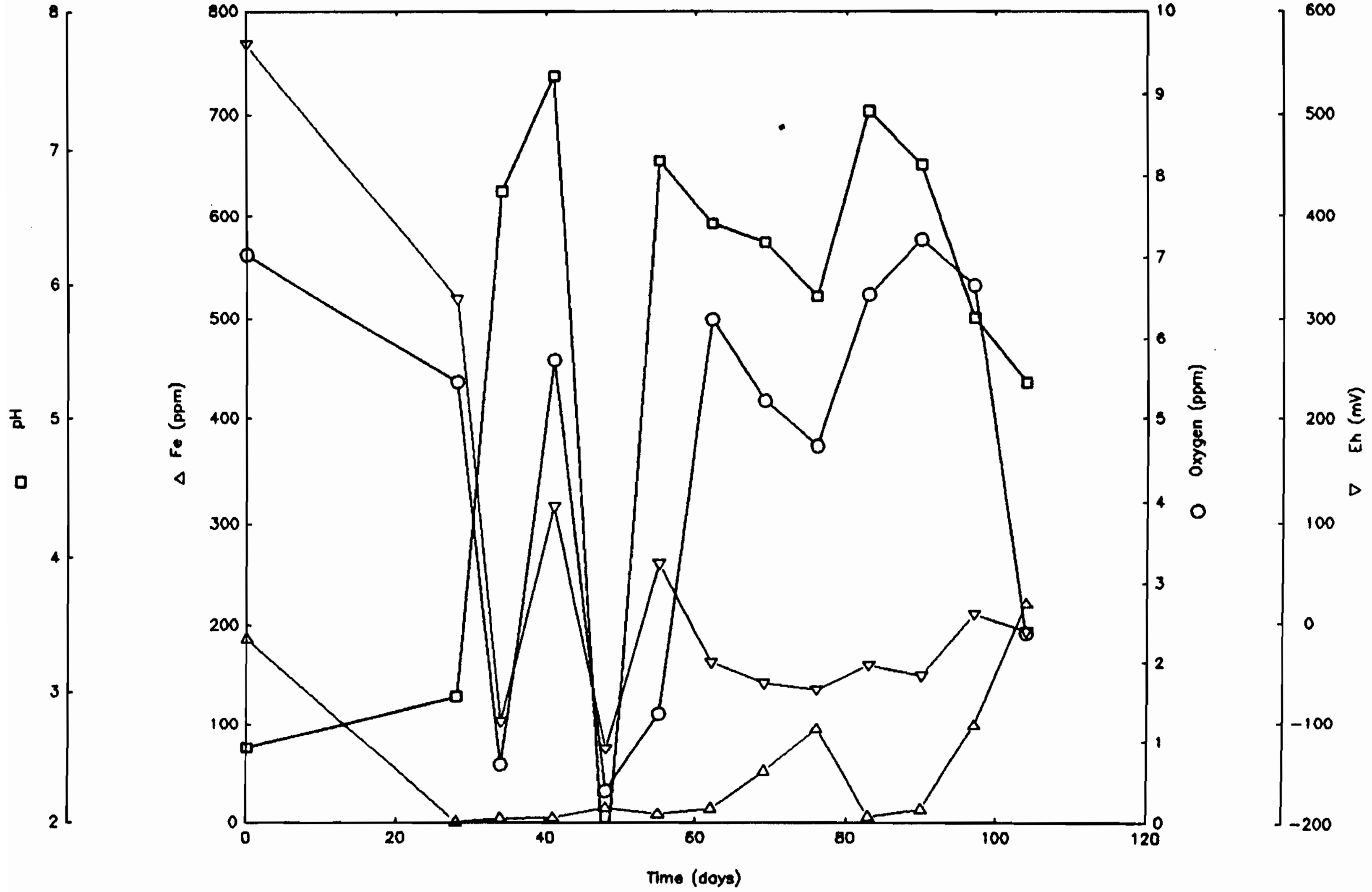

Figure 49. Column 9 pH, total iron, dissolved oxygen and Eh.

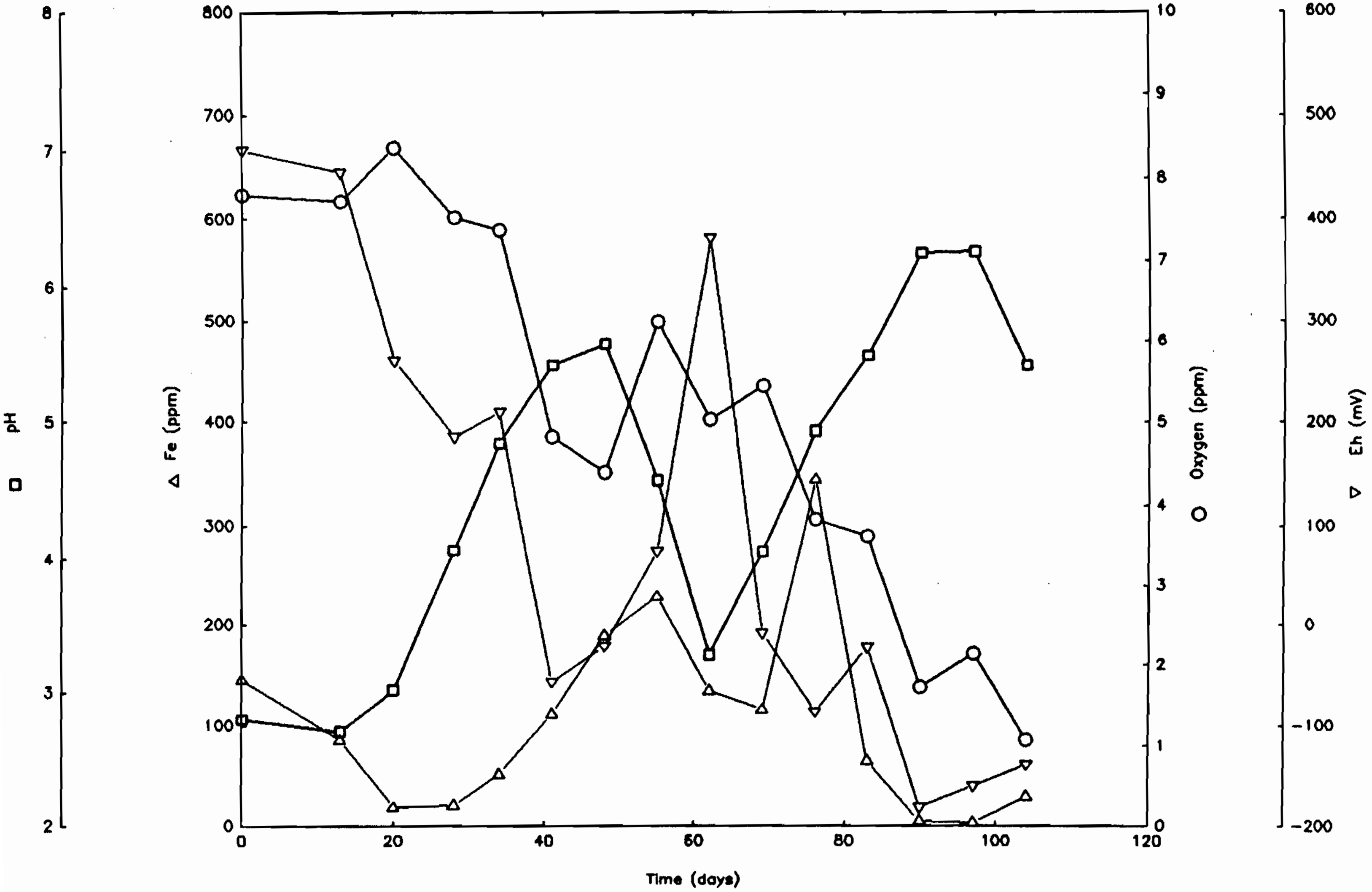

Figure 50. Column 10 pH, total iron, dissolved oxygen and Eh.

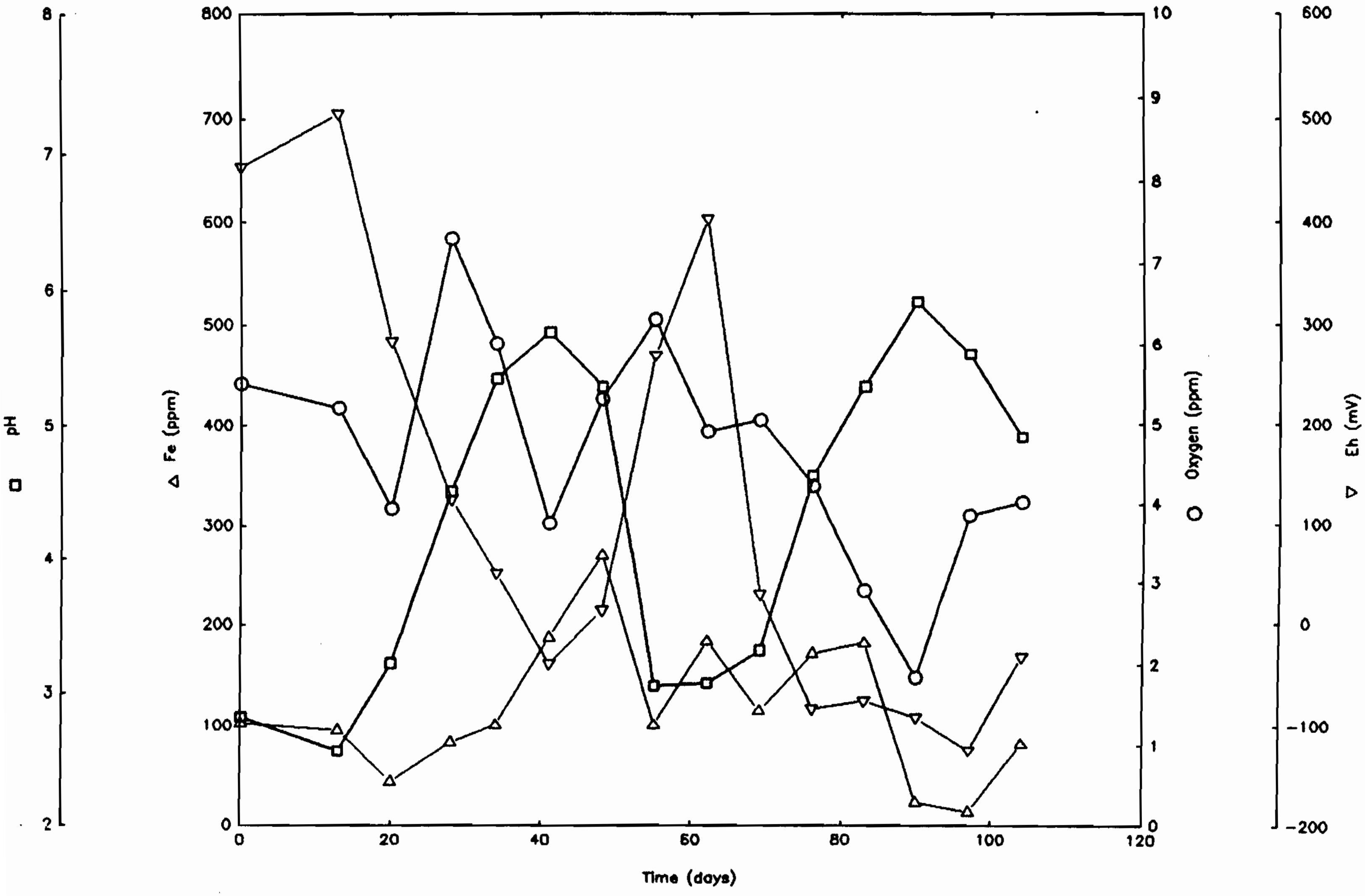

Figure 51. Column 11 pH, total iron, dissolved oxygen and Eh.

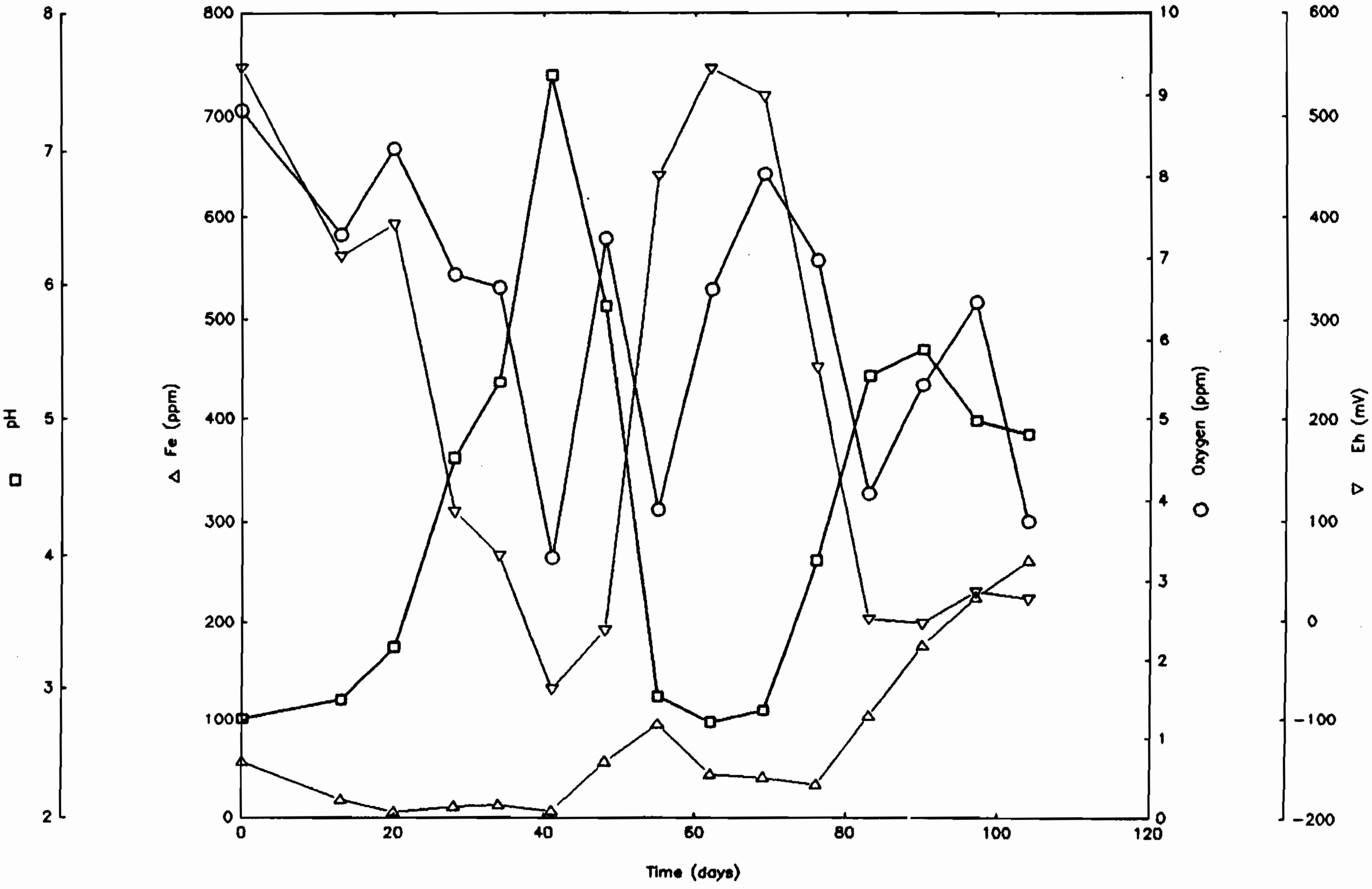

Figure 52. Column 12 pH, total iron, dissolved oxygen and Eh.

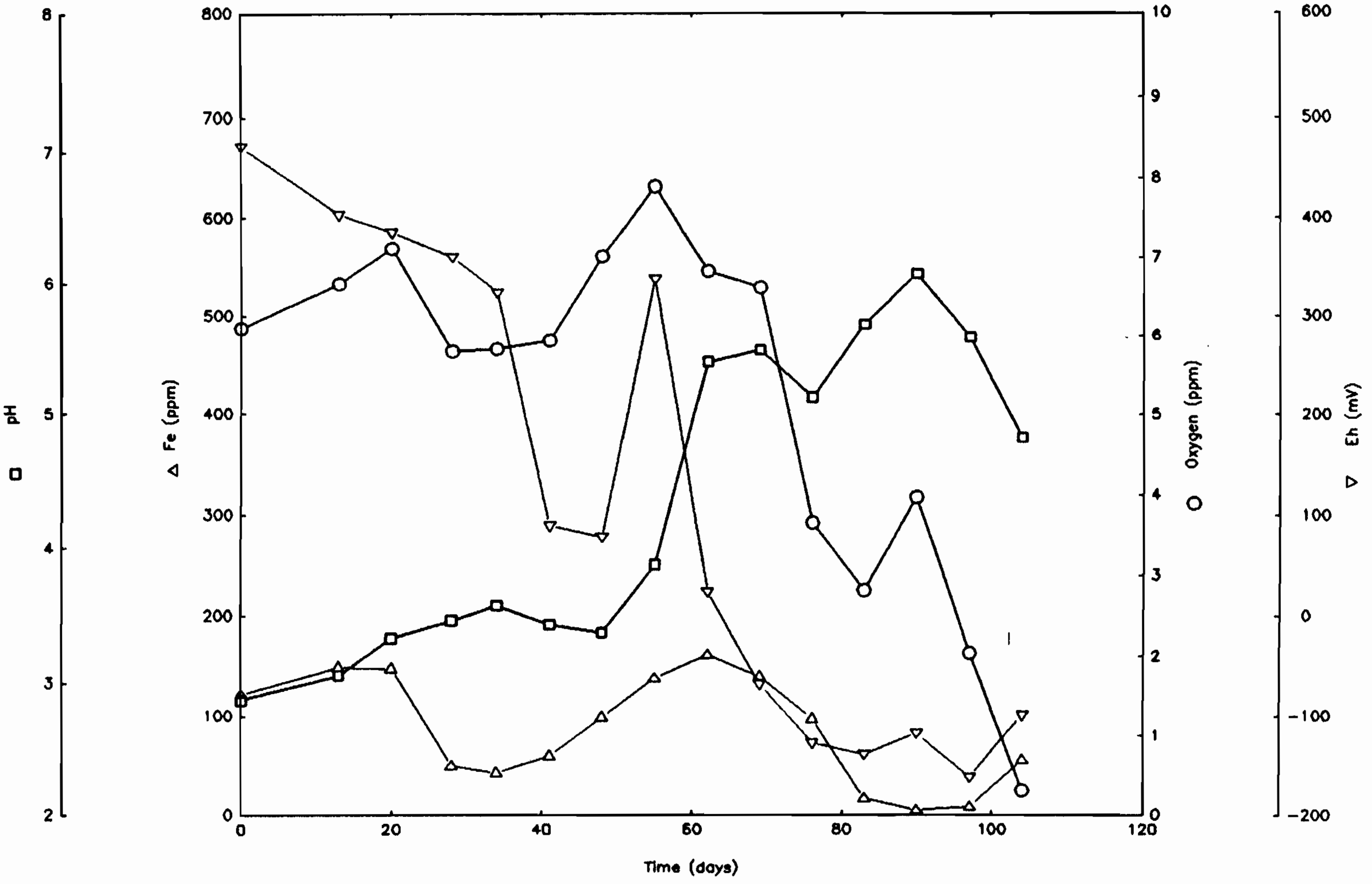

Figure 53. Column 13 pH, total iron, dissolved oxygen and Eh.

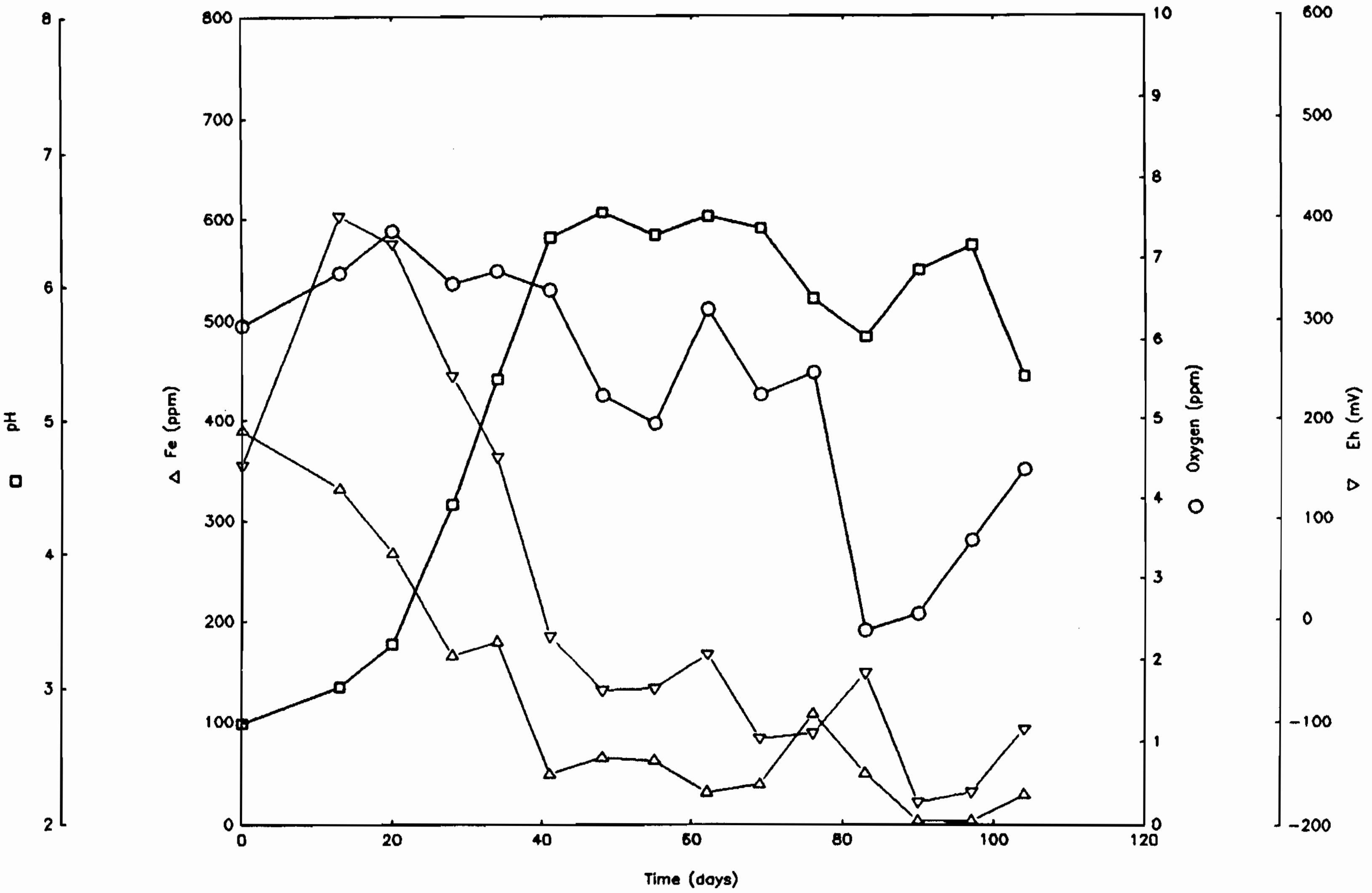

Figure 54. Column 14 pH, total iron, dissolved oxygen and Eh.

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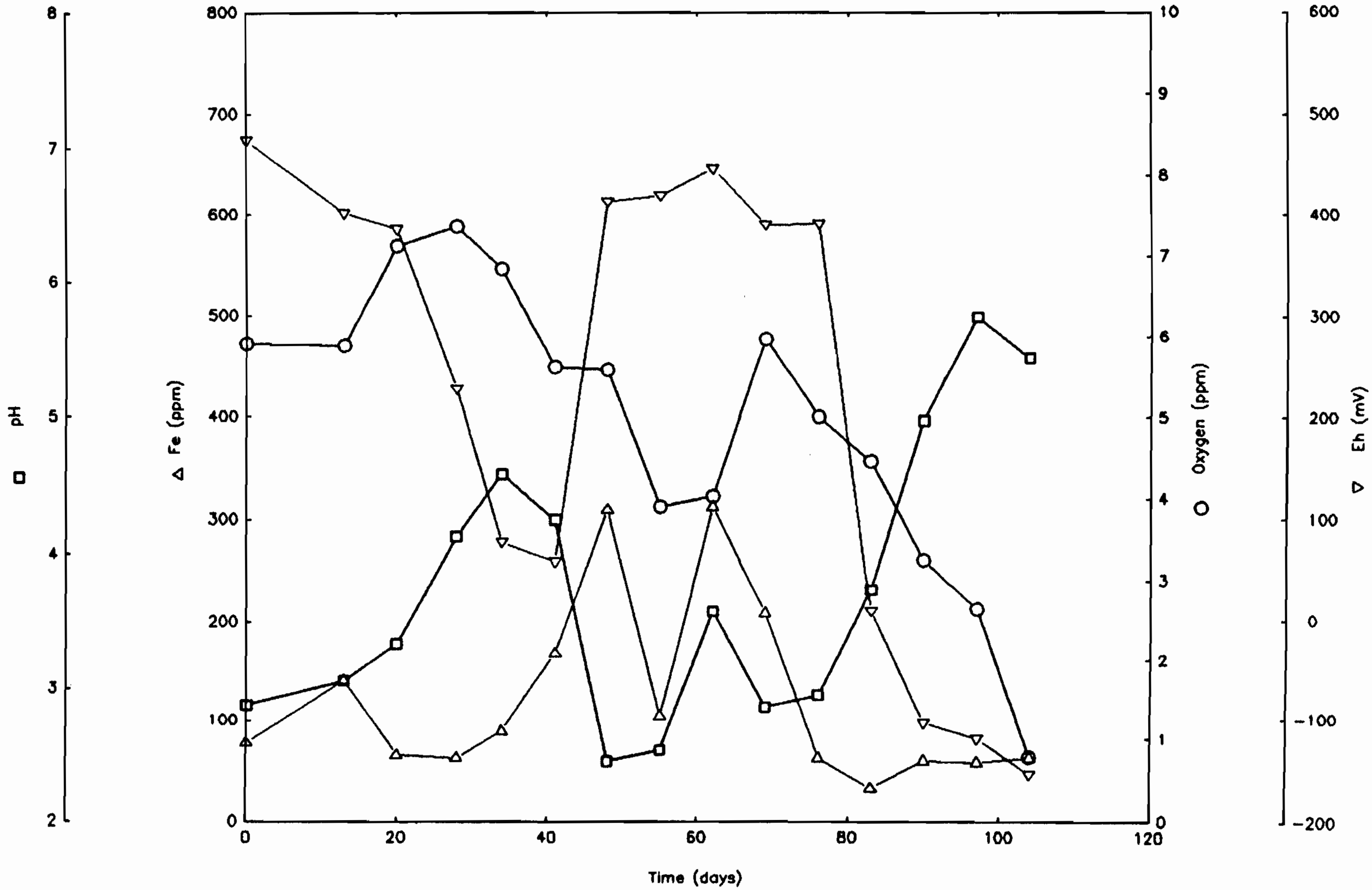

Figure 55. Column 15 pH, total iron, dissolved oxygen and Eh.