3.3 Present Conditions of Acidic Water Pollution

16. The present conditions of rivers, ground waters, active mines and abandoned mines in the region are summarized below:

(a) Target three rivers

17. Based on the precipitation data, the seasonal change in precipitation is relatively clear in this area, rainy season in summer and dry season in winter. As this monitoring has been conducted through half a year from December to May, the water quality characteristics including the seasonal change can be investigated. In this section, the abstract of the present conditions of acidic water pollution in the rivers were discussed based on the average data. The evaluation for the water quality and the sediment were conducted according to the Brazilian water quality standard class four which is the most loose class in the Brazilian standard and the natural contents of the heavy metals in the soil published by Bowen (1983) respectively.

18. *(pH)*: The uppermost reaches of each of these three rivers are almost neutral (pH 7). However, pH values abruptly decrease to 2 or 4 near mined-out areas, coal mine facilities, or discharge points of the coal mine effluents. Compared with Brazilian standards, the water quality in most of the rivers are below the standard value pH 6-9 except for the uppermost reaches and a few branches (Figure B-11).

19. *(Iron)*: The iron concentrations in the uppermost reaches of each of these three rivers are generally less than 4 mg/l. However, iron concentration abruptly increases to the order of 10-100 mg/l near the active or abandoned mines. Rio Sangão is the worst of all the rivers, with iron concentrations is ranging from 120 to 190 mg/l. The iron concentrations in most of the rivers are in excess of the Brazilian standard value 5 mg/l as dissolved iron except for the uppermost reaches and a few branches. The iron concentrations in sediment are almost constant despite of the locations (Figure B-12).

20. *(Sulfate)*: The sulfate concentrations in the uppermost reaches of each of these three rivers range from 8 to 25 mg/l. The concentrations near the mine areas increase to 100 to 1,000 mg/l. Rio Sangão is the most polluted river of all the rivers, with sulfate concentrations ranging from 1,000 to 2,000 mg/l. The sulfate concentrations in most of the rivers are 10 times higher than Brazilian standard value of 250 mg/l, except for the uppermost reaches and a few branches. The sulfate concentrations in sediment are less than detection limit in all of the points (Figure B-13).

21. *(Aluminum)*: The aluminum concentrations in the uppermost reaches of each of these three rivers range from less than 0.2 to 0.5 mg/l. The concentrations near the mine areas increase to the order of 10 to 100 mg/l. Rio Sangão is the most polluted river of all the rivers with respect to

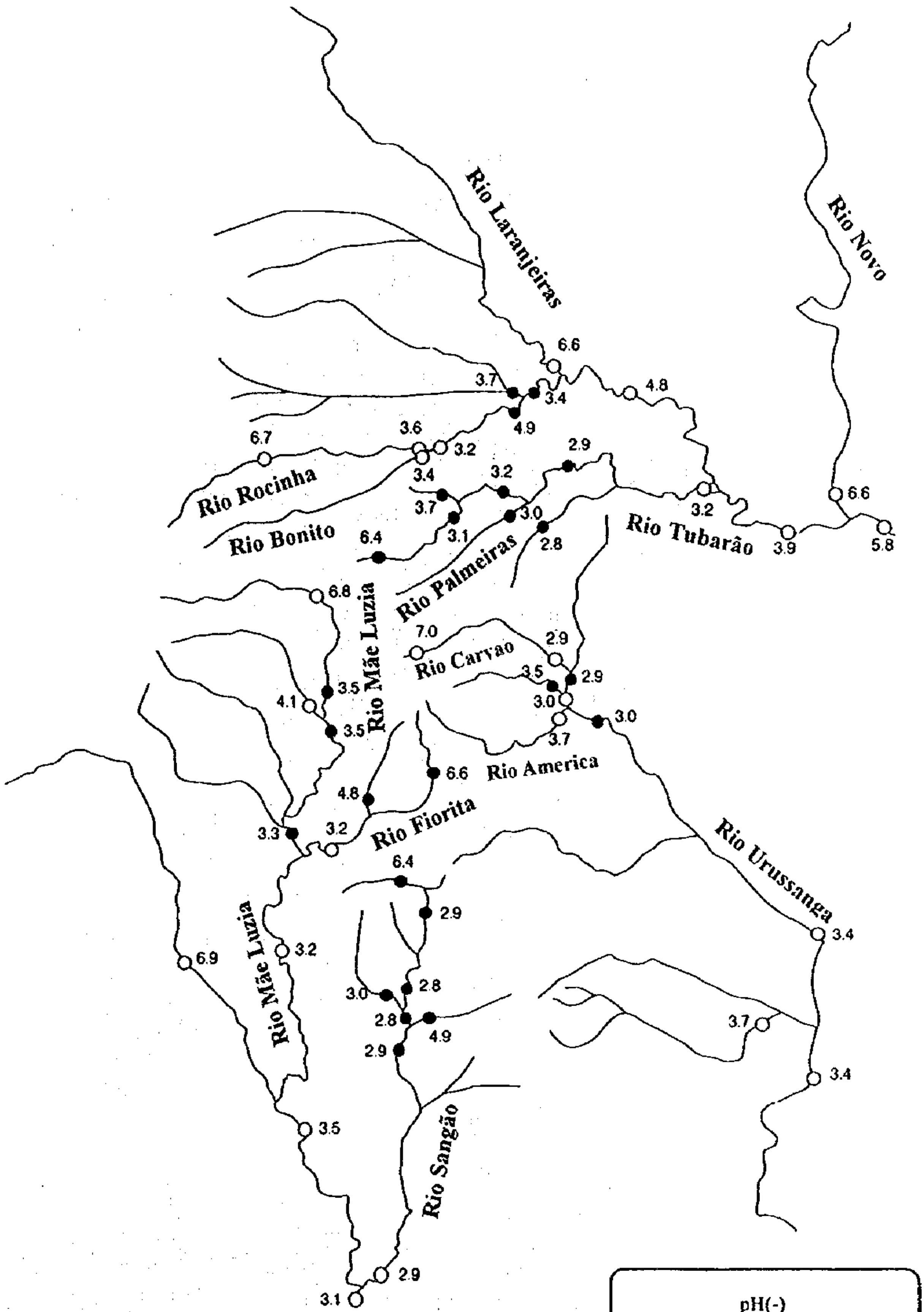

FIGURE B-11

HORIZONTAL DISTRIBUTION OF WATER QUALITY AVERAGED FROM DEC. 1996 TO MAY 1997 (PH)

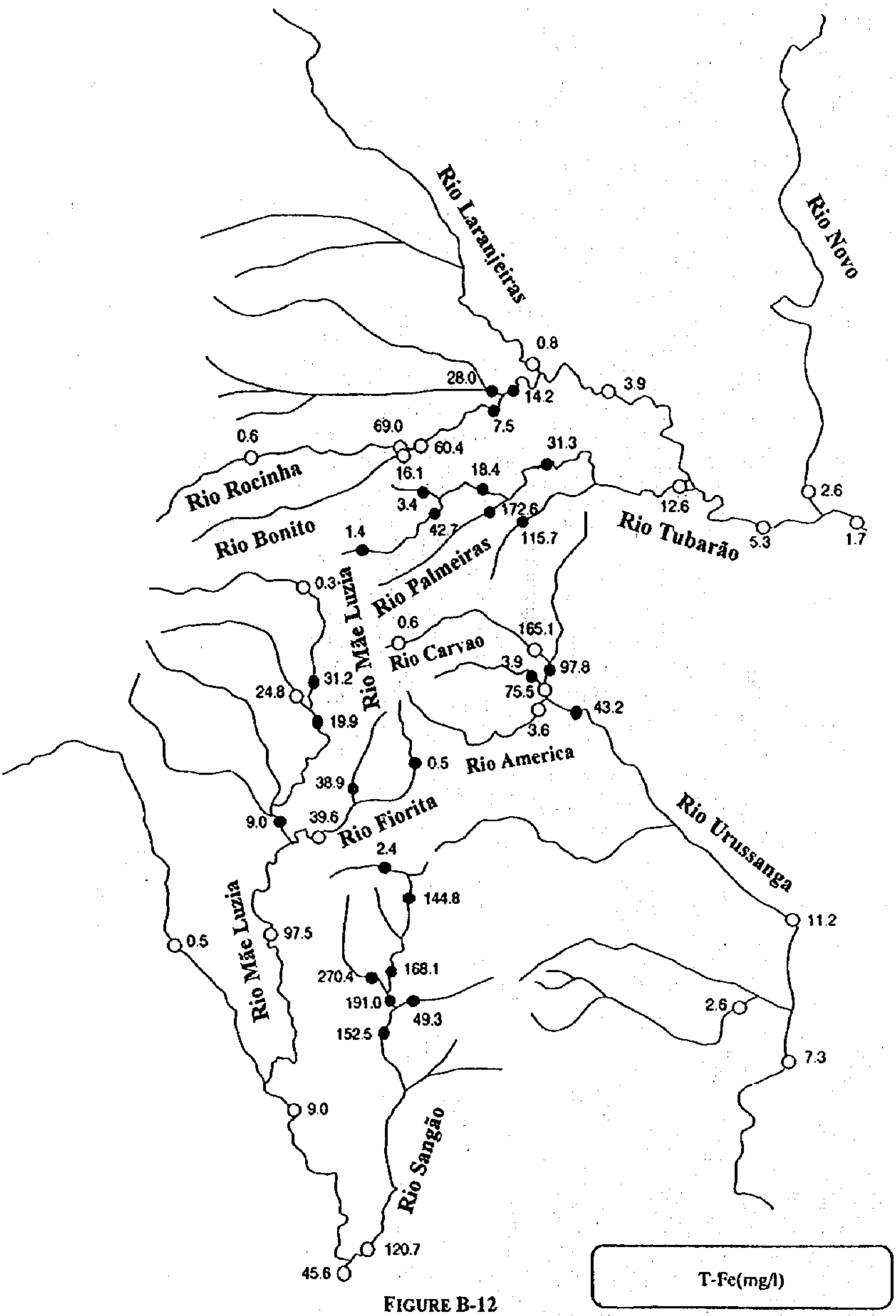

FIGURE B-12

HORIZONTAL DISTRIBUTION OF WATER QUALITY AVERAGED FROM DEC. 1996 TO MAY 1997 (T-FE)

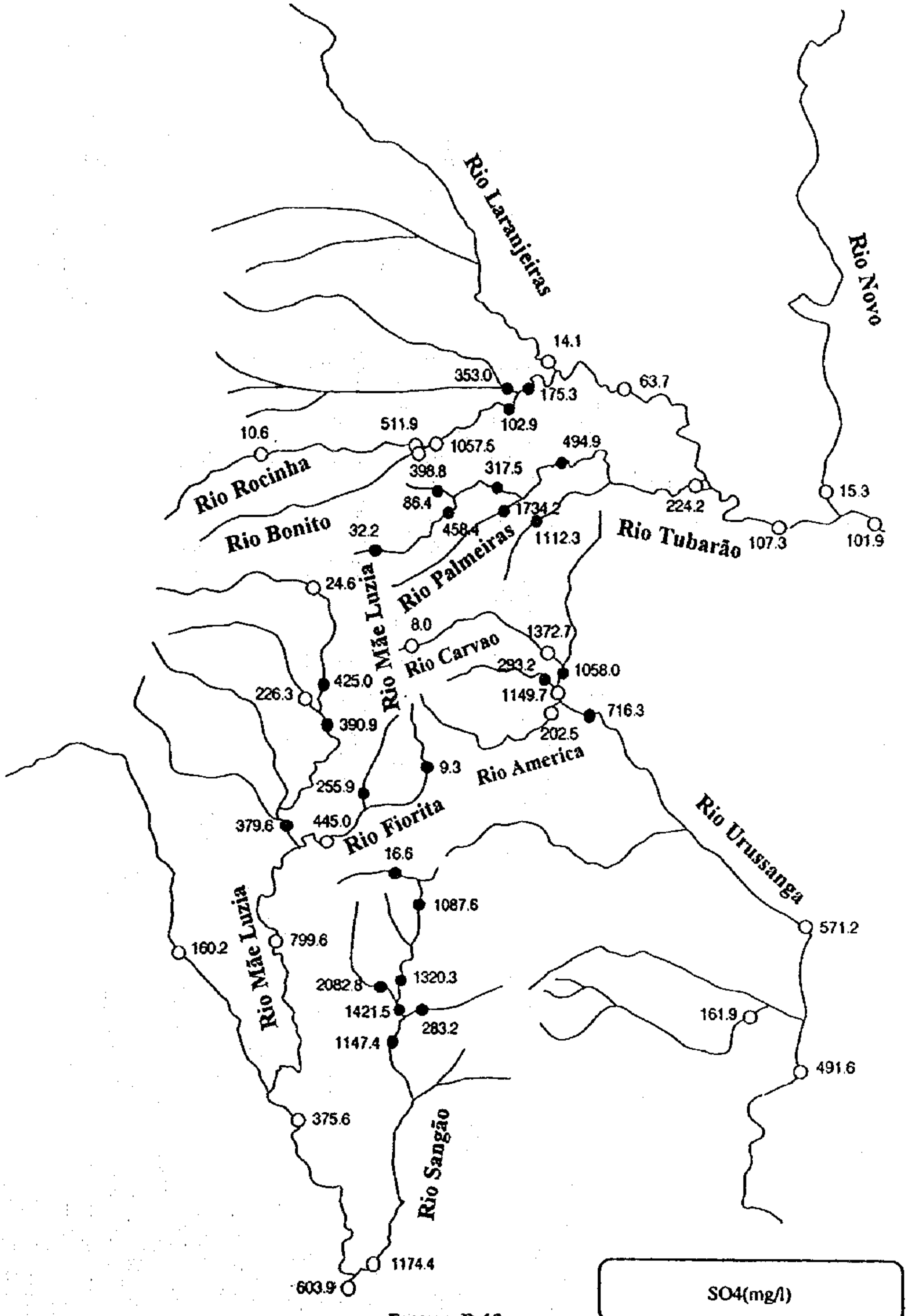

FIGURE B-13

HORIZONTAL DISTRIBUTION OF WATER QUALITY AVERAGED FROM DEC. 1996 TO MAY 1997 (SO4)

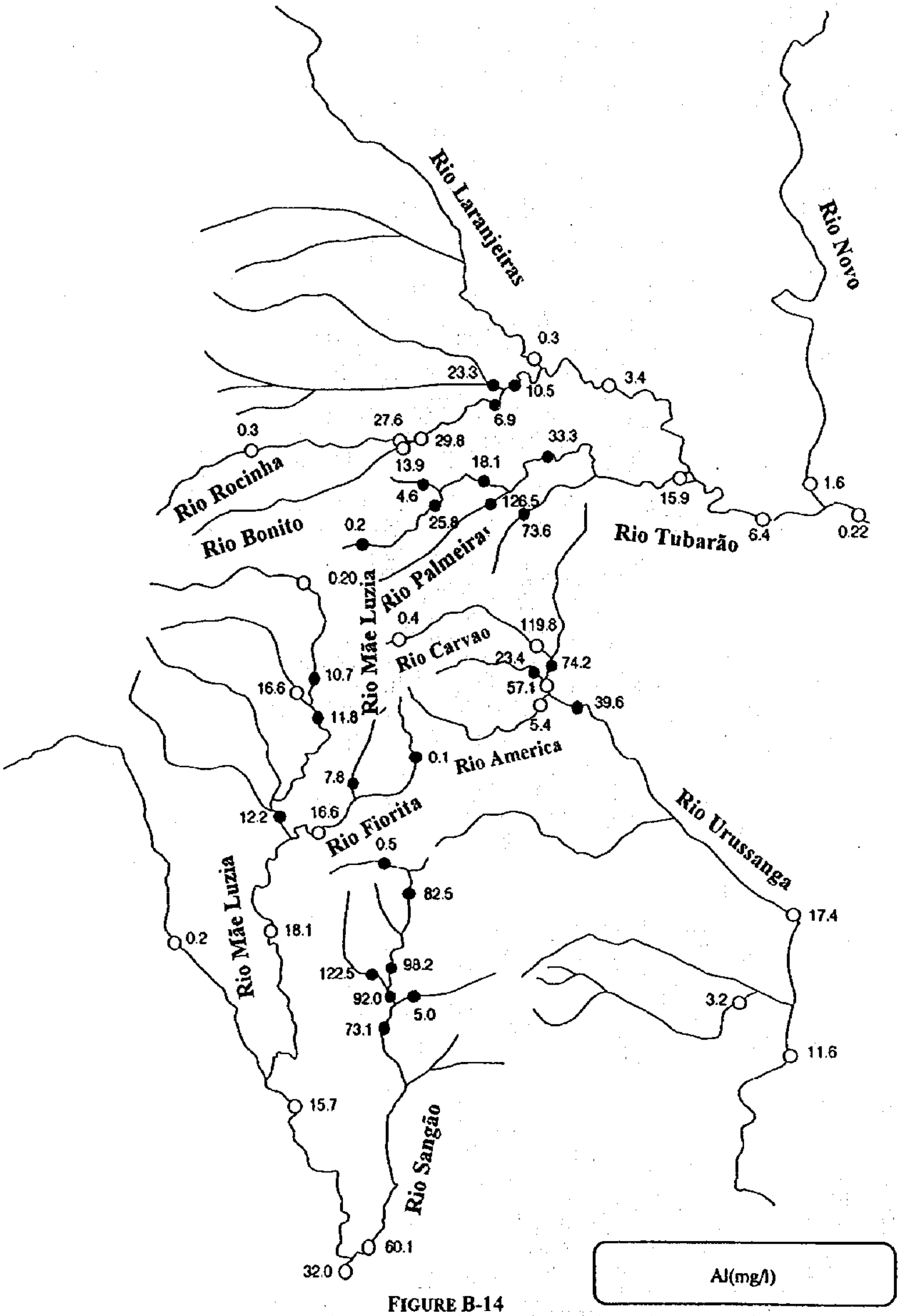

FIGURE B-14

HORIZONTAL DISTRIBUTION OF WATER QUALITY AVERAGED FROM DEC. 1996 TO MAY 1997 (AL)

aluminum concentrations. The aluminum concentrations in the polluted area are 10^2 to 10^3 times higher than the Brazilian standard value of 0.1 mg/l, except for the uppermost reaches and a few branches (Figure B-14 above).

22. (***Heavy metals***): Heavy metal concentrations in water are as follows. The distribution patterns of lead, chromium, and manganese are the same as sulfate, iron, and aluminum. These concentrations in the mine areas are in excess of the Brazilian standard (lead: 0.05 mg/l, chromium: Cr^{3+} 0.5 mg/l, manganese: 0.5 mg/l). Rio Sangao is the worst of all the rivers. The concentrations of zinc and copper increase near the mine area, too. However, the concentrations of both substances are less than the Brazilian standard (zinc: 5 mg/l, copper: 0.5 mg/l). Arsenic, cadmium, and mercury are not detected in most of the monitoring points. The heavy metal concentrations in sediment increase near the mine areas. However, the concentrations of all substances are within the range of the heavy metal contents of the natural soil.

(b) Ground water

23. Obvious time variation of the groundwater level and pH in all of the wells (Figure B-15 (a)) were not observed. The pH values ranged from 2.5 to 3.7 in the Fiorita, Rocinha, and Capivari sites (Figure B-15 (b)). The pollution level of the groundwater in these sites are the same level of the surface water. The pH value in the monitoring well LBG1 is almost neutral. LBG1 is located in an area that has already been mitigated by covering with ten centimeters of the top soil. This mitigation method can be seen in many places in this area. This monitoring result in LBG1 shows that the covering mitigation method may be useful to prevent the groundwater pollution to some degree. Electric conductivity tends to decrease in the rainy season in January and February (Figure B-15 (c)). This decrease may be caused by the dilution with the precipitation.

(c) Active mine effluent

24. The average water quality of the active mine effluent was compared with Brazil, Japan, U.S., world bank, and U.S. EXIM standards. The concentrations of the effluents are largely in excess of all of the criteria such as pH, suspended solid, total iron, zinc, and sulfate. Especially, the concentrations of iron and sulfate are much higher than the criteria on the order of 10 to 10^3 times. As for suspended solid, the concentration is slightly higher than the criteria. The ponds which many mines prepare for coal washing may operate as a settling ponds to decrease the suspended solid concentrations.

(d) Pollution load from abandoned mines

25. The distributions of the average values of pH, total iron, sulfate, and aluminum in the four FS sites are as follows:

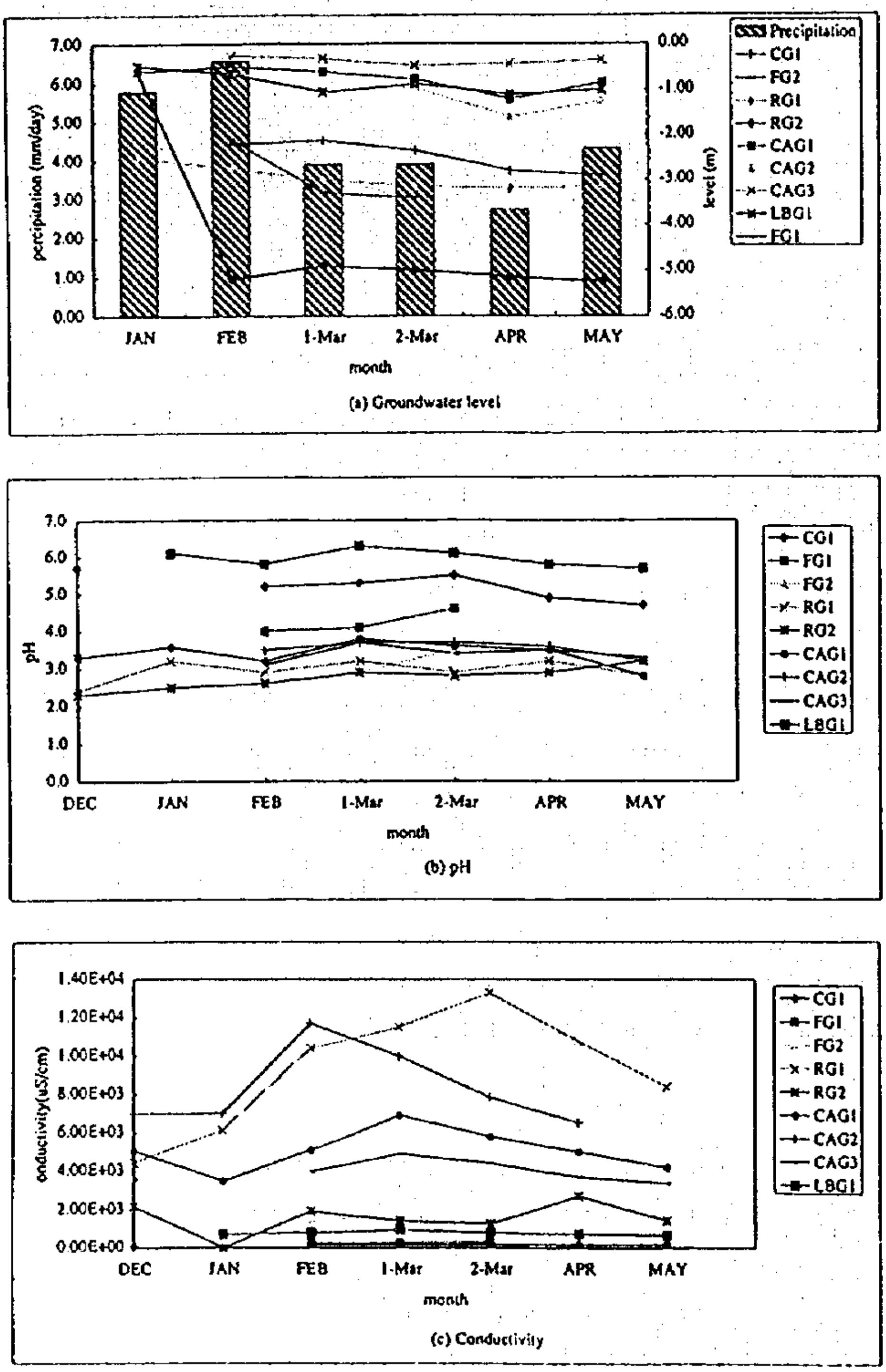

FIGURE B-15 **RESULT OF GROUND WATER MONITORING**

26. *(Fiorita)*: In the main stream between JA4 and FS9, the acidity/alkalinity at the uppermost reach JA4 is almost neutral (pH 7). However, the pH value gradually decreases to 3.3 at FS9, the final downstream discharge point . The water quality of inflow from FS1 is the worst one. In another major stream between FS5 and FS10, the pH at the uppermost reach FS5 is 6.1. However, at the other points pH values range from 2 to 3. The water quality of inflow from FS6 and FS12 are the worst in this water basin. The distribution patterns of the other parameters show the same as pH.

27. *(Rocinha)*: In the main stream between PT4 and RS11, the acidity/alkalinity at the uppermost reach PT4 is almost neutral (pH 7). However, pH value gradually decreases to 3.4 at RS11, the final downstream discharge point. The loading amount at the RS11 is the largest of the main stream points and its loading amount is 10 to 10^3 times higher than the other points on the main stream. RS9 is the largest pollution loading branch and its loading amount is 10 to 10^3 times the other branches. The section between RS10 and RS11 is the largest pollution loading area in Rocinha site.

28. *(Carvão)*: There is no difference of water quality between CS1 the portal of underground water and CS2 located at the downstream from CS1. CS3 is the upstream control point at this site. MC4 is one of the active mine effluent monitoring points and the water quality is worse than other points in this site. CS5 is the point located on Rio Carvão and its water quality (pH 2.4) is worse than CS1.

29. *(Capivari)*: PT16 (pH 5.9) is the upstream control point in this site. CAS2 shows the same pH level as PT16. pH decreases to 3.2 at the downstream point CAS3. The section between CAS2 and CAS3 is polluted by the seepage from the pond. CAS4 is also polluted by the seepage from the pond and surface runoff from the coal reject area located on the west side of the pond. Its pH is 3.1 as same as CAS3. However, the concentrations of the other acidic pollution substances are approximately two times higher than CAS3. At PT14 located downstream from the confluence of CAS3 and CAS4, the water quality is better than CAS3 and CAS4. This point is located in the large and wet land, there may exist some kind of natural water purification mechanism such as neutralization by inflow of the organic acids originated from the plants.

4. Mitigated Water Quality Prediction in the FS Sites

30. The pollution mechanisms in the Fiorita and Rocinha FS sites are more complicated than those in the Carvão and Capivari FS sites. Many streams are running through the areas stacked with pollution source materials and polluted waters are discharged through groundwater and directly to the streams in the Fiorita and Rocinha FS sites. On the other hand, Carvão and Capivari has only one pollution source, which is a groundwater discharge from the abandoned mine portal and a large pond , respectively. The numerical simulation model was constructed to predict water quality after taking mitigation measures for Fiorita and Rocinha. The simple equations were used for the Carvão and

Capivari prediction by assuming "a completely mixed condition" in the river.

4.1 Simulation Model for Fiorita and Rocinha

(a) Abstract of numerical simulation model

31. The numerical simulation model consists of a flow model and a water quality model. The flow model, which simulates the flow volume of the river, is the box model using the precipitation data and the catchment area. The water quality model simulates the water quality of the river based on the calculation results of the flow model and the pollution loading amounts from natural and mine-related sources.

32. (*Flow model*): The following is the basic equation of the model.

$$\frac{dV}{dt} = Q_w + Q_i - Q_o + Q_p$$

V : Box volume
Q_w : Flow volume from the upper box
Q_i : Inflow volume from the catchment area
Q_o : Flow volume to the lower box
Q_p : Water volume generated from the inside of the box

33. The model was calculated by the Runge-Kutta method with a time step of one day. Figure B-16 shows the structure of the boxes in the FS sites. Figure B-17 shows the calculation result to reproduce the present condition at the confluence point of FS 9 and FS 10, the final discharge points in the two major streams in Fiorita. Figure B-18 is the calculation result at RS 11, the final discharge point in Rocinha. Figures B-19 and B-20 show the reproducibility of the present condition. The measurement values are almost within the calculated flow volume fluctuations.

34. (*Water quality model*): Figure B-21 shows the concept of the water quality model. Sulfate, total iron, and aluminum were selected as the parameters of the model. pH was estimated by using the multi-regression equation with the calculation results of the above parameters. The following is the mass balance equation in a box.

$$C_i = \frac{1}{Q_i} \{Q_{i-1} C_{i-1} + (Q_N - \Sigma Q_{AC} - \Sigma Q_{AB}) C_N + \Sigma Q_{AC} C_{AC} + \Sigma Q_{AB} C_{AB}\}$$

C_i : Concentration in the box
C_N : Concentration of the upper box
Q_N : Inflow volume from the catchment area
$\Sigma Q_{AC} C_{AC}$: Loading amount from active mines
$\Sigma Q_{AB} C_{AB}$: Loading amount from abandoned mines

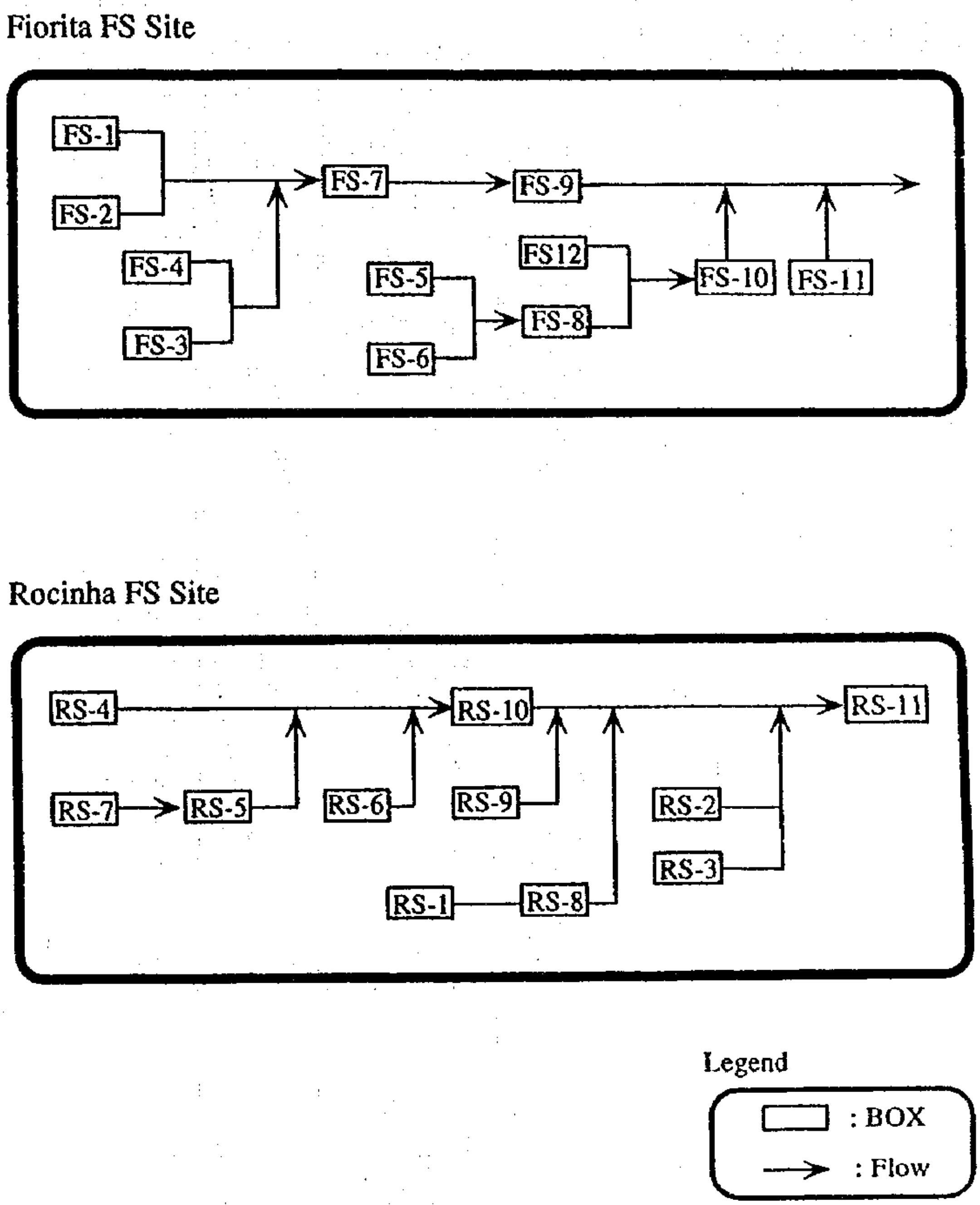

FIGURE B-16 Simulation Model Box Structure for the Fiorita and Rocinha FS Sites

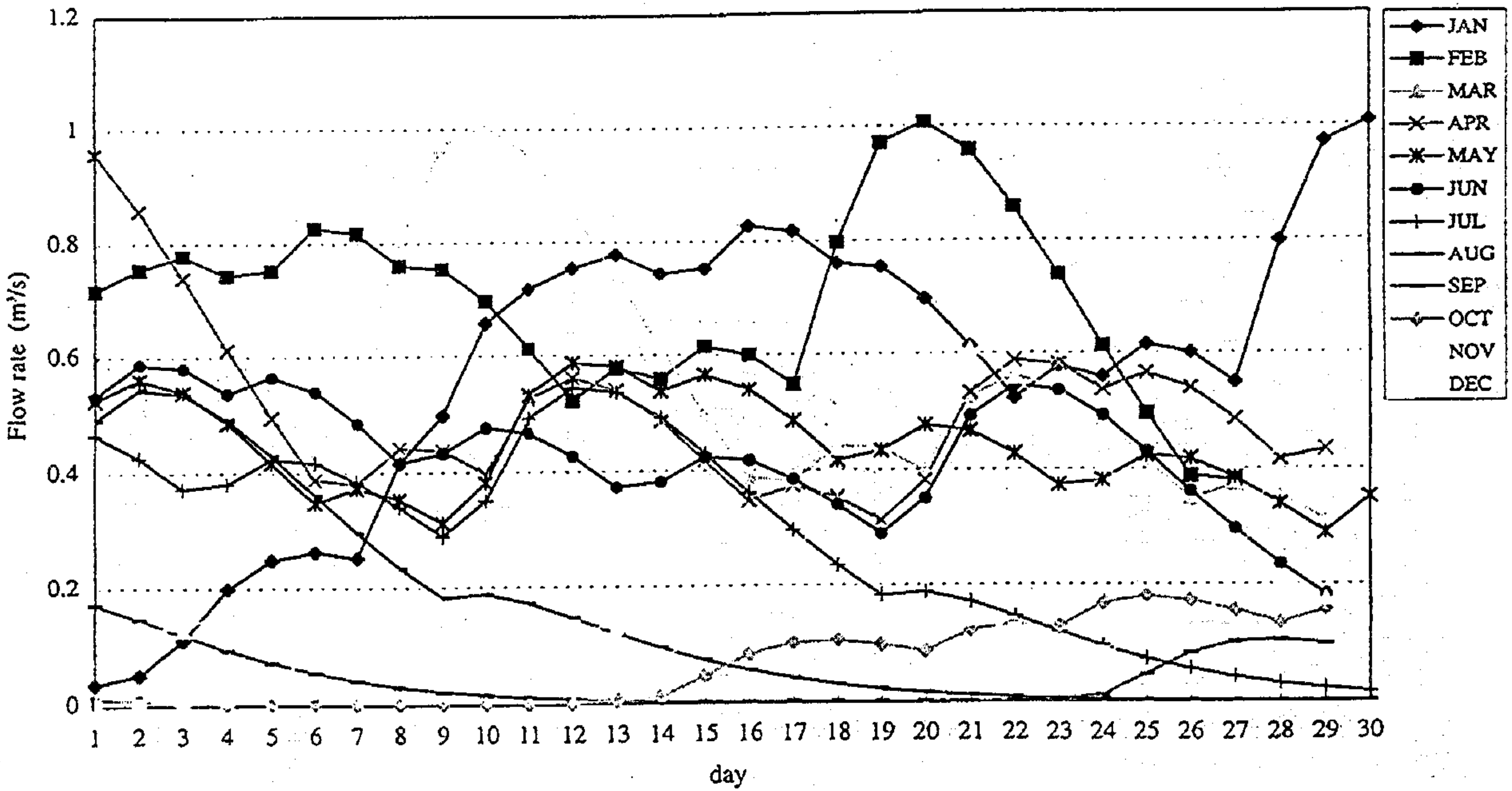

FIGURE B-17

Flow Volume Calculation Results at the Confluence of FS 9 and FS 10

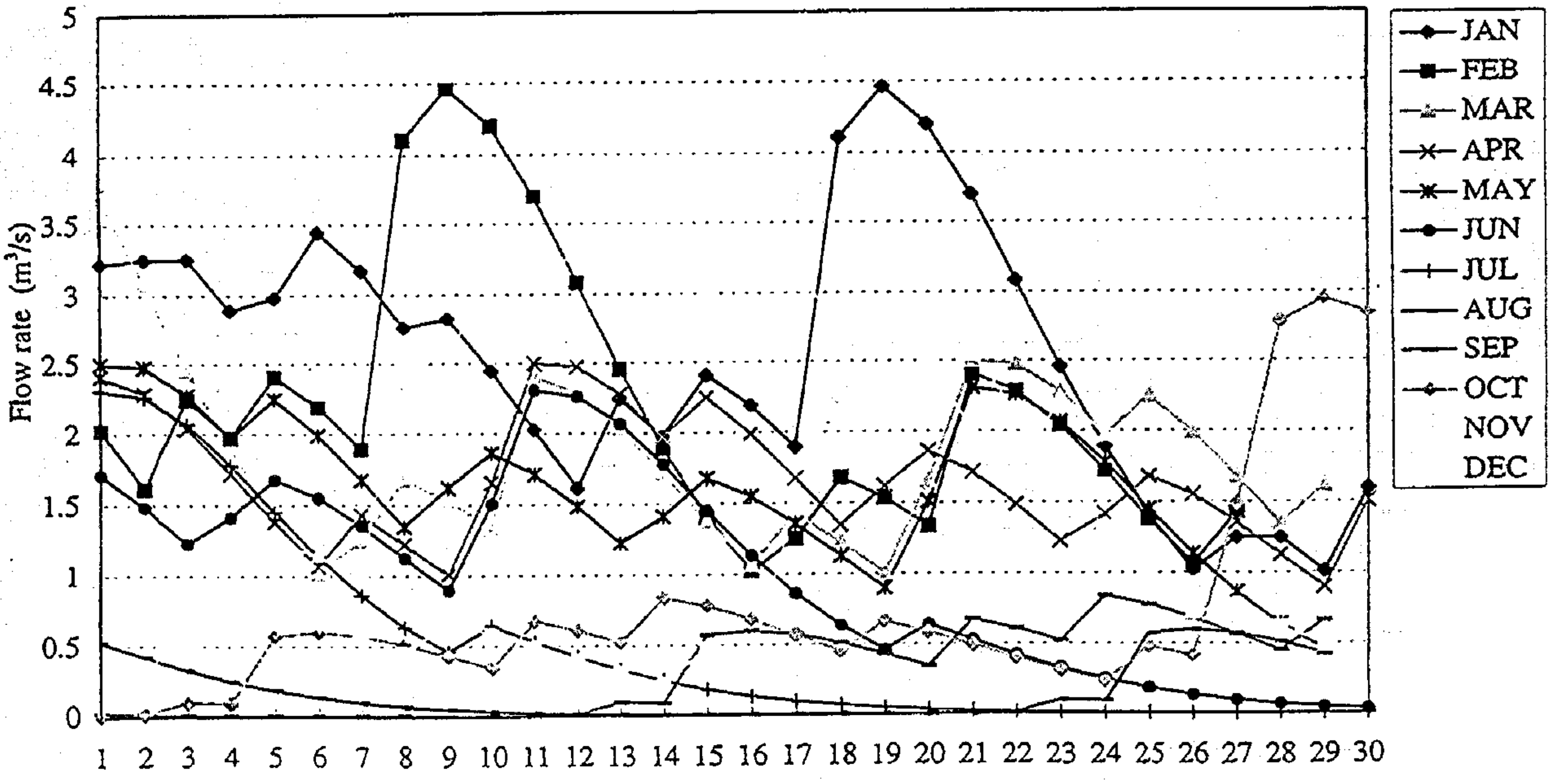

FIGURE B-18

Flow Volume Calculation Results at RS 11

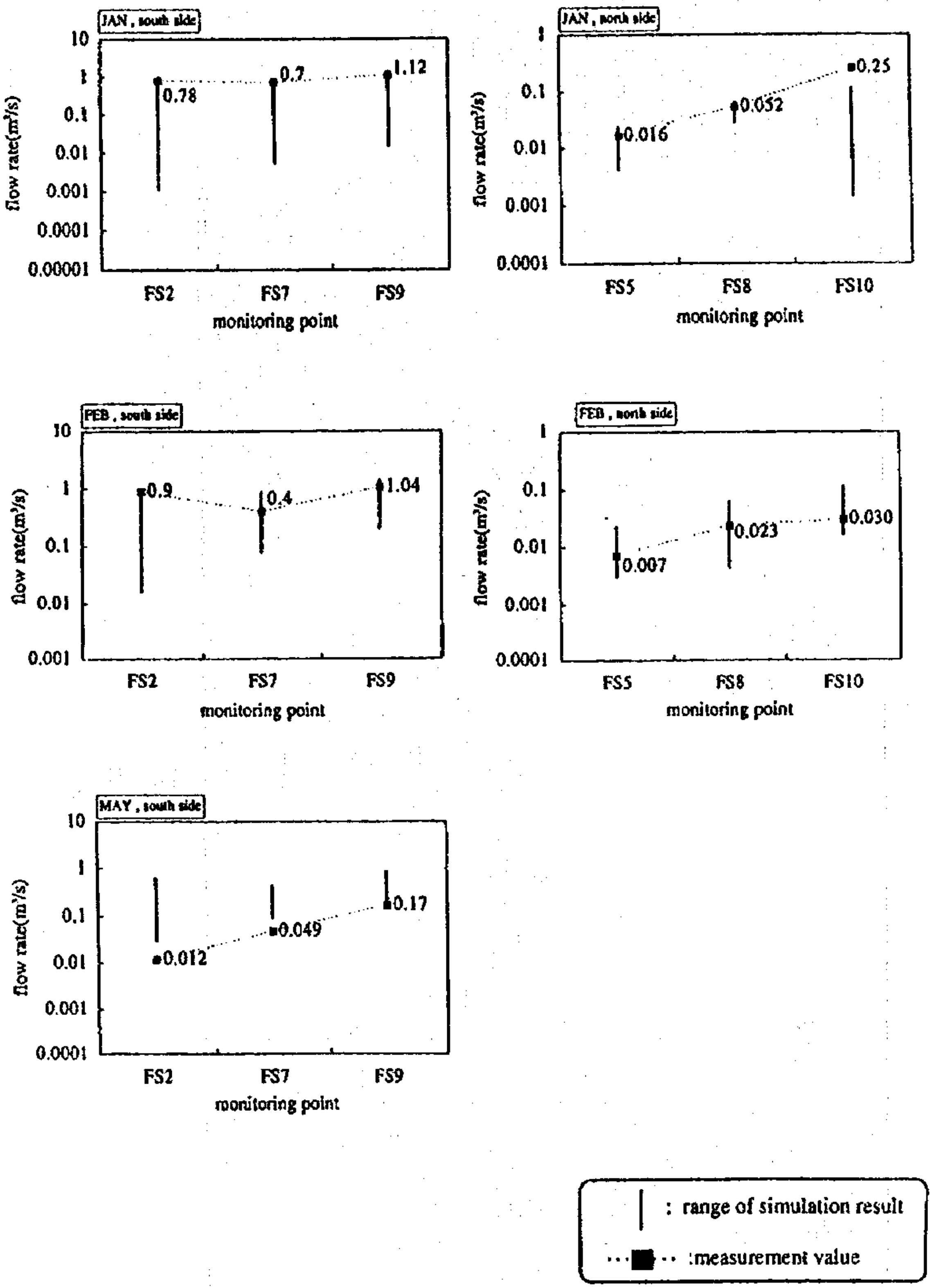

FIGURE B-19

Comparison of Flow Volume between Calculated and Measured in Fiorita

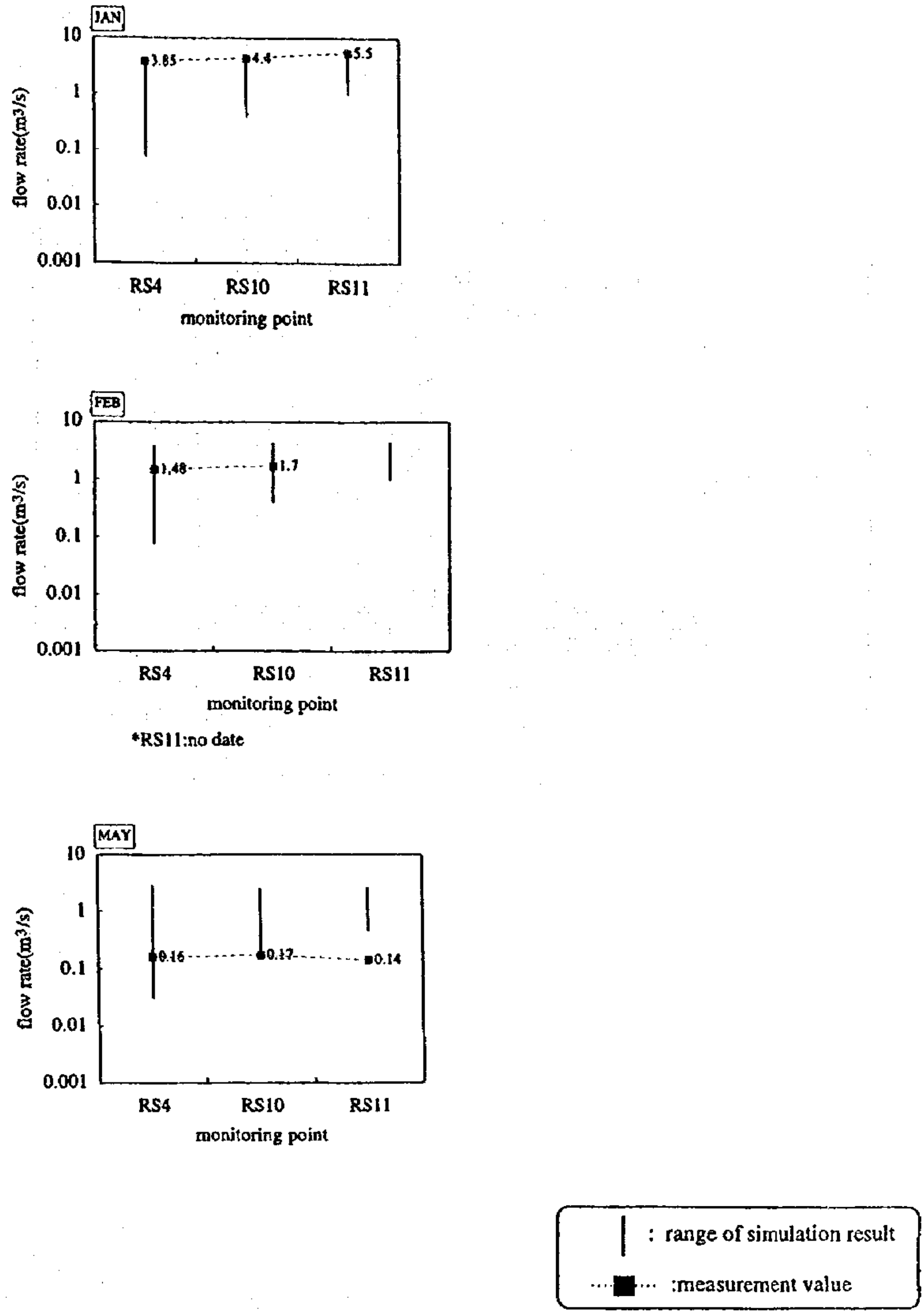

FIGURE B-20

Comparison of Flow Volume between Calculated and Measured in Rocinha

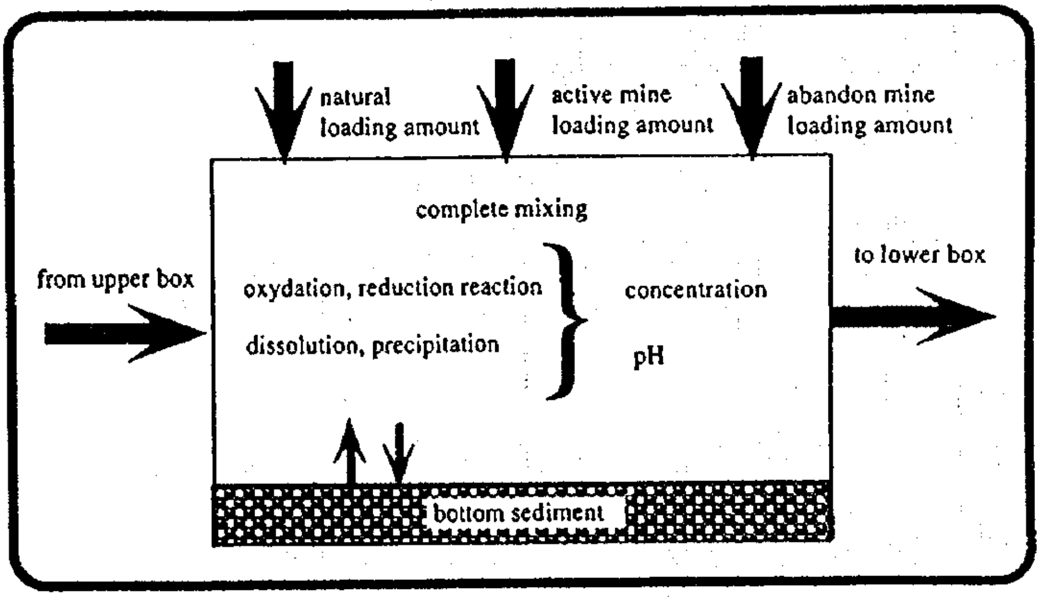

FIGURE B-21 **CONCEPT OF WATER QUALITY MODEL**

35. Tables B-4 and B-5 show the reproducibility of the present conditions at FS9 and FS10, and RS11 and RS10, respectively. The measurement values are almost within the calculated concentration fluctuations.

(b) Prediction of water quality improvement effect

36. ***(Method)***: A water quality improvement effect generated by the mitigation was estimated by using the simulation model on the assumption that all of the pollution sources in the FS sites, are evenly reduced at fixed rates. The reduction rates were assumed as follows;

case1: 90% reduction
case2: 50% reduction
case3: 25% reduction

37. The following is the prediction equation.

$$C_i = \frac{1}{Q_i} \{Q_{i-1} C_{i-1} + (Q_N - \Sigma Q_{AC} - \Sigma Q_{AB}) C_N + \alpha_I \Sigma Q_{AC} C_{AC} + \beta_I \Sigma Q_{AB} C_{AB}\}$$

α_I: Reduction rate for the loading amount from the active mines
β_I: Reduction rate for the loading amount from the abandoed mines

38. ***(Prediction result)***: Figure B-22 shows the case study results of pH at FS 9 , FS 10, and the confluence of the both points in Fiorita. Figure B-23 shows the case study results of pH at RS 10 and RS 11 in Rocinha. pH was predicted to increase from 3.5 in the present condition to 4.6 by the 90% reduction for the active mines and the abandoned mines at the confluence point in Fiorita. In Rocinha, pH was predicted to increase to maximum 4.0 by the 90% reduction at RS 11. The concentrations of sulfate, iron, and aluminium will remain high and will exceed the Brazilian standard class four in the case of the 90% reduction. These remaining high concentrations are expected to prevent the pH recovery.

4.2 Simulation Model for Carvao

39. ***(Method)***: The water quality at CS 4, the final downstream discharge point in Rio Carvao site, was predicted by using the simple equation assuming the completely mixed condition. As there is no difference of water quality between CS 1 and CS 2, CS 2 was selected as the target of the mitigation. The case study conditions are the same as Fiorita and Rocinha. The following is the prediction equation:

$$C = \frac{\alpha_I Q_1 C_1 + Q_2 C_2 + Q_3 C_3}{Q_1 + Q_2 + Q_3}$$

TABLE B-4

Comparison of Water Quality between Calculated and Measured in Fiorita .

[pH]

		FS9					FS10				
	UNIT	DEC	JAN	FEB	MAY	Average	DEC	JAN	FEB	MAY	Average
measurement value	mg/l	3.3	4.0	3.5	3.4	3.55	2.5	2.8	2.6	2.9	2.7
simulation result	mg/l	3.3	3.8	3.8	3.3	3.55	2.4	2.7	2.6	2.4	2.5

[SO_4]

		FS9					FS10				
	UNIT	DEC	JAN	FEB	MAY	Average	DEC	JAN	FEB	MAY	Average
measurement value	mg/l	299.4	101.8	75.8	401.0	219.5	1876.0	616.0	163.0	1462.0	1029.3
simulation result	mg/l	218.3	144.4	129.9	428.1	230.2	1320.5	1009.6	834.9	1262.0	1106.7

[T-Fe]

		FS9					FS10				
	UNIT	DEC	JAN	FEB	MAY	Average	DEC	JAN	FEB	MAY	Average
measurement value	mg/l	1.6	1.0	2.3	1.8	1.7	131.4	41.3	22.6	140.5	83.9
simulation result	mg/l	2.8	1.9	1.9	2.8	2.4	97.0	64.2	51.6	109.5	80.6

[Al]

		FS9					FS10				
	UNIT	DEC	JAN	FEB	MAY	Average	DEC	JAN	FEB	MAY	Average
measurement value	mg/l	11.5	4.9	3.1	14.7	8.6	132.4	62.8	31.9	93.3	80.1
simulation result	mg/l	7.6	6.0	5.7	11.7	7.8	96.2	66.2	54.0	107.4	80.9

TABLE B-5

Comparison of Water Quality between Calculated and Measured in Rocinha

[pH]

	UNIT	RS10 DEC	RS10 JAN	RS10 FEB	RS10 MAY	RS10 Average	RS11 DEC	RS11 JAN	RS11 FEB	RS11 MAY	RS11 Average
measurement value	-	4.3	5.9	5.4	3.9	4.9	2.9	3.2	3.4	3.2	3.2
simulation result	-	4.7	4.3	4.1	4.6	4.4	3.0	3.2	3.0	3.3	3.1

[SO_4]

	UNIT	RS10 DEC	RS10 JAN	RS10 FEB	RS10 MAY	RS10 Average	RS11 DEC	RS11 JAN	RS11 FEB	RS11 MAY	RS11 Average
measurement value	mg/l	75.6	290.0	46.7	206.1	154.6	160.0	740.0	325.7	869.5	523.8
simulation result	mg/l	84.3	295.6	289.2	130.0	199.8	398.7	1032.3	994.7	538.6	741.1

[T-Fe]

	UNIT	RS10 DEC	RS10 JAN	RS10 FEB	RS10 MAY	RS10 Average	RS11 DEC	RS11 JAN	RS11 FEB	RS11 MAY	RS11 Average
measurement value	mg/l	5.2	2.5	4.0	12.1	5.9	126.7	141.6	13.4	144.2	106.5
simulation result	mg/l	5.2	10.6	9.6	6.4	7.9	94.2	185.7	177.1	115.0	143.0

[Al]

	UNIT	RS10 DEC	RS10 JAN	RS10 FEB	RS10 MAY	RS10 Average	RS11 DEC	RS11 JAN	RS11 FEB	RS11 MAY	RS11 Average
measurement value	mg/l	2.1	0.5	0.3	6.7	2.4	39.4	77.2	6.2	51.0	43.5
simulation result	mg/l	1.9	5.4	5.2	2.6	3.8	31.5	75.0	72.9	41.7	55.3

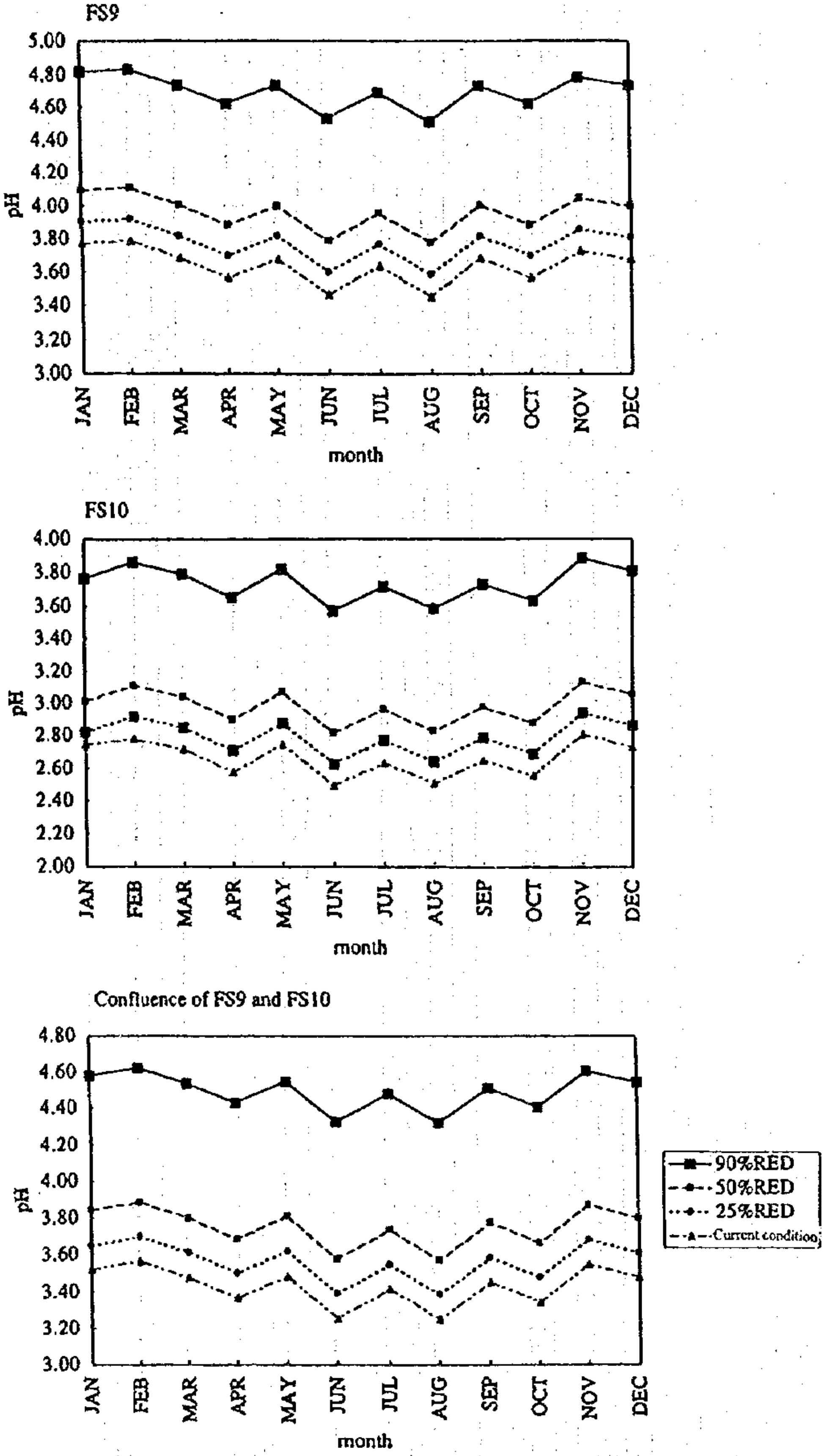

FIGURE B-22 **WATER QUALITY IMPROVEMENT EFFECT IN FIORITA SITE**

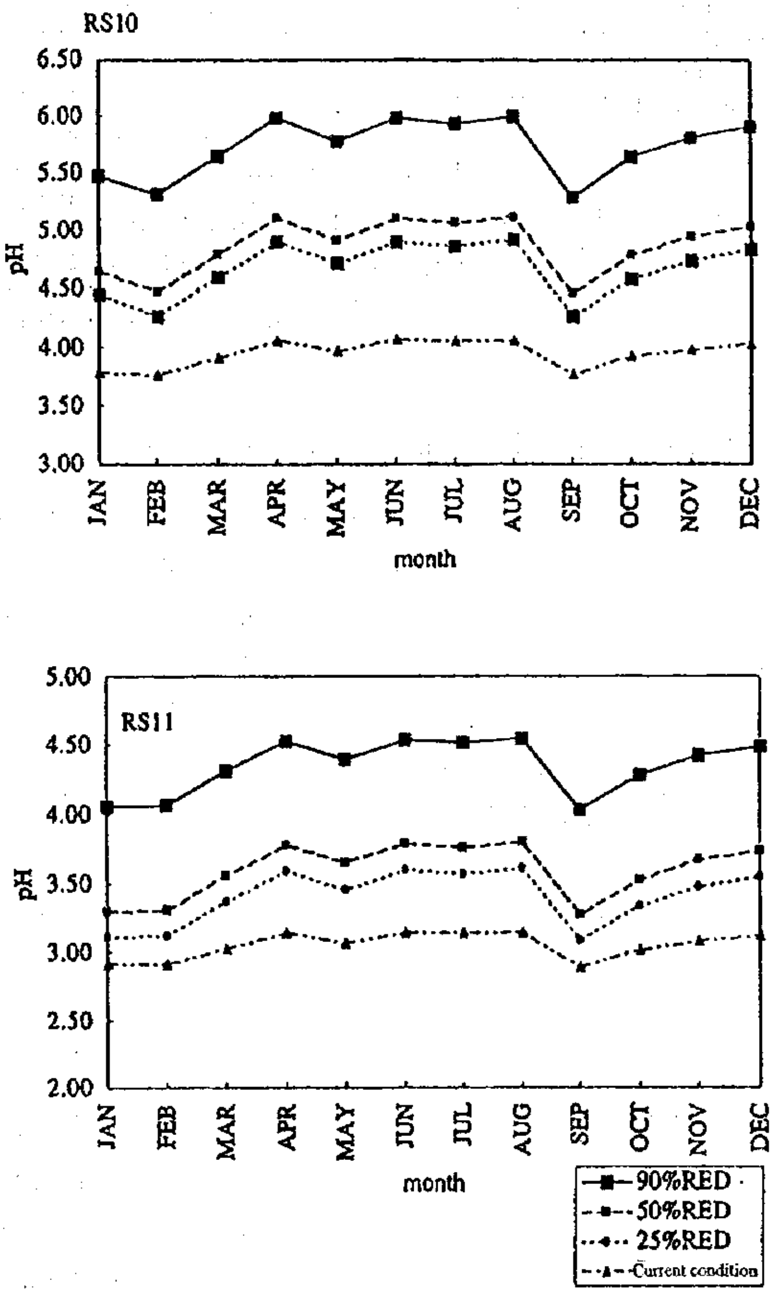

FIGURE B-23 WATER QUALITY IMPROVEMENT EFFECT IN ROCINHA SITE

C : Water quality of CS4 (mg/l)
α_1 : Load amount reduction rate
Q_1 : Flow volume of CS2 (m^3/s)
Q_2 : Flow volume of CS3 (m^3/s)
Q_3 : Flow volume of MC4 (m^3/s)
C_1 : Water quality of CS2 (mg/l)
C_2 : Water quality of CS3 (mg/l)
C_3 : Water quality of MC4 (mg/l)

40. ***(Prediction result)***: Figure B-24 shows the case study results. pH is predicted to increase from 3.6 to 4.5 by 90% reduction. However, this value is below the Brazilian standard class four. The other parameters are in excess of this standard by 90% reduction, too. Even if 100% reduction is conducted, the water quality at CS 4 will not be largely improved caused by the influence of the active mine MC 4.

4.3 Simulation Model for Capivari

41. ***(Method)***: The water quality of PT14, final discharge point to the Rio Tubarao, was predicted by using the simple equation assuming the completely mixed condition. CAS3 and CAS4 were selected as the target of loading amount reduction by the mitigation. The case study conditions are the same as the other sites. The following is the prediction equation:

$$C = \frac{\alpha_1(-Q_1 C_1 + Q_2 C_2 + Q_3 C_3) + Q_1 C_1}{Q_2 + Q_3}$$

C : Water quality of PT14 (mg/l)
α_1 : Load amount reduction rate by mitigation
Q_1 : Flow volume of PT16 (m^3/s)
Q_2 : Flow volume of CAS3 (m^3/s)
Q_3 : Flow volume of CAS4 (m^3/s)
C_1 : Water quality of PT16 (mg/l)
C_2 : Water quality of CAS3 (mg/l)
C_3 : Water quality of CAS4 (mg/l)

42. ***(Prediction result)***: Figure B-25 shows the case study results. pH was predicted to increase from 3.7 to 5.1 by 90% reduction. In this case, sulfate concentration was predicted to be less than the Brazilian standard class 2 (250 mg/l). However, the other parameters were predicted in excess of this standard. There may exist larger water quality improvement effects at the Capivari site compared with the other FS sites.

5. Overall Water Quality Simulation

43. Overall water quality simulatiom aimed at mitigated water quality prediction was conducted for the three affected river basins, i.e., Rio Tubarão, Rio Urussanga and Rio Ararangua, except for the

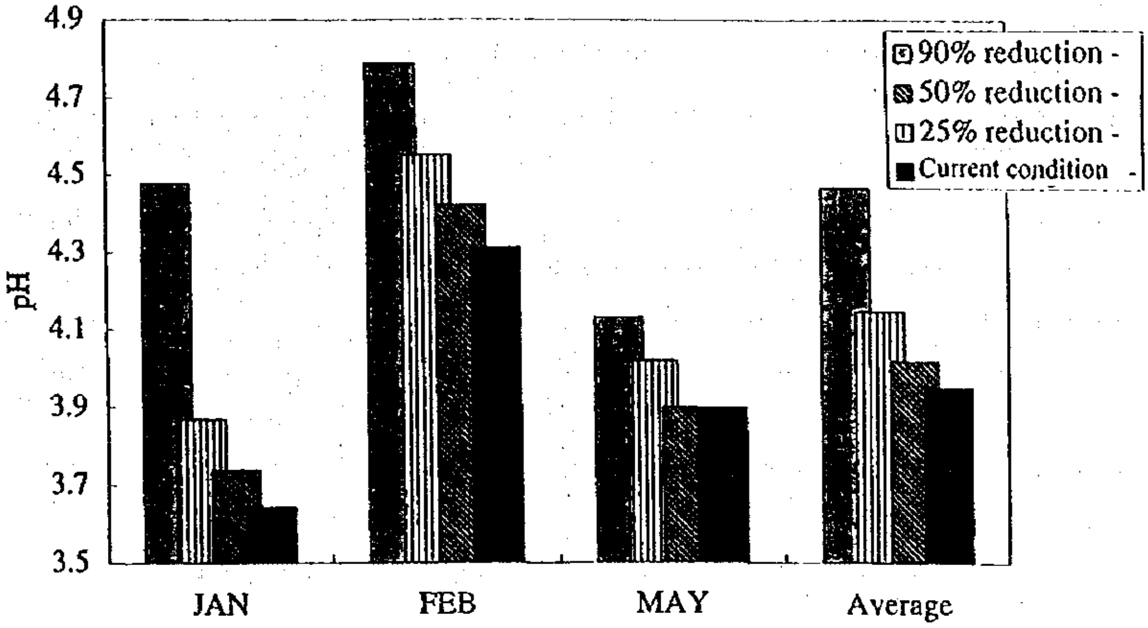

FIGURE B-24 WATER QUALITY IMPROVEMENT EFFECT IN CARVAO SITE

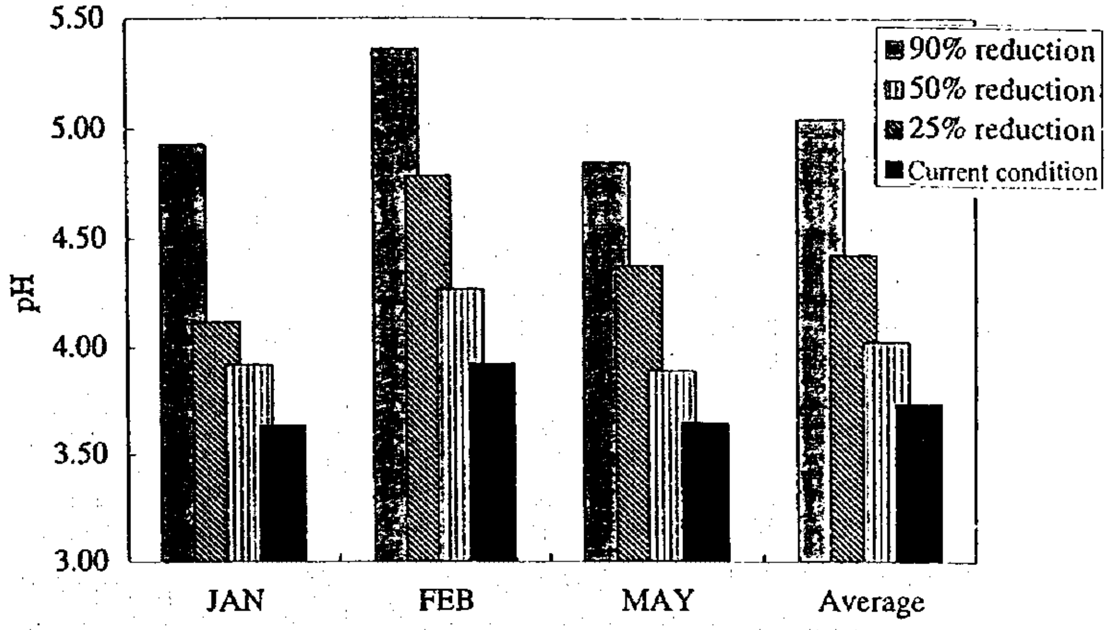

FIGURE B-25 WATER QUALITY IMPROVEMENT EFFECT IN CAPIVARI SITE tidal areas.

5.1 Abstract of Numerical Simulation Model

44. The numerical simulation model consists of a flow model and a water quality model. The flow model simulates the flow volume of the river and the water quality model simulates the water quality of the river. Both the models are bacically identical ones applied for the Rocinha and Fiorita FS sites. Since iron(Fe^{+3}) and aluminium ions were known to precipitate in form of iron hydroxide and aluminium hydroxide around the pH 5.5 where a large volume of the clean water from branches inflows to the main course, the precipitation mechanisms of iron and aluminium ions were additionally programed into the model used for the FS sites. Figure B-26 shows the structure of the boxes in the simulation model. Also the simulation conditions of the pollution loads from the active and abandoned mines are shown in Table B-6.

(a) Flow model

45. Figures B-27 through B-29 show the results of the calculation intended to reproduce the present flow condition at the final discharge points in the three rivers. The fluctuations of flow volume were well reproduced, indicating the flow volume was abundant during rainy season in summer and poor during dry season in winter. Tables B-7 through B-9 show the comparison of flow volume between simulation results and monitoring results at the major monitoring points in the three rivers. The measurement values were mostly within the calculated flow volume fluctuations.

(b) Water quality model

46. The following is the mass balance equation by the model used to calculate the concentrations of various parameters in each box.

$$C_i = \frac{1}{Q_i} \{Q_{i-1} C_{i-1} + (Q_N - \Sigma Q_{AC} - \Sigma Q_{AB}) C_N + \Sigma L_{AC} + \Sigma L_{AB}\} \quad \text{------------} \quad (1)$$

Q_i : River flow volume (m^3/s)
C_i : Concentration in the box (mg/l)
C_N : Concentration of the uppermost area (mg/l)
Q_N : Inflow volume from the catchment area (m^3/s)
Q_{AC} : Inflow volume from active mines (m^3/s)
Q_{AB} : Inflow volume from abandoned mines (m^3/s)
ΣL_{AC} : Load amount from active mines (m^3/s)
ΣL_{AB} : Load amount from abandoned mines (m^3/s)

5.2. Assumption of Pollution Load

47. The simulation conditions for the load amounts from active and abandoned mines and the precipitation mechanisms of iron and aluminum ions were set up as follows:

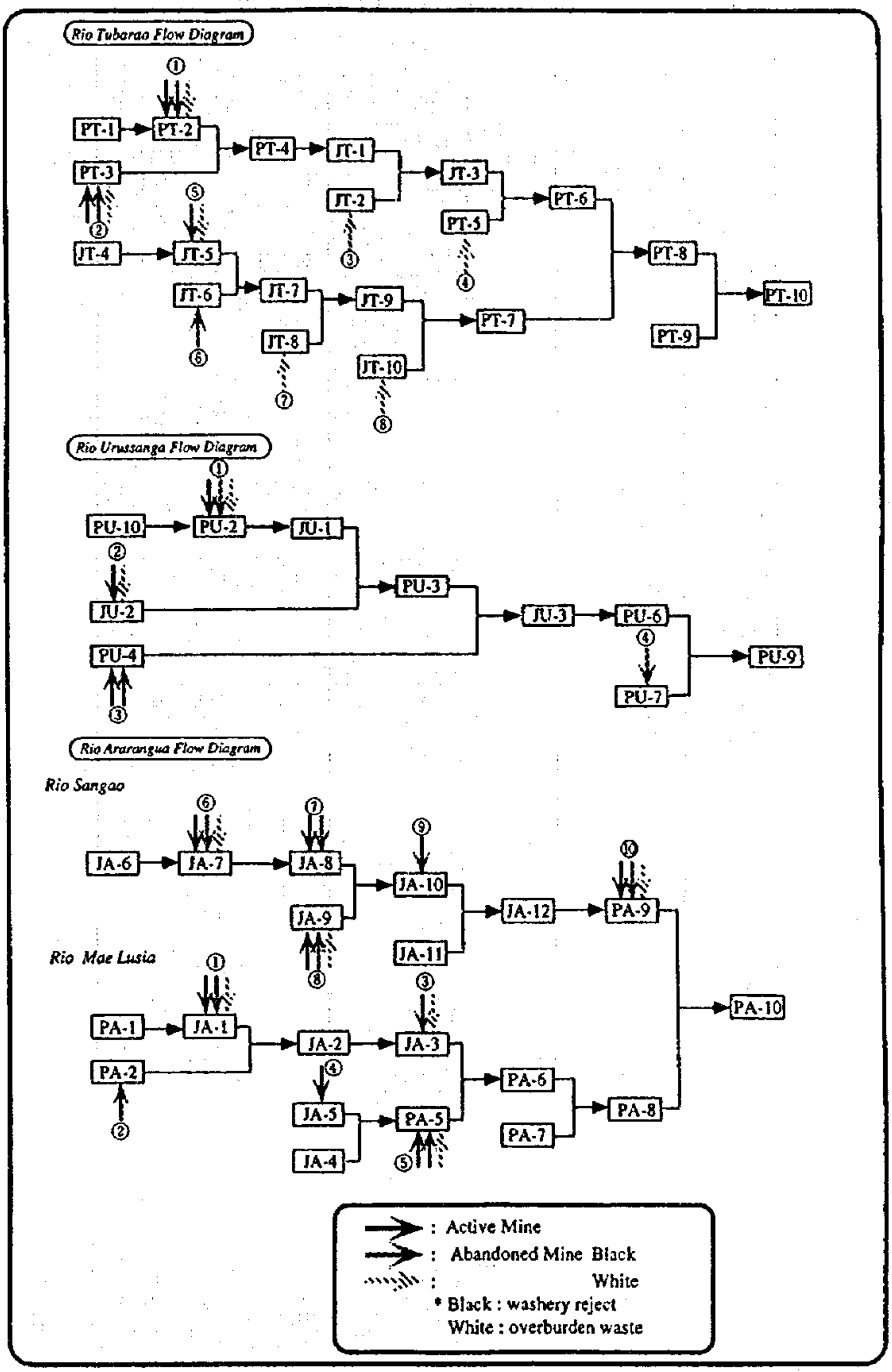

FIGURE B-26 Simulation Model Box Structure for the Overall Region's River Systems

TABLE B-6

LOAD CONDITION IN EACH RIVER

No.	Active mine	Abondoned mine	
		Black	White
		Washery reject	Overburden waste
	Number of facility	Total Area (ha)	Total Area (ha)
Rio Tubarao			
PT-2	1	1.3	69.3
PT-3	1	8	40.8
JT-2			98
PT-5			59
JT-5		42.7	70.1
JT-6	1	54.1	78.2
JT-8			89
JT-10			294.8
Sum	3	106.1	799.2
Rio Urussanga			
PU-2	3	187.2	247
JU-2	1		7
PU-4	1	38.2	
PU-7		44.8	
Sum	5	270.2	254
Rio Ararangua			
JA-1	2	120.8	118.6
PA-2			110.2
JA-3		28.8	225.8
JA-5	1		
PA-5	3	151	738.6
JA-7	2	76.5	10
JA-8	2	101	
JA-9	2	206.5	45.5
JA-10		147	
PA-9	5	598.4	28
Sum	17	1430	1276.7

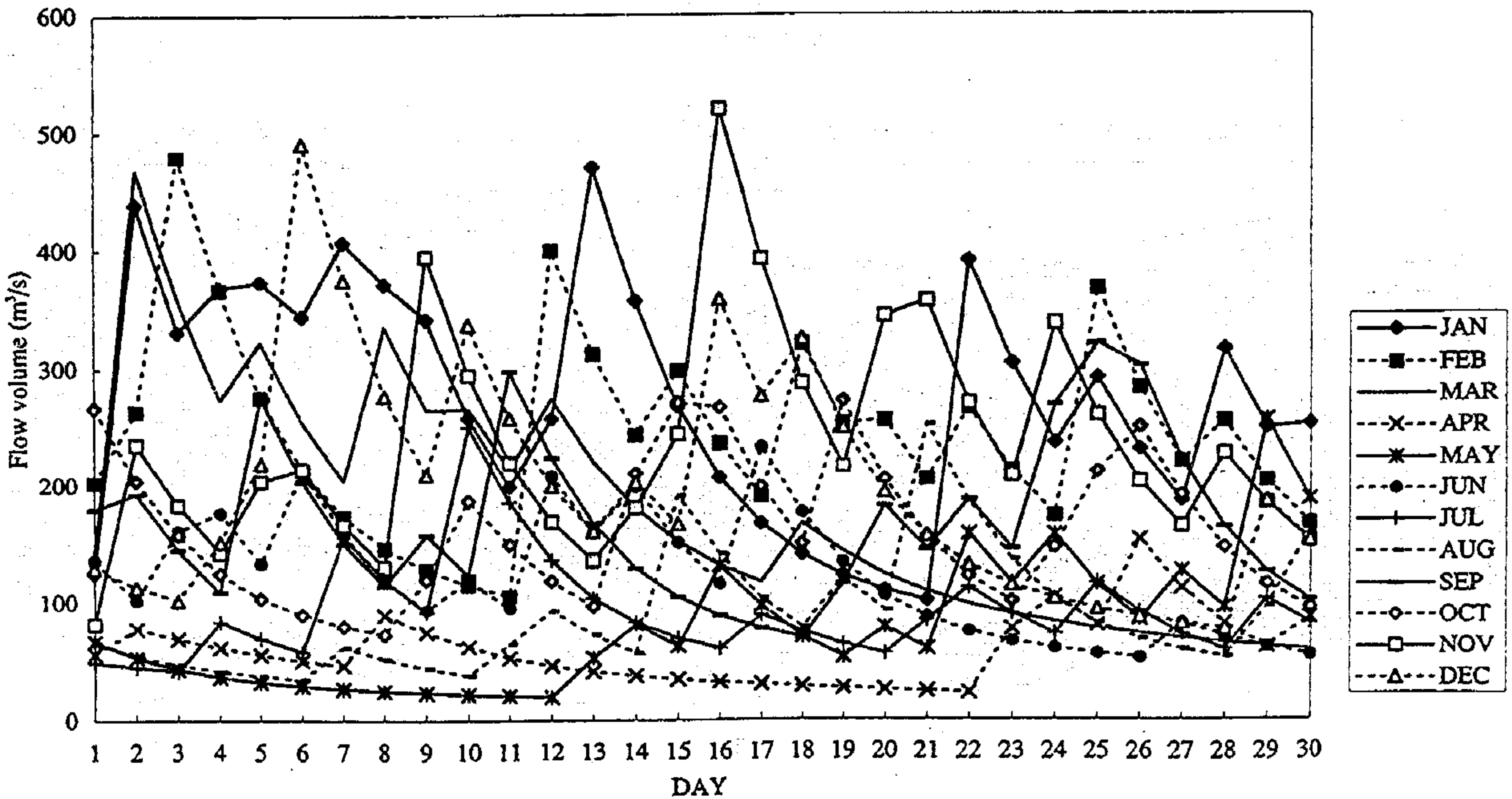

FIGURE B-27

Floe Volume Simulation Results for the Rio Tubarão

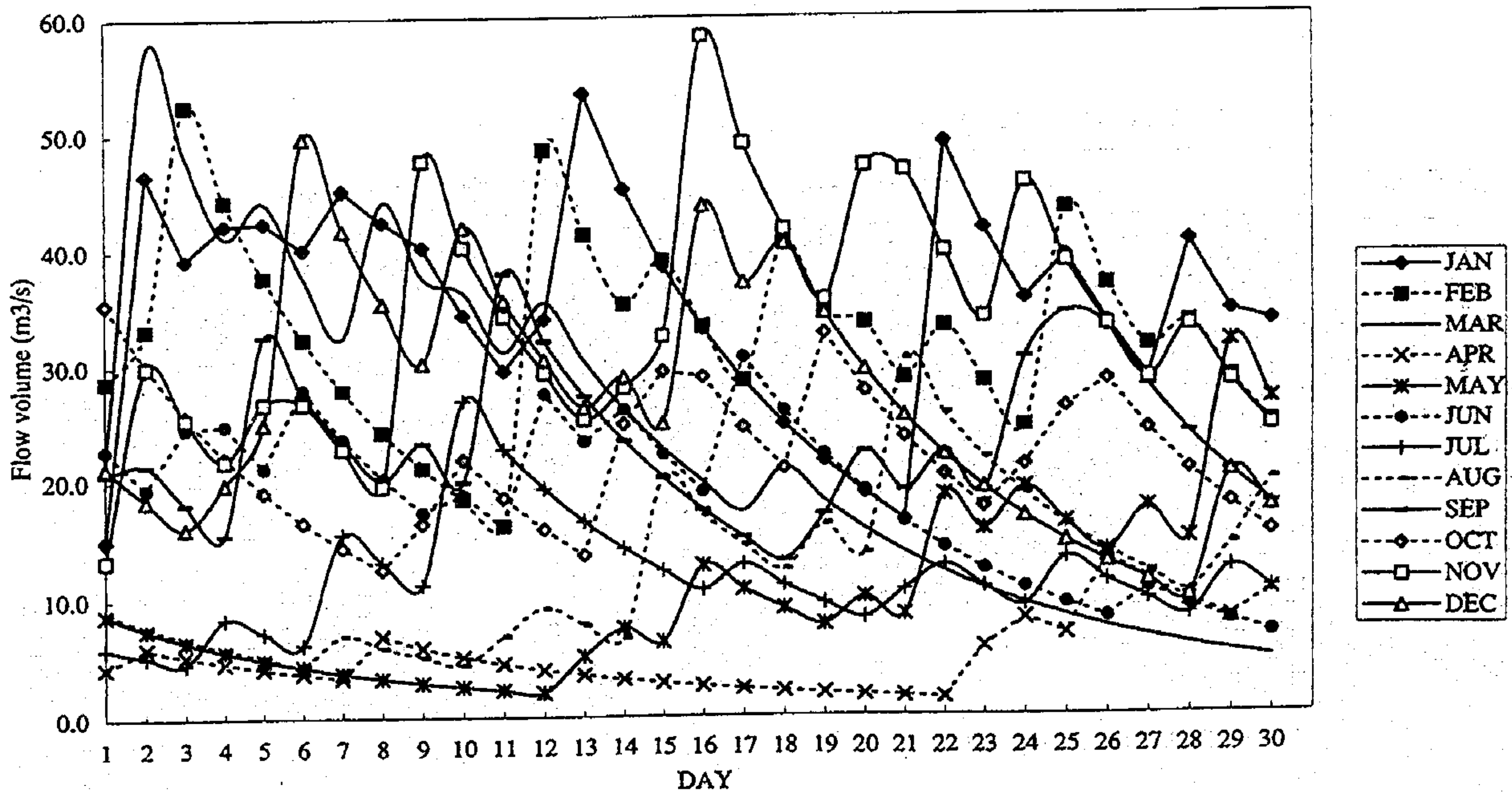

FIGURE B-28

Floe Volume Simulation Results for the Rio Urussanga

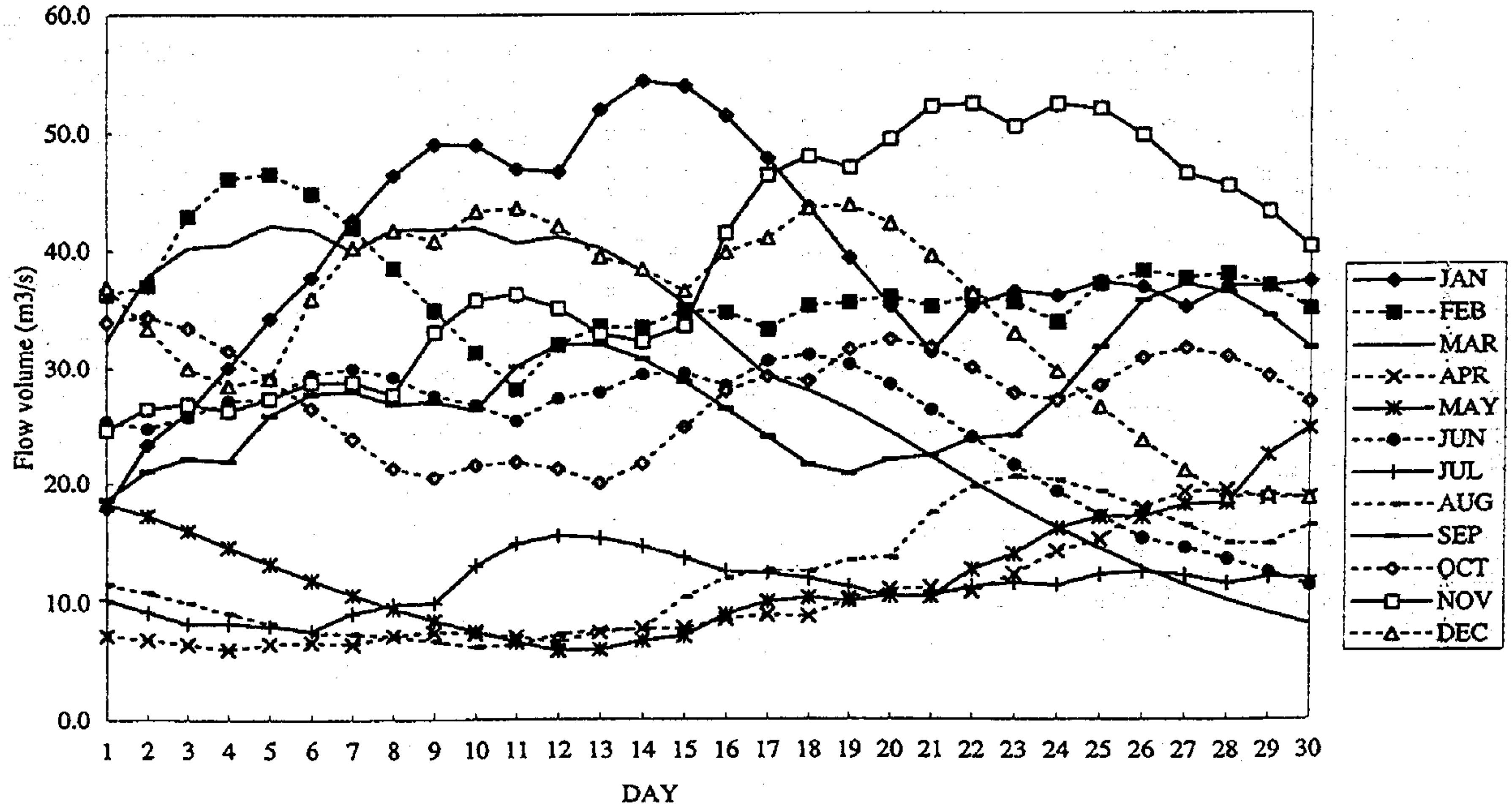

FIGURE B-29

Floe Volume Simulation Results for the Rio Araranguá

TABLE B-7

Comparison of Flow Volume between Simulated and Measured in Rio Tubarão

unit: m3/s

Location		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	DEC	NOV	DEC
PT4													
	Max	10.09	9.70	9.12	1.81	5.77	5.99	4.18	5.30	7.48	6.27	10.70	8.54
	Min	2.68	3.28	0.54	0.10	0.28	1.31	0.78	0.85	2.93	2.66	3.06	1.74
	Average	7.23	6.74	4.83	0.62	1.98	4.19	2.23	2.47	5.30	4.74	7.27	5.54
	Measurement value	-	5.51	1.55	0.53	0.12	-	-	-	-	-	-	-
JT3													
	Max	12.18	12.53	12.99	7.99	3.65	6.98	6.03	4.88	7.87	8.34	12.07	11.98
	Min	9.85	12.03	8.36	2.60	2.10	3.86	4.53	3.40	4.97	7.82	8.05	10.09
	Average	11.32	12.29	11.71	4.44	2.52	5.94	5.07	4.06	6.66	8.09	9.83	11.48
	Measurement value	-	-	8.40	2.13	3.42	-	-	-	-	-	-	-
PT6													
	Max	27.41	28.14	29.27	17.19	8.82	14.68	12.43	11.02	16.92	17.91	25.65	25.72
	Min	20.99	25.99	17.95	6.49	5.07	9.23	10.10	7.55	11.23	16.60	16.92	21.41
	Average	25.34	27.54	25.83	10.10	6.15	12.77	11.27	9.22	14.63	17.40	21.52	24.46
	Measurement value	-	-	18.20	5.28	6.40	-	-	-	-	-	-	-
PT7													
	Max	21.89	21.35	20.03	5.71	12.48	10.31	10.05	11.66	13.93	12.21	25.42	23.17
	Min	2.66	2.66	0.88	0.28	0.34	1.20	0.79	0.76	2.02	1.91	2.37	1.59
	Average	9.66	8.27	5.61	1.41	2.94	4.53	2.91	3.13	6.42	5.88	8.95	6.87
	Measurement value	21.00	9.20	6.27	1.97	-	-	-	-	-	-	-	-
PT8													
	Max	269.53	279.33	248.26	86.46	143.20	117.46	136.75	140.38	177.43	149.69	330.66	324.37
	Min	30.08	31.47	20.03	7.49	5.76	16.05	13.71	10.57	19.47	21.26	24.23	24.94
	Average	114.79	96.65	67.32	24.35	33.52	47.10	36.83	36.07	71.86	67.59	98.84	82.34
	Measurement value	188.59	41.66	28.58	6.38	5.56	-	-	-	-	-	-	-
PT10													
	Max	469.60	478.76	467.62	153.09	256.45	232.99	249.84	252.27	321.41	272.47	520.45	490.37
	Min	101.31	105.43	58.85	22.59	19.55	52.12	41.49	34.31	69.71	72.47	81.63	77.28
	Average	273.81	244.42	179.75	59.92	79.42	121.79	92.29	89.54	169.72	162.58	237.37	199.30
	Measurement value	324.17	157.19	205.68	56.63	19.34	-	-	-	-	-	-	-

* Max, Min, Average: Daily average

** Measurement value: Monitoring data

TABLE B-8

Comparison of Flow Volume between Simulated and Measured in Rio Urussanga

unit: m3/s

Location		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	DEC	NOV	DEC
PU2													
	Max	4.42	4.33	4.06	1.06	2.82	2.32	2.18	2.63	3.07	2.57	5.16	4.37
	Min	0.45	0.45	0.08	0.02	0.04	0.20	0.11	0.12	0.40	0.35	0.50	0.21
	Average	2.14	1.84	1.22	0.23	0.69	1.09	0.64	0.74	1.51	1.33	2.13	1.52
	Measurement value	4.41	2.09	2.76	0.61	0.40	-	-	-	-	-	-	-
PU3													
	Max	4.56	4.19	3.97	0.90	2.59	2.65	1.89	2.37	3.23	2.90	4.62	3.81
	Min	1.09	1.37	0.30	0.08	0.13	0.53	0.34	0.36	1.17	1.05	1.33	0.71
	Average	3.16	2.93	2.12	0.35	0.31	1.80	0.98	1.09	2.21	2.06	3.18	2.41
	Measurement value	4.53	-	3.59	1.02	0.99							
JU3													
	Max	10.74	10.21	11.27	2.52	6.30	5.93	5.09	5.94	7.45	7.13	11.38	9.66
	Min	2.61	3.03	0.96	0.32	0.38	1.21	0.85	0.83	2.39	2.24	2.57	1.79
	Average	6.65	6.15	4.54	1.01	1.93	3.52	2.16	2.31	4.40	4.21	6.38	5.04
	Measurement value	10.60	-	5.40	2.38	-	-	-	-	-	-	-	-
PU6													
	Max	29.17	28.28	31.15	6.86	17.56	16.91	14.51	16.65	20.94	19.70	31.66	26.52
	Min	7.99	8.86	2.19	0.60	1.81	3.61	2.35	2.38	7.41	6.96	7.53	5.20
	Average	19.68	18.07	13.17	2.54	5.61	10.48	6.33	6.81	12.96	12.33	18.82	14.75
	Measurement value	28.84	20.30	19.01	6.14	1.84	-	-	-	-	-	-	-
PU9													
	Max	53.34	53.49	56.91	13.23	31.74	30.51	26.91	30.35	37.93	35.44	58.30	49.66
	Min	14.99	16.10	4.76	1.46	2.06	6.81	4.61	4.51	13.07	12.47	13.30	9.89
	Average	35.54	32.76	24.03	5.14	10.19	18.55	11.63	12.27	23.16	22.13	33.54	26.64
	Measurement value	53.15	53.84	32.54	-	3.90	-	-	-	-	-	-	-

* Max, Min, Average: Daily average

** Measurement value: Monitoring data

TABLE B-9

Comparison of Flow Volume between Simulated and Measured in Rio Araranguá

unit: m3/s

Location		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	DEC	NOV	DEC
Rio Mucheia													
JA1													
	Max	19.57	19.48	15.27	7.85	11.83	9.14	8.25	10.81	12.96	10.03	24.32	20.88
	Min	1.10	1.07	0.10	0.08	0.10	0.47	0.21	0.28	1.03	0.89	1.27	0.46
	Average	7.61	6.21	3.93	2.25	2.59	3.73	2.04	2.49	5.48	4.68	7.54	5.25
	Measurement value	19.00	-	5.01	1.70	0.44	-	-	-	-	-	-	-
JA3													
	Max	11.16	9.43	8.48	4.28	5.44	6.31	3.16	4.64	7.57	7.04	11.25	8.67
	Min	2.52	5.02	0.73	0.48	0.71	1.60	0.97	0.94	3.80	3.51	4.66	2.69
	Average	7.56	7.08	5.41	1.89	2.45	4.94	2.10	2.48	5.57	5.37	7.99	6.45
	Measurement value	-	-	7.56	0.79	0.39	-	-	-	-	-	-	-
PA8													
	Max	71.51	65.94	54.25	29.03	39.44	36.97	25.70	33.48	52.41	40.93	74.89	64.01
	Min	11.44	10.67	1.61	1.33	1.53	4.76	2.40	2.65	9.14	8.28	11.54	5.68
	Average	38.90	32.55	21.90	10.34	12.43	20.60	10.04	11.70	27.72	24.52	37.88	28.01
	Measurement value	45.88	44.80	49.22	3.71	1.22	-	-	-	-	-	-	-
Rio Sengao													
JA7													
	Max	1.31	1.23	0.81	0.46	0.68	0.51	0.47	0.61	0.81	0.60	1.56	1.38
	Min	0.04	0.04	0.01	0.01	0.01	0.02	0.01	0.01	0.04	0.03	0.05	0.02
	Average	0.41	0.31	0.19	0.11	0.14	0.18	0.10	0.12	0.29	0.24	0.38	0.27
	Measurement value	1.20	0.57	0.77	0.21	0.07	-	-	-	-	-	-	-
JA10													
	Max	1.47	1.40	1.42	0.55	0.72	0.86	0.60	0.65	0.95	0.99	1.44	1.28
	Min	0.67	0.90	0.34	0.26	0.21	0.39	0.30	0.22	0.59	0.62	0.67	0.63
	Average	1.24	1.20	0.96	0.37	0.39	0.69	0.42	0.40	0.77	0.80	1.13	1.03
	Measurement value	0.76	4.61	2.19	0.81	0.34	-	-	-	-	-	-	-
JA12													
	Max	4.97	4.28	3.91	1.94	1.56	1.64	1.73	2.27	3.30	2.82	4.66	3.80
	Min	1.19	1.63	0.43	0.36	0.28	0.65	0.45	0.40	1.33	1.25	1.49	0.95
	Average	3.18	2.99	2.22	0.94	1.04	1.09	0.98	1.08	2.26	2.14	3.23	2.55
	Measurement value	1.09	-	3.63	1.86	1.22	-	-	-	-	-	-	-

* Max, Min, Average: Daily average

** Measurement value: Monitoring data

(a) Pollution load from active mines

48. Based on the hypothesis that pollution load increases in proportion to coal production from active mines, pollution load from active mines was estimated by calculating the load per unit of coal production, using active mine's effluent monitoring results and their coal production records except for Metropolitana Company, whose coal production was one order of magnitude larger than the other monitored mines. Using this unit load and the coal production of each active mine, the pollution load from all of active mines were estimated. The set up water quality of the active mine's effluent is as follows:

TABLE B-10

WATER QUALITY OF ACTIVE MINES' EFFLUENT

• pH	(-)	2.81
• SO4	(mg/l)	2,838
• Dis. Fe	(mg/l)	391
• Al	(mg/l)	123

(b) Pollution load from Reject Areas

49. The abandoned mine areas are classified as washery reject areas and overburden waste areas. Washery reject areas generally have a high potential for acidic water generation. On the other hand, overburden waste areas have a low potential for acidic water generation. However, overburden areas tend to be pollution sources due to the mixture of pyrite contained overburden or illegal dumping of washery waste. In this model, the pollution load per unit of waste area (ha) was estimated based on the monitoring data from the Rocinha and Fiorita FS sites, as representative of the washery reject area and the overburden waste area, respectively. The set up water quality of the effluent discharged from washery reject areas and overburden waste areas are as follows:

TABLE B-11

WATER QUALITY OF EFFLUENT FROM REJECT AREAS

		Washery reject areas	Overburden waste areas
pH	(-)	3.3	3.2
SO4	(mg/l)	645.0	494.0
Dis.Fe	(mg/l)	94.8	29.5
Al	(mg/l)	44.8	32.7

5.3 Iron and Aluminum Precipitation Model

50. The precipitation reactions of iron and aluminum ions were not considered in the water quality model for the FS sites, as there are no large rivers supplying clean water and decreasing pH in the main

stream in the FS sites. However, considering the simulation model for the entire area, the precipitation mechanisms of both ions have to be put into the model because there are many large branches with clean water entering the polluted rivers within the entire area. The construction procedures of the precipitation models are as follows:

i). First of all, sulfate concentration was predicted based on equation (1), as sulfate ion is stable under aerobic conditions; and

ii). Then, assuming the following equation based on the conservation of charge in water (B.J.Cosby et al I,1985, II,1985, N. Cristophersen et al 1990), dissolved iron and aluminum concentrations in a condition of electrical charge equilibrium to sulfate ion were predicted using the relationship between dissolved iron, aluminum, and sulfate monitoring data.

$$3[Al^{3+}] + 2[Al(OH)^{2+}] + [Al(OH)_2^{+}] + 3[Fe^{3+}] + 2[Fe(OH)^{2+}] + [Fe(OH)_2^{+}] + 2[Ca^{2+}] + [H^{+}]$$
$$= [HCO_3^{-}] + 2[SO_4^{2-}] + [NO_3^{-} + Cl^{-}]$$

Reference:

- Nils Christophersen et al. (1990). Modelling Streamwater Chemistry as a Mixture of Soil Water End-Members. Journal of Hydrology, 116 307-320
- B.J.Cosby, et al. (1985). Modelling the Effects of Acid Deposition, Water Resources Research, Vol. 21 51-63
- B.J.Cosby, et al. (1985). Modelling the Effects of Acid Deposition, Water Resources Research, Vol. 21 1591-1601

51. Figure B-30 shows the example of the comparison between measurement values and simulation result of aluminum in Rio Tubarão. From this figure, a rapid decrease of the aluminum/sulfate concentration ratio was observed around aluminum concentration 1.0 x 10-5 mol/l. Based on the additional remarks of pH measurement values in this figure, the precipitation was observed in the pH interval pH 4-7 and maximum precipitation was observed around pH 5.6. These behavior of aluminum ion was similar to the existing solubility curve of aluminum included in Figure B-30. This precipitation model well represented the precipitation mechanism of aluminum in the Rio Tubarão.

52. Tables B-12 through B-14 show the reproducibility of the present conditions at all the points. The measurement values were mostly within the calculated concentration fluctuations.

5.4 Method of Predicting Water Quality Improvement Effects

(a) Scenarios

53. Improvements in water quality generated by taking the acid water control measures were estimated by using the simulation model on the assumption that pollution load from all of the abandoned mines would be evenly reduced at fixed rates of 90% and effluent discharge from all active areas would comply with Brazilian effluent standard. The scenarios are assumed as follows;

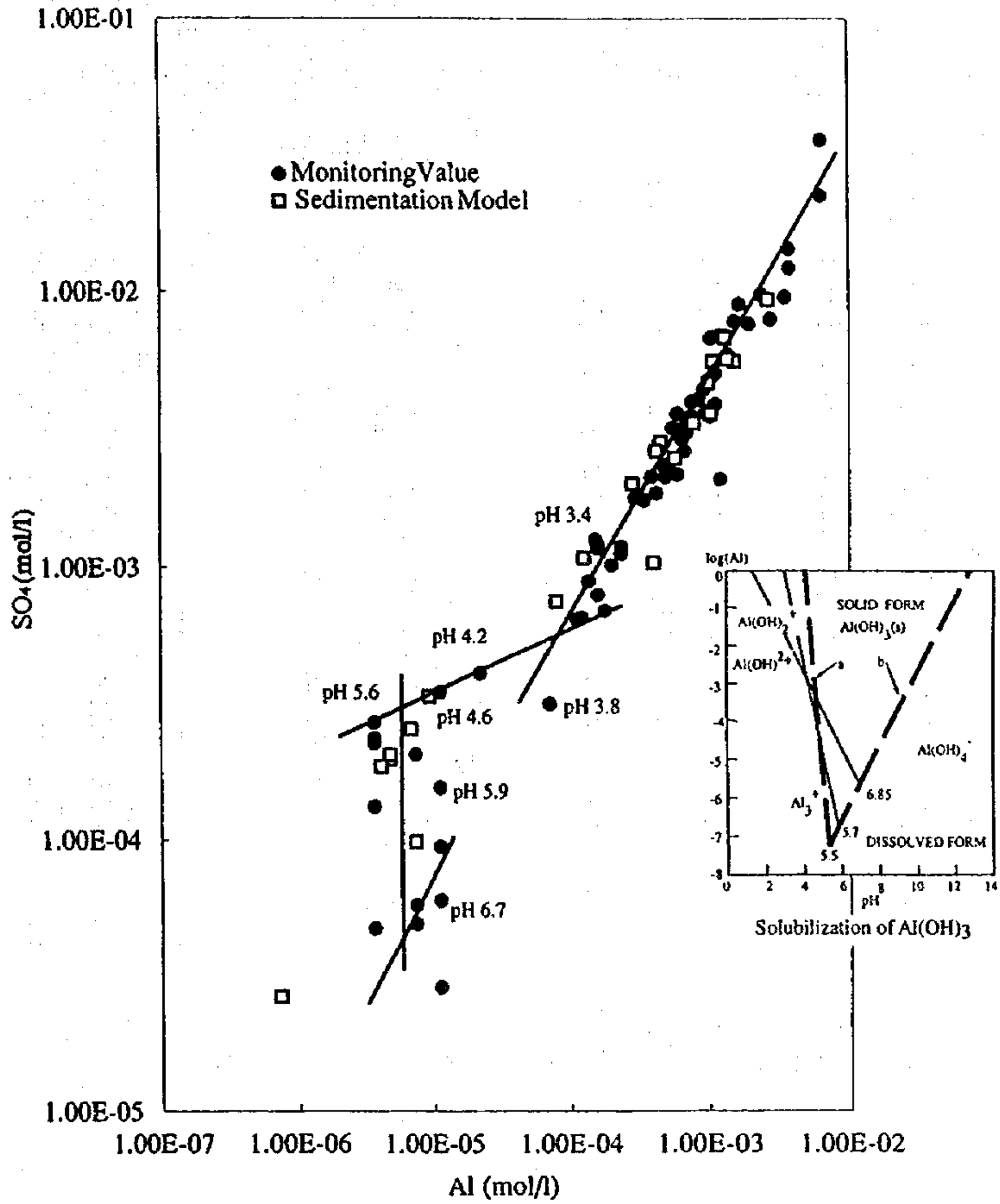

FIGURE B-30

Comparison of Aluminum Sedimentation between Simulated and Measured.

TABLE B-12

Comparison of Water Quality between Calculated and Measured in Rio Tubarão

unit: mg/l

Location		Measurement value	Simulation result		
		average	average	max	min
PT-2					
	pH	3.6	3.3	3.5	2.9
	SO4	512	490	962	291
	Dis-Fe	53.5	40.9	76.8	24.5
	Dis-Al	27.6	32.2	63.8	18.9
PT-3					
	pH	3.4	3.3	3.5	3.0
	SO4	399	375	565	237
	Dis-Fe	13.2	46.1	69.6	39.2
	Dis-Al	13.9	28.2	42.6	17.9
PT-4					
	pH	3.2	3.5	3.7	3.1
	SO4	1,057	473	802	274
	Dis-Fe	53.7	11.4	18.1	6.8
	Dis-Al	29.8	24.5	46.7	11.4
JT-1					
	pH	4.9	3.6	3.8	3.2
	SO4	103	498	1,115	242
	Dis-Fe	5.4	11.9	24.7	6.0
	Dis-Al	6.9	26.3	66.6	10.2
JT-2					
	pH	3.7	3.3	3.4	3.2
	SO4	353	367	441	329
	Dis-Fe	22.4	25.9	30.6	23.5
	Dis-Al	23.3	22.9	27.6	20.4
JT-3					
	pH	3.4	4.1	4.4	3.8
	SO4	175	192	370	102
	Dis-Fe	8.6	4.8	8.8	2.6
	Dis-Al	10.5	8.0	18.9	3.3
PT-5					
	pH	6.6	5.5	5.7	5.2
	SO4	14	8	13	5
	Dis-Fe	0.1	0.5	0.9	0.4
	Dis-Al	0.3	0.5	0.9	0.4
PT-6					
	pH	4.8	4.6	4.9	4.3
	SO4	64	90	172	45
	Dis-Fe	2.2	2.3	4.3	1.2
	Dis-Al	3.4	3.0	7.6	1.2
JT-5					
	pH	3.1	3.5	3.6	3.1
	SO4	458	304	558	197
	Dis-Fe	32.4	42.5	78.2	27.6
	Dis-Al	25.8	23.8	43.8	15.4
JT-6					
	pH	3.7	3.7	3.8	3.7
	SO4	86	212	221	208
	Dis-Fe	2.3	28.0	28.6	27.8
	Dis-Al	4.6	9.6	10.1	9.3
JT-7					
	pH	3.2	3.9	4.0	3.6
	SO4	317	242	350	176
	Dis-Fe	15.7	6.0	8.7	4.4
	Dis-Al	18.1	10.5	17.3	6.5
JT-8					
	pH	3.0	2.4	2.6	2.1
	SO4	1,734	1,782	3,069	1,129
	Dis-Fe	149.0	249.7	430.0	158.3
	Dis-Al	126.5	139.9	240.9	88.7
JT-9					
	pH	2.9	3.2	3.3	2.7
	SO4	495	565	1,070	389
	Dis-Fe	24.4	55.3	126.1	34.0
	Dis-Al	33.3	37.7	76.8	24.3
JT-10					
	pH	2.8	2.8	2.9	2.5
	SO4	1,112	979	1,643	801
	Dis-Fe	110.3	62.2	104.4	50.9
	Dis-Al	73.6	63.0	105.8	51.6
PT-7					
	pH	3.2	3.7	3.8	3.3
	SO4	265	297	471	224
	Dis-Fe	7.2	7.4	11.7	5.6
	Dis-Al	15.9	13.2	22.6	8.7
PT-8					
	pH	3.9	4.5	4.9	4.3
	SO4	76	87	154	48
	Dis-Fe	0.7	2.2	3.8	1.2
	Dis-Al	4.3	2.9	6.7	1.3
PT-10					
	pH	5.8	6.0	6.4	5.7
	SO4	23	22	38	13
	Dis-Fe	0.2	0.1	0.5	0.1
	Dis-Al	0.3	0.2	0.6	0.1

*Measurement value: Monitoring data measured from December, 1996 to June, 1997

** Averaghe, max, min: monthly value

TABLE B-13

Comparison of Water Quality between Calculated and Measured in Rio Urussanga

unit: mg/l

Location		Measurement value	Simulation result		
		average	average	max	min
FU-2					
	pH	3.0	2.8	3.0	2.6
	SO4	1,527	1,396	1,602	1,254
	Dis-Fe	123	197	255	177
	Dis-Al	113	98	130	87
JU-1					
	pH	3.0	3.1	3.2	2.9
	SO4	1,037	854	1,199	672
	Dis-Fe	64	121	179	95
	Dis-Al	72	60	86	47
JU-2					
	pH	3.6	4.3	4.4	4.1
	SO4	112	149	182	124
	Dis-Fe	15	17	19	16
	Dis-Al	25	7	10	6
FU-3					
	pH	3.0	3.5	3.6	3.3
	SO4	2,020	657	944	517
	Dis-Fe	70	11	14	9
	Dis-Al	56	20	28	16
FU-4					
	pH	3.7	3.7	4.0	3.3
	SO4	318	352	637	205
	Dis-Fe	2.6	51.4	94.7	28.9
	Dis-Al	4.9	22.7	45.7	10.8
JU-3					
	pH	3.0	3.7	3.9	3.5
	SO4	687	457	664	342
	Dis-Fe	23	8	11	6
	Dis-Al	38	14	20	11
FU-6					
	pH	3.5	3.8	4.0	3.6
	SO4	249	349	388	287
	Dis-Fe	4	6	7	5
	Dis-Al	16	11	12	9
FU-7					
	pH	3.8	4.0	4.1	3.8
	SO4	160	172	237	152
	Dis-Fe	2	26	35	23
	Dis-Al	3	14	18	12
FU-9					
	pH	3.4	4.2	4.3	4.1
	SO4	185	202	221	153
	Dis-Fe	3	4	5	4
	Dis-Al	10	6	7	5

*Measurement value: Monitoring data measured from December, 1996 to June, 1997

** Averaghe, max, min: monthly value

TABLE B-14

Comparison of Water Quality between Calculated and Measured in Rio Araranguá

unit: mg/l

Location		Measurement value	Simulation result		
		average	average	max	min
Ararangua basin					
JA-1					
	pH	3.6	3.4	3.5	3.2
	SO4	426	391	505	350
	Dis-Fe	34.7	54.4	70.1	40.3
	Dis-Al	11.1	19.0	28.4	15.7
PA-2					
	pH	4.0	3.6	4.3	3.0
	SO4	229	261	533	54
	Dis-Fe	14.3	16.6	33.9	3.4
	Dis-Al	17.1	16.8	34.3	3.5
JA-2					
	pH	3.6	3.4	3.8	3.1
	SO4	393	416	632	253
	Dis-Fe	13.3	7.8	11.3	4.9
	Dis-Al	12.1	15.6	27.4	8.1
JA-3					
	pH	3.4	3.1	3.3	2.7
	SO4	381	611	1,012	392
	Dis-Fe	6.4	34.3	79.5	19.5
	Dis-Al	12.3	31.4	58.1	18.0
JA-5					
	pH	4.9	3.7	3.7	3.7
	SO4	254	254	254	254
	Dis-Fe	20.2	35.0	35.0	35.0
	Dis-Al	7.8	11.0	11.0	11.0
PA-5					
	pH	3.2	3.5	3.6	3.3
	SO4	465	331	406	302
	Dis-Fe	15.2	44.9	53.4	41.4
	Dis-Al	17.4	16.0	21.2	13.8
PA-6					
	pH	3.2	3.2	3.5	3.0
	SO4	811	564	878	359
	Dis-Fe	13.5	10.5	16.1	7.0
	Dis-Al	19.1	21.4	34.1	11.6
PA-8					
	pH	3.4	3.6	3.9	3.3
	SO4	391	346	448	213
	Dis-Fe	6.2	6.6	8.2	4.2
	Dis-Al	15.7	13.3	17.7	6.4
Sangao basin					
JA-7					
	pH	2.9	2.9	3.0	2.7
	SO4	1,124	801	1,006	665
	Dis-Fe	143.3	114.3	144.9	94.1
	Dis-Al	85.6	47.7	64.1	36.8
JA-8					
	pH	2.0	2.5	2.7	2.1
	SO4	1,367	1,446	2,612	1,016
	Dis-Fe	162.5	211.2	389.0	145.4
	Dis-Al	103.3	95.3	189.5	60.5
JA-9					
	pH	3.0	2.5	2.6	2.4
	SO4	2,083	1,626	1,928	1,385
	Dis-Fe	249.0	232.2	277.6	195.9
	Dis-Al	123.0	94.7	119.0	75.3
JA-10					
	pH	2.8	2.6	2.8	2.3
	SO4	1,557	1,521	2,144	1,157
	Dis-Fe	185.3	26.7	36.5	20.9
	Dis-Al	94.2	67.9	107.4	47.1
JA-12					
	pH	3.1	3.1	3.2	2.8
	SO4	1,111	740	1,076	605
	Dis-Fe	118.2	13.6	19.2	11.4
	Dis-Al	72.0	29.4	46.6	21.6
PA-9					
	pH	3.2	2.6	2.7	2.5
	SO4	1,013	1,351	1,736	1,144
	Dis-Fe	113.6	111.0	148.5	85.3
	Dis-Al	60.4	71.5	87.5	58.2
PA-10					
	pH	3.1	3.3	3.5	3.0
	SO4	569	531	722	366
	Dis-Fe	39.3	9.9	12.9	7.0
	Dis-Al	31.9	19.5	30.0	12.4

*Measurement value: Monitoring date measured from December, 1996 to June, 1997

** Averaghe, max, min: monthly value

- **Scenario I**: This scenario would illustrate the extent of mitigation under ideal conditions, i.e., (a) the whole area would be remedied using a wet/dry cover system and wetland treatment method; and (b) effluent discharge from all active areas would comply with Brazilian effluent standards.
- **Scenario II**: This scenario is identical to scenario I except that the quality of effluent from active areas remains low, i.e., not in compliance with Brazilian norms.
- **Scenario III**: This scenario would be the reverse of scenario II, i.e., operators comply with Brazilian norms, but no land remediation at all.

(b) Equation

54. The following is the prediction equation.

$$C_i = \frac{1}{Q_i} \{Q_{i-1} C_{i-1} + (Q_N - \Sigma Q_{AC} - \Sigma Q_{AB}) C_N + \Sigma L_{AC}' + \Sigma L_{AB}\}$$

L_{AC}': Pollution load when all active areas would comply with Brazilian effluent standards.(mg/s)
α : Pollution load reduction rates 90% of those from all of the abandoned mines

(c) Prediction Result

55. Tables B-15 through B-17 show the case study result as annual average. Table B-18 is the summary of the pH improvement effect in the rivers.

56. *Scenario I*: The largest improvement effect was generated by assuming acid water is controlled at both active and abandoned mines. The water quality of all the rivers was improved by achieving an average pH value of 5.5, except for the Rio Sangão in the Rio Ararangua basin. In the most effective points, the pH was increased up to 6-7. However, some less effective points below the pH 4 remained. As for the Rio Sangao, the improvement effects were very small and, even at the most effective point, the pH value was about 5. Figure B-31 shows the comparison between the current pH value and predicted pH value in scenario I.

57. *Scenario II*: The pH was increased up to 4.5-5.0 in average, including the lower and upper areas in the Rio Tubarão and Rio Urussanga. The pH of the upper areas, however, remained below the pH value 4.0. In the Rio Ararangua, both branches remained below the pH value of 4.0 due to the effect of the active mine's effluent.

58. *Scenario III*: Relatively large improvement effect was observed in the Rio Mae Luzia in the Rio Ararangua basin, as the average pH was increased to over 4.0. In other rivers, pH remained less than the value of 4.0.

TABLE B-15

WATER QUALITY IMPROVEMENT EFFECT IN RIO TUBARAO

unit: mg/l

Location	Parameter	Current condition	Scenario 1 ・90% load reduction for Abandoned mine ・Regulation for Active mine	Scenario 2 90% load reduction for Abandoned mine	Scenario 3 Regulation for Active mine	Brazilian Ambient Standard class 4
PT-2	pH	3.3	4.6	4.3	3.3	6-9
	SO4	490.4	46.2	24.9	461.7	250.0
	Dis-Fe	40.0	3.8	7.6	36.2	5.0
	Dis-Al	32.2	3.1	4.3	31.0	0.1
PT-3	pH	3.3	4.6	4.6	3.3	6-9
	SO4	374.8	37.5	37.5	374.8	250.0
	Dis-Fe	46.1	4.6	4.6	46.1	5.0
	Dis-Al	28.2	2.8	2.8	28.2	0.1
PT-4	pH	3.5	8.1	4.7	3.5	6-9
	SO4	472.9	44.9	69.1	448.6	250.0
	Dis-Fe	11.4	1.1	1.7	10.8	5.0
	Dis-Al	24.5	1.5	2.1	23.1	0.1
JT-1	pH	3.6	5.2	4.8	3.6	6-9
	SO4	497.5	47.2	72.6	472.2	250.0
	Dis-Fe	11.9	1.2	1.8	11.3	5.0
	Dis-Al	26.1	1.4	2.3	24.7	0.1
JT-2	pH	3.3	4.7	4.3	3.4	6-9
	SO4	357.1	33.2	68.4	331.9	250.0
	Dis-Fe	23.9	2.3	7.0	21.3	5.0
	Dis-Al	23.9	2.1	3.7	21.4	0.1
JT-3	pH	4.8	6.7	5.2	4.1	6-9
	SO4	191.7	17.9	30.7	178.9	250.0
	Dis-Fe	4.8	0.5	0.8	4.4	5.0
	Dis-Al	8.0	0.4	0.8	7.4	0.1
PT-5	pH	5.5	6.6	6.6	5.5	6-9
	SO4	8.4	2.5	2.5	8.4	250.0
	Dis-Fe	0.5	0.1	0.1	0.5	5.0
	Dis-Al	0.5	0.1	0.1	0.5	0.1
PT-6	pH	4.6	6.3	5.8	4.6	6-9
	SO4	89.6	8.4	14.1	83.9	250.0
	Dis-Fe	2.3	0.2	0.4	2.1	5.0
	Dis-Al	3.0	0.2	0.3	2.8	0.1
JT-5	pH	3.5	4.8	4.8	3.5	6-9
	SO4	303.5	30.4	30.4	303.5	250.0
	Dis-Fe	42.5	4.3	4.3	42.5	5.0
	Dis-Al	23.8	2.4	2.4	23.8	0.1
JT-6	pH	3.7	6.2	3.8	5.1	6-9
	SO4	212.3	2.5	197.9	16.1	250.0
	Dis-Fe	28.0	1.1	27.1	2.1	5.0
	Dis-Al	9.6	0.1	8.6	1.1	0.1
JT-7	pH	3.9	5.8	4.4	4.2	6-9
	SO4	241.5	15.4	103.2	153.7	250.0
	Dis-Fe	6.0	0.4	2.6	3.8	5.0
	Dis-Al	10.5	0.3	3.4	6.4	0.1
JT-8	pH	2.4	3.7	3.7	2.4	6-9
	SO4	1,782.2	178.2	178.2	1,782.2	250.0
	Dis-Fe	249.7	25.0	25.0	249.7	5.0
	Dis-Al	139.9	14.0	14.0	139.9	0.1
JT-9	pH	3.2	4.5	4.2	3.2	6-9
	SO4	565.3	50.7	108.8	507.2	250.0
	Dis-Fe	55.3	5.4	8.9	53.9	5.0
	Dis-Al	37.7	3.2	5.1	35.0	0.1
JT-10	pH	2.8	4.1	4.6	2.8	6-9
	SO4	978.8	97.9	97.9	978.8	250.0
	Dis-Fe	62.3	6.2	6.2	62.2	5.0
	Dis-Al	63.0	6.3	6.3	63.0	0.1
PT-7	pH	3.7	5.3	4.8	3.7	6-9
	SO4	297.3	27.2	52.4	272.1	250.0
	Dis-Fe	7.4	0.7	1.3	6.8	5.0
	Dis-Al	13.2	0.6	1.4	11.9	0.1
PT-8	pH	4.5	6.1	5.7	4.6	6-9
	SO4	87.0	8.1	14.4	80.6	250.0
	Dis-Fe	2.2	0.2	0.4	2.0	5.0
	Dis-Al	2.9	0.1	0.3	2.6	0.1
PT-10	pH	6.8	6.9	6.9	6.8	6-9
	SO4	21.6	2.9	3.7	20.0	250.0
	Dis-Fe	0.2	0.1	0.1	0.2	5.0
	Dis-Al	0.2	0.0	0.0	0.2	0.1

* Values are annual average

TABLE B-16

WATER QUALITY IMPROVEMENT EFFECT IN RIO URUSSANGA

unit: mg/l

Location	Parameter	Current condition	Scenario 1 • 90% load redction for Abandoned mine • Regulation for Active mine	Scenario 2 90% load redction for Abandoned mine	Scenario 3 Regulation for Active mine	Brazilian Ambient Standard class 4
PU-2	pH	2.8	4.3	3.6	2.9	6-9
	SO4	1,396	106	441	1,061	250.0
	Dis-Fe	197	16.9	61.3	152.6	5.0
	Dis-Al	98	8.4	22.9	83.7	0.1
JU-1	pH	3.1	4.6	3.9	3.2	6-9
	SO4	854	65	268	651	250.0
	Dis-Fe	121	10.3	37.3	93.7	5.0
	Dis-Al	60	5.2	14.0	51.4	0.1
JU-2	pH	4.3	6.4	4.5	5.0	6-9
	SO4	145	4.6	109.1	39.4	250.0
	Dis-Fe	17	0.8	14.7	3.1	5.0
	Dis-Al	7.1	0.3	4.8	2.5	0.1
PU-3	pH	3.5	5.1	4.1	3.7	6-9
	SO4	657	49	216	489	250.0
	Dis-Fe	11	1.5	4.6	8.4	5.0
	Dis-Al	20	1.7	6.8	14.9	0.1
PU-4	pH	3.7	5.6	4.2	4.2	6-9
	SO4	352	19.9	173.3	199.0	250.0
	Dis-Fe	51.4	3.8	24.2	31.1	5.0
	Dis-Al	22.7	1.6	8.3	16.1	0.1
JU-3	pH	3.8	5.3	4.3	3.9	6-9
	SO4	687	33	161	328	250.0
	Dis-Fe	23	1.1	3.7	6.2	5.0
	Dis-Al	38	1.1	5.2	10.2	0.1
PU-6	pH	3.5	5.4	4.5	4.0	6-9
	SO4	249	25	124	250	250.0
	Dis-Fe	3.7	0.9	3.0	5.0	5.0
	Dis-Al	16	0.9	4.0	7.8	0.1
PU-7	pH	3.8	5.4	5.4	4.0	6-9
	SO4	160	17	17	172	250.0
	Dis-Fe	1.8	2.6	2.6	26.3	5.0
	Dis-Al	2.9	1.4	1.4	13.9	0.1
PU-9	pH	3.4	5.7	4.9	4.3	6-9
	SO4	185	16	62	156	250.0
	Dis-Fe	2.7	0.7	1.8	3.6	5.0
	Dis-Al	10	0.6	2.1	5.0	0.1

* Values are annual average

TABLE B-17

WATER QUALITY IMPROVEMENT EFFECT IN RIO ARARANGUA

unit: mg/l

Location	Parameter	Current condition	Scenario 1 • 90% load reduction for Abandoned mine • Regulation for Active mine	Scenario 2 90% load reduction for Abandoned mine	Scenario 3 Regulation for Active mine	Brazilian Ambient Standard class 4
Mae Luzia						
JA-1	pH	3.4	3.7	3.5	4.4	6-9
	SO4	392.5	6.7	342.8	55.4	250.0
	Dis-Fe	54.4	2.6	47.2	9.8	5.0
	Dis-Al	19.0	0.5	15.1	4.4	0.1
PA-2	pH	3.6	4.9	4.9	3.6	6-9
	SO4	260.7	26.1	26.1	260.7	250.0
	Dis-Fe	16.6	1.7	1.7	16.6	5.0
	Dis-Al	16.8	1.7	1.7	16.8	0.1
JA-3	pH	3.4	6.2	3.6	4.4	6-9
	SO4	416.4	12.5	308.1	120.4	250.0
	Dis-Fe	7.8	0.2	5.9	2.1	5.0
	Dis-Al	15.6	0.3	10.1	4.8	0.1
JA-3	pH	3.1	4.7	3.6	3.3	6-9
	SO4	611.2	35.0	299.4	346.5	250.0
	Dis-Fe	34.3	2.9	8.0	29.2	5.0
	Dis-Al	31.6	2.0	10.8	22.0	0.1
JA-5	pH	3.7	7.0	3.7	7.0	6-9
	SO4	254.1	2.5	254.1	2.5	250.0
	Dis-Fe	35.0	1.3	35.0	1.3	5.0
	Dis-Al	11.0	0.7	11.0	0.7	0.1
PA-5	pH	3.5	4.3	3.6	4.0	6-9
	SO4	331.0	74.8	285.3	120.6	250.0
	Dis-Fe	44.9	11.3	39.2	17.0	5.0
	Dis-Al	16.0	3.4	12.5	6.9	0.1
PA-6	pH	3.2	5.2	3.7	3.7	6-9
	SO4	563.8	42.3	303.1	302.8	250.0
	Dis-Fe	10.5	0.7	5.8	5.7	5.0
	Dis-Al	21.4	0.7	9.8	10.8	0.1
PA-8	pH	3.6	5.6	4.0	4.0	6-9
	SO4	345.7	25.3	193.0	177.7	250.0
	Dis-Fe	6.6	0.3	3.8	3.4	5.0
	Dis-Al	11.9	0.3	5.7	5.7	0.1
Sangao basin						
JA-7	pH	2.9	4.5	3.3	3.2	6-9
	SO4	801.0	35.3	484.8	351.5	250.0
	Dis-Fe	114.3	7.6	67.2	54.8	5.0
	Dis-Al	47.7	2.9	22.3	28.2	0.1
JA-8	pH	2.5	4.0	3.1	2.7	6-9
	SO4	1,446.4	87.7	658.6	875.6	250.0
	Dis-Fe	211.2	16.3	91.9	135.5	5.0
	Dis-Al	95.3	7.1	31.8	70.6	0.1
JA-9	pH	2.5	4.1	2.9	2.9	6-9
	SO4	1,625.7	65.5	1,039.4	651.7	250.0
	Dis-Fe	232.2	14.9	144.0	103.1	5.0
	Dis-Al	94.7	5.3	47.5	52.5	0.1
JA-10	pH	2.6	4.5	3.1	2.9	6-9
	SO4	1,521.2	94.9	668.4	947.7	250.0
	Dis-Fe	26.7	1.8	12.5	17.0	5.0
	Dis-Al	67.9	2.3	24.4	40.3	0.1
JA-12	pH	3.1	5.1	3.6	3.4	6-9
	SO4	739.6	45.5	331.4	453.7	250.0
	Dis-Fe	13.6	0.7	6.5	8.5	5.0
	Dis-Al	28.4	0.8	10.5	16.4	0.1
PA-9	pH	3.6	4.2	3.2	3.8	6-9
	SO4	1,351.2	84.5	592.0	843.8	250.0
	Dis-Fe	111.0	8.6	47.5	72.4	5.0
	Dis-Al	71.5	4.2	23.9	49.8	0.1
PA-10	pH	3.3	5.3	3.7	3.7	6-9
	SO4	531.3	35.6	270.4	296.4	250.0
	Dis-Fe	9.9	0.6	5.3	5.7	5.0
	Dis-Al	19.5	0.5	8.4	10.1	0.1

* Values are annual average

TABLE B-18

SUMMARY OF THE pH IMPROVEMENT EFFECT IN THE RIVERS

Unit: -

River			Current condition			Scenario 1 • 90% load rediction for Abandoned mine • Regulation for Active mine			Scenario 2 90% load rediction for Abandoned mine			Scenario 3 Regulation for Active mine		
			Average	Max	Min	Average	Max	Min	Average	Max	Min	Average	Max	Min
Rio Tubarao		pH (-)	3.8	6.0	2.4	5.3	6.9	3.7	4.9	6.9	3.7	3.9	6.0	2.4
		Increasing rate	1.0	-	-	1.4	1.7	1.2	1.3	1.5	1.0	1.0	1.4	1.0
Rio Urussanga		pH (-)	3.5	4.3	2.8	5.3	6.4	4.3	4.4	5.4	3.6	3.9	5.0	2.9
		Increasing rate	1.0	-	-	1.5	1.8	1.4	1.3	1.4	1.0	1.1	1.3	1.0
	Rio Mae Luzia	pH (-)	3.4	3.7	3.1	5.4	7.0	4.3	3.8	4.9	3.5	4.3	7.0	3.3
		Increasing rate	1.0	-	-	1.6	1.9	1.2	1.1	1.4	1.0	1.2	1.9	1.0
Rio Ararangua														
	Rio Sangao	pH (-)	2.8	3.3	2.5	4.5	5.3	4.0	3.3	3.7	2.9	3.1	3.7	2.7
		Increasing rate	1.0	-	-	1.6	1.7	1.6	1.2	1.2	1.1	1.1	1.14	1.08

* Values are annual average

** Increasing rate: Case # / Present condition

*** Brazilian ambient standard: pH 6-9

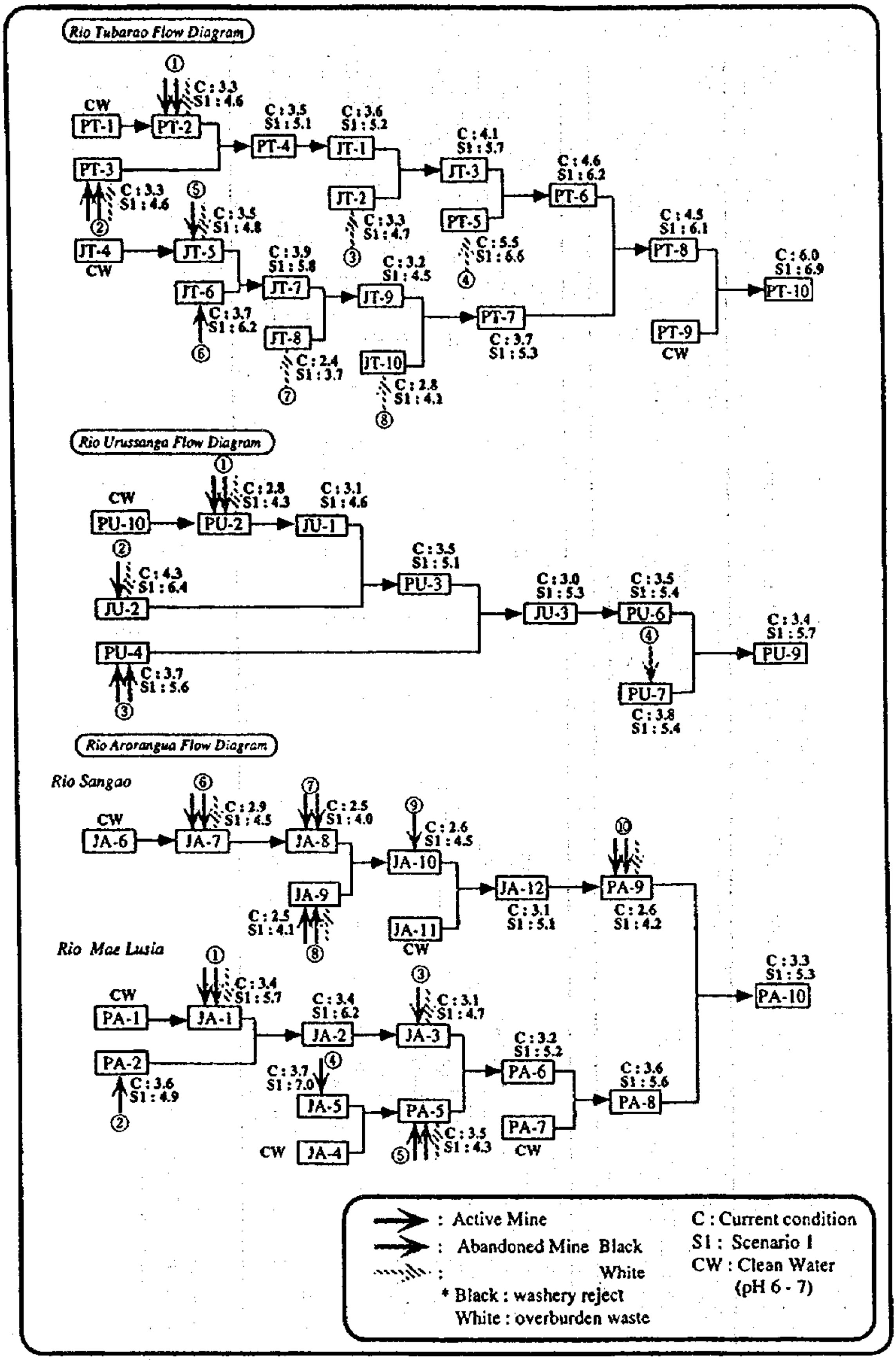

FIGURE B-31

Current pH Value and Predicted pH Value in Scenario I

(d) Evaluation

59. Mitigated water quality prediction in the entire area is assessed as follows:

60. Based on the existing reports regarding phytoplankton and zooplankton in acidified lakes, a decrease in species richness and diversity of phytoplankton with decrease in pH was observed and the greatest changes in composition were found in the pH interval 5-6, below which characteristic species may often establish large populations in acidified lake. An effect of pH on zooplankton was not observed until lake pH dropped below values of 5-5.5. In the lake with pH less than 5.0, many species are completely eliminated (Green & Leuven, 1986). An effect of pH on benthos was observed in the pH interval 5-6 in the Kitakami river (Hukusima, 1986) and an effect of pH on the high trophic level began below pH value of 6.0 (Sakamoto, 1991). Summarizing the existing reports, the negative effects of pH on aquatic life are found in the pH interval 5-6. These studies imply the possibility of restoring the ecosystem in the polluted rivers, if the pH level can be increase to more than 5, as in Scenario I.

Reference:

- F. M. Geelen and R.S.E.W. (1986). Leuven: Impact of acidification on phytoplankton and zooplankton communities. Exprientia 42
- Hukusima (1967). Yokohama city university report (c), 173, 1
- Sakamoto (1991). Acid rain and aquatic environment, Water pollution research, 14, 599-606

61. The pH was increased more than 5.0 on average for all the rivers except for Rio Sangao only in Scenario I. These case study results indicate the importance of taking measures for both active and abandoned mines to recover the ecosystem in the polluted rivers. Recovery over pH value of 5.0 in Rio Sangao is considered to be difficult because of the narrow catchment area, no large branches with clean water, and excessive concentration of mines.

62. The water quality of all the rivers will not achieve the Brazilian ambient criteria pH 6-9, even if Scenario I would be executed. However, as some aquatic life can inhabit water with a pH value of 5.0 or greater, the execution of Scenario I would enhance the self-purification capacity by neutralization of acid with organic materials originating from aquatic life, and would prevent dissolution and leaching of some kinds of heavy metals. Therefore, water quality will be restore in the long term by the execution of Scenario I.

6. Environmental Monitoring System for the Future

6.1 Functions

63. In general, the main functions of environmental monitoring are: (i.) monitoring of water quality; and (ii.) pollution control. Unless there is evidence of possible catastrophe (e.g., presence of a dangerous chemical plant near by), systematic emergency monitoring is not necessary. Since the

region's pollution is not subject to sudden increases in toxic matter in the rivers, emergency action would not be part of the environmental monitoring system for the future. Accordingly, it would not be necessary to install continuous, automatic monitoring equipment for the system.

6.2 Monitoring of water quality

64. The monioring system would consist of periodical sampling, field measurement, chemical analysis and flow volume measurement. The current water quality auto-monitoring equipment will be continuosly used at the three stations without any expansion in a number of auto-monitoring locations and facilities. Monitoring methods including location, parameters and frequency are as folows:

65. *Monitoring location*: Figure B-32 shows proposed monitoring locations. The most important monitoring points in each basin are as follows:

- Tubarão basin: PT 4, PT 6, PT 7, PT 8, PT 10;
- Urussanga basin: JU 3, PU 9;
- Araranguá basin: JA 3, PA 5, PA 6, PA 9, PA10; and
- Capivari: PT 14, PT 16.

66. *Monitoring frequency and parameters*:

Frequency: Every month or every two months

Parameters: Based on field measurement with portable meters and laboratory analysis.

- Field measurement: water temperature, pH, DO, EC, flow rate
- Laboratory analysis: total acidity and alkalinity, sulfate, iron, aluminum, heavy metals including lead and Zn, SS.

67. *Equipment for monitoring system*: Incorporation of the auto monitoring equipment connecting with the on-line/off-line network into the system would not be required as mentioned above. Water quality monitoring data collected would be dealt with by personal computers with appropriate software. Personal computers and portable meters currently existing at the FATMA's office, which were provided by JICA in the early stage of this Study, are available for the future monitoring system. FUCRI/UNESC has facilities required for the system to be operable as well as sufficient capability for conducting chemical analysis.

6.3 Pollution Control

68. Potential polluters such as active mines and waste re-washers should monitor their effluent themselves at their own cost and FATMA should check their monitoring records whenever it wants.

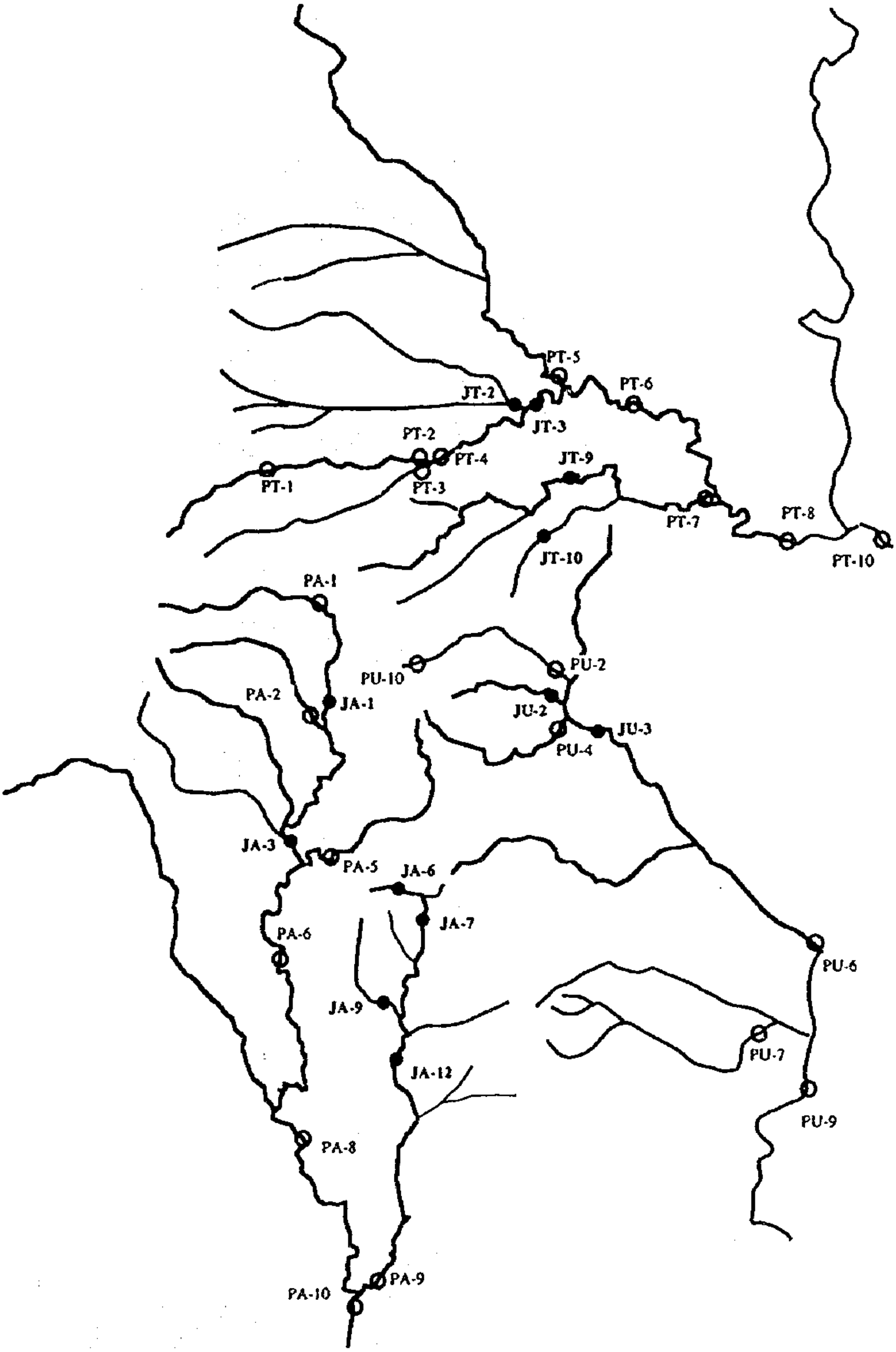

FIGURE B-32 **PROPOSED MONITORING LOCATIONS**

C ACID WATER TREATMENT

C-I ACID ROCK DRAINAGE MITIGATION

1. The objective of this section is to provide a clear concept of acid rock drainage (ARD) mitigation for the region's remediation with a view to transferring ARD technology. This section describes the process of developing site-wide remedial alternatives for abandoned mine sites, such as the FS sites, as well as for active coal mining and processing facilities, including design criteria.

1. TECHNOLOGY SELECTION

2. The most effective remediation technologies for different site conditions and the costs for applying these technologies were identified in the FS site study. The approach for developing the site-wide mitigation plan will be to apply the technologies identified for use at the FS site to all affected areas, including active mine sites. The appropriateness of various technologies is determined by identifying categories of site conditions under which specific technologies were applied at the FS sites. Then, the same technologies are applied under similar conditions site-wide.

3. Table C-I-1 summarizes the ARD mitigation technologies selected for use at the FS sites. This table includes only the technologies that were deemed the most cost-effective in the FS sites study. Although the FS sites are not completely representative of active mining and coal processing sites, the ARD mitigation technologies identified for use at the FS sites are assumed to be generally applicable for active mining and processing facilities. However, opportunities to use ARD prevention techniques may also be available at active sites, whereas ARD prevention measures are generally not applicable at abandoned sites. Therefore, prevention technologies are included in Table C-I-1 for possible use at active sites, if appropriate.

TABLE C-I-1

SUMMARY OF ARD TECHNOLOGY SELECTION FROM THE FS SITES STUDY

General Response Action	Selected Technologies	Applicability
ARD Prevention	Biocide treatment	For use during deposition of new coarse rejects at active mine sites before the onset of ARD
	Lime treatment	For use at active mines during deposition of new coarse rejects before the onset of ARD
	Capillary barriers or wet covers	For use at active mines during deposition of new coarse tailings before the onset of ARD
ARD Control	Limited excavation and on-site disposal	For limited use in removing reactive wastes from streams or river channels
	Capillary barriers or wet soil cover systems	Applicable for active and abandoned waste piles where ARD has the potential to affect surface and ground water
	Compacted clay or dry soil cover systems	Applicable for active and abandoned waste piles were ARD may not affect surface or ground water
	Vegetative cover systems	Used in conjunction with all types of cover systems to prevent surface erosion
	Surface drainage and erosion controls	Used in conjunction with all cover systems to prevent surface erosion
	Clean water diversions	Applicable a sites where relatively clean streams or rivers flow through ARD source areas
	Stream and river channel erosion controls	Applicable a sites where streams or rivers have the potential to erode reactive waste piles
	Draining, filling, and capping surface impoundments	Applicable at active or abandoned re-washing facilities with surface impoundments
	Ground water controls, such as cut-off walls or French drains	Applicable at sites were ground water infiltrates through reactive waste piles, such as valley fill deposits
ARD Treatment	Active chemical neutralization	Applicable at sites with acidic ground water discharging from active or abandoned mines where land area is not sufficient for passive treatment systems
	Passive anaerobic treatment systems	Applicable for adding alkalinity to net-acidic surface-water or ground-water at sites with adequate land availability
	Passive aerobic treatment systems	Used for metals removal down stream of anaerobic treatment systems or at sites with net-alkaline water.
	Open limestone channels	Applicable a sites with small ARD sources and no land available for anaerobic treatment systems

2. DEVELOPING SITE-WIDE ARD MITIGATION PLAN

4. This section presents the general site-wide mitigation plans for the study area. Design details for the prescribed control measures are presented in the following section.

5. In developing site-wide mitigation plans, the JICA database of active and abandoned sites is used to categorize the sites. In this way, mitigation plans are developed for groups of similar sites rather than for each individual site. Table C-I-2 summarizes the ARD mitigation plans for the different categories of sites identified within the study area. These plans consist of combinations of applicable technologies designed to address the ARD sources and conditions specific to each site category.

TABLE C-I- 2

MITIGATION PLANS

FOR SITE-WIDE REMEDIATION OF ARD

Site Category Description	Mitigation Plan Description
Active Mines and Coal Washing Plants with Potential Impacts on Rivers and Ground Water	• Cover wastes with a "wet" soil cover systems during the deposition process • Install a vegetative cover on the waste dumps during final closure • Install surface drainage and erosion controls on covered waste dumps • Treat acidic drainage and seepage from waste dumps with passive anaerobic and aerobic wetland treatment systems • Implement true closed-circuit coal washing systems or treat acidic or metal-laden waters discharged from washing plants with passive anaerobic and aerobic treatment systems
Active Mines Disposing of Rejects without Direct Impacts to Rivers	• Cover waste dumps with a "dry" soil cover systems during active operation • Reclaim waste dumps by installing vegetative covers during closure • Install surface drainage and erosion controls on covered waste dumps • Treat acidic drainage and seepage from waste dumps with passive anaerobic and aerobic wetland treatment systems
Active Mines Discharging Acidic or Metal-Laden Ground Water to Rivers	• Treat water to comply with Brazilian standards using passive anaerobic and aerobic wetland treatment systems. • If land is not available for wetlands, construct active chemical neutralization treatment plants
Active Re-washing Facility	• Same as active mining and coal washing facilities

TABLE C-I-2

MITIGATION PLANS

FOR SITE-WIDE REMEDIATION OF ARD

Site Category Description	Mitigation Plan Description
Abandoned Mines and Coal Washing Facilities with Potential Impacts on Rivers and Ground Water	· Selectively excavate pyretic wastes in contact with surface waters and dispose of on site · Re-grade and re-contour abandoned waste dumps and install capillary barriers or "wet" soil cover systems to reduce acid drainage · Reclaim the covered waste dumps by installing vegetative cover systems · Install surface drainage systems to prevent erosion of soil covers · Drain, fill, and cap any existing acidic ponds · Divert streams or rivers with clean water around sources of ARD contamination · Collect acidic or metal-laden seeps and treat using passive anaerobic and aerobic wetland treatment systems · Stabilize river channels by constructing revetment, rip-rap, or concrete retaining walls, as needed · Prevent ground water from seeping through waste dumps by constructing cutoff walls or subsurface drains.
Abandoned Mines or Wash Plants without Ground Water Impacts	· Re-grade and re-contour abandoned waste dumps and install "dry" compacted clay cover systems to control acid drainage · Reclaim the covered waste dumps by installing vegetative cover systems · Install surface drainage systems to prevent erosion of soil covers · Drain, fill, and cap any existing acid ponds to prevent infiltration · Collect acidic seeps and neutralize the acidity using constructed wetland treatment systems
Abandoned Sites Discharging Acidic or Metal-Laden Ground Water to Rivers	· Treat water to comply with Brazilian standards using passive anaerobic and aerobic wetland treatment systems.

6. Table C-I-2 addresses all sites within the study area with the potential to generate ARD. It is assumed that any active or abandoned sites that produce pyretic black shale wastes during the mining or coal washing process have the potential to generate acid drainage. Table C-I-2 does not address sites that contain only non-reactive sandstone overburden. Sites without reactive pyretic wastes can simply be reclaimed by re-grading and re-vegetating the overburden piles without the need to address ARD.

3. ARD Mitigation Plan Details

7. This section presents detailed descriptions of the site-wide ARD mitigation plans. The purpose of these detailed plan descriptions is to transfer ARD technology and design information to the Brazilian counterparts and to provide sufficient information to prepare reasonably accurate mitigation cost estimates.

3.1 Designing and Installing Capillary Barriers or "Wet" Soil Cover Systems

8. This section describes the design and installation of "wet" soil cover systems for the purpose of reducing ARD from pyretic waste dumps at active and abandoned mining and coal washing facilities.

(a) General Description

9. "Wet" cover systems, also known as capillary barriers, are soil barriers designed to reduce or eliminate infiltration of both air and water into the underlying buried wastes. Wet covers are so called because they are designed for use in wet climates in which annual precipitation exceeds evaporation and because they are designed to maintain nearly saturated conditions in the cover soils throughout the cycle of wet and dry seasons. The importance of designing soil covers that meet site-specific climatic conditions is discussed by Swanson et al. (1997).

10. Figure C-I-1, Wet Cover System or Capillary Barrier, illustrates the features of a wet cover system designed for the JICA project sites. The wet cover or capillary barrier consists of the following soil layers:

- Layer 1 - 30 cm of uncompacted soil suitable for growth of a vegetative cover of shallow-rooted native grasses. The purpose of Layer 1 is to protect the subsequent layers from erosion, facilitate surface runoff, and promote evapotranspiration of incident precipitation.

- Layer 2 - 50 cm of compacted native clay acting as a low permeability barrier to retard or prevent infiltration of precipitation into the buried wastes. Also, in conjunction with Layer 3, a high level of soil saturation would be maintained in this layer to prevent oxygen flux into the wastes; and

- Layer 3 - 10 to 20 cm of coarse sand or gravel placed between the waste and the clay layer to act as a capillary break. The functional mechanisms and advantages of capillary barriers is described in detail by Stormont et al. (1996). Due to its large pore spaces and high permeability, the capillary break acts as a discontinuity in the capillary pore spaces between the low permeability layer and the buried waste. Under wetting conditions, this discontinuity prevents the wicking of soil moisture into the wastes, thereby creating a barrier of infinitely low permeability. Under drying conditions, the capillary break acts to facilitate the long-term storage of soil moisture in the clay layer by balancing the upward evaporative forces with opposing downward capillary suction forces.

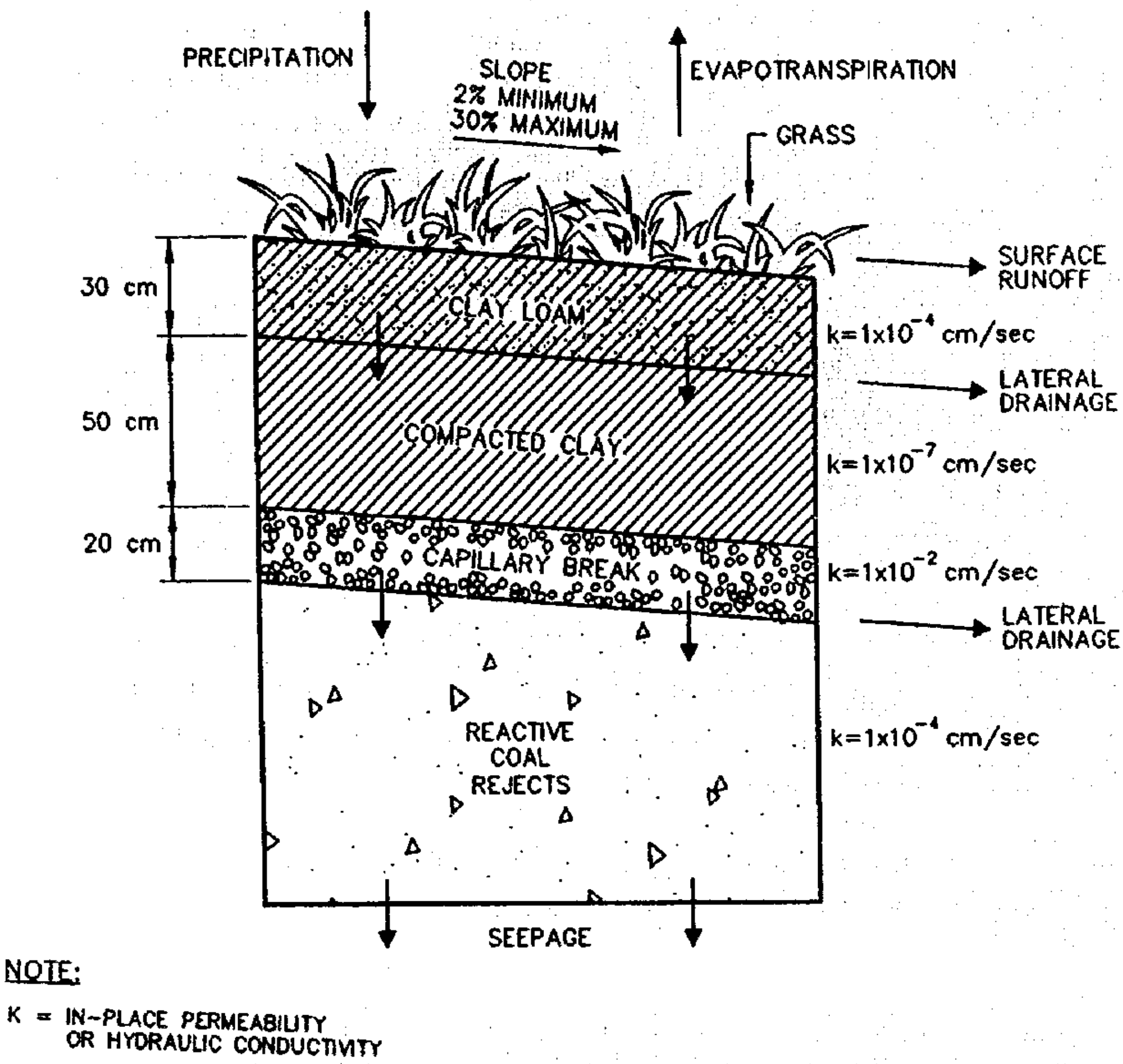

FIGURE C-I-1 WET COVER SYSTEM OR CAPILLARY BARRIER

(b) Design Objectives

11. Wet soil covers are designed and installed at mining and mineral processing sites to meet the following objectives:

- Significantly reducing infiltration of precipitation into reactive waste dumps by providing a low permeability water barrier, thereby reducing the leaching of pyrite oxidation products and seepage of acidic drainage from the wastes;
- Limiting the flux of atmospheric oxygen into the wastes by providing an effective gas barrier, thereby slowing or stopping the rate of pyrite oxidation; and
- Facilitating lateral drainage and surface evaporation as additional mechanisms for reducing infiltration.

12. The wet cover system should be designed to meet these objectives during wet and dry times of the year. The capillary barrier helps to ensure the wet cover will remain nearly saturated during dry seasons, thereby preventing desiccation cracking of the compacted clay layer. This helps ensure increased effectiveness over "dry" soil covers.

(c) Anticipated Effectiveness

13. Properly designed and installed capillary barriers are expected to reduce ARD from pyretic waste dumps by 90 to 95 percent compared with uncovered waste dumps. Hence, wet cover systems are one of the most effective means available for reducing acid loads to surface and ground water. It must be emphasized, however, that a high level of quality assurance testing and inspection is needed during construction to ensure the effectiveness of these cover systems.

(d) Design Details and Criteria

14. Design details and criteria for wet covers or capillary barriers include the following:

- Vegetative Soils - For Layer 1, provide vegetative soils capable of supporting plant growth. To ensure the soils provide a proper plant growth medium, consult with EPAGRI for recommendations on amending the soils with chemical fertilizer, organic matter, and lime;

- Seeding - Establish a vegetative cover of shallow-rooted, perennial, native grasses. Grass seeds should be planted using a seed drill in rows running perpendicular to the slope of the cover. If hydroseeding is used, slopes should be contoured with furrows to prevent the seeds from washing away in the rain, as is typical current hydroseeding practices;

- Cover Slope - The cover should be sloped no less than 2 percent to promote adequate surface drainage. Slopes should not exceed 30 percent to ensure the constructability of the soil cover and prevent excessive runoff velocities (Norecol Dames & Moore et al., 1989). Construction of effective soil covers on slopes greater than about 30 percent is difficult;

- Clay Soils - For Layer 2, use clays with an in-place permeability after compaction of 10^{-7}cm/sec or less (Norecol Dames & Moore, 1989). The clays should be spread to a uniform depth and compacted in lifts not to exceed 10 cm. The finished clay layer should be a uniform 50 cm in thickness. Compact the clay using a vibrating sheeps-foot or similar equipment to 95 percent of the standard Proctor density. Maintain optimum moisture content during and after construction. The clay soil must not be allowed to dry out during or after compaction;

- Capillary Break - Material used for construction of the Layer 3 capillary break must be free draining and have a high permeability. The in-place permeability of this layer should be greater than 10^{-2} cm/sec. Suitable materials include coarse to very coarse sands (1 to 2 millimeters (mm)), fine gravel (4 to 8 mm), or medium to coarse gravel (8 to 32 mm). Materials should be well-graded and screened and washed to remove fine particles; and

- Geotextile - It is important to prevent the migration of fines into the capillary break. Depending on size and gradation of the capillary break materials used to construct the cover, it may be necessary to install a geotextile between the compacted clay and capillary break layers.

15. Table C-I-3 summarizes the design criteria for the three components of the capillary barrier or

wet soil cover system described above.

TABLE C-I-3

CAPILLARY BARRIER OR WET COVER SYSTEM DESIGN CRITERIA SUMMARY

Design Criterion	Vegetative Soil Layer	Low Permeability Clay Layer	Capillary Break
Purpose	Plant growth medium, erosion control, and lateral drainage	Infiltration and oxygen barrier	Capillary break
Common Description	Clay loam or sandy clay loam	Inorganic clay or silty clay	Very coarse sand to medium gravel
Unified Soil Classification	SM or SC	CH or MH	GP or SP
In-Place Permeability	10^{-5} to 10^{-4} cm/sec	10^{-7} cm/sec	$> 10^{-2}$ cm/sec
Grain Size Distribution	< 50% passing No. 200 Sieve	100% passing No. 200 Sieve	0% passing No. 200 Sieve, 90% retained by No. 20 Sieve
Compaction Standard	Light compaction	95% standard Proctor density	Not compacted
Plasticity Index	Low or Non-Plastic	High	Non-plastic
Liquid Limits	<50%	>50%	Non-liquid
In-Place Layer Thickness	30 cm	50 cm	20 cm

(e) Construction Quality Assurance

16. The effectiveness of soil barriers is highly dependent on the quality of the construction. Rigorous construction inspection and testing is needed to ensure the soil covers are installed in accordance with design specifications. The following minimum inspection and testing requirements should be met during construction of any soil cover systems:

- <u>Materials Selection and Testing</u> - Materials selected for use in the soil covers should be tested to ensure they meet design specifications and to establish baseline geotechnical indexes. Minimum testing requirements include grain size distribution, Atterberg limits, saturated hydraulic conductivity, and standard Proctor moisture density tests.

- <u>Testing During Construction</u> - Random samples of construction materials should be collected and analyzed for the above referenced list of geotechnical parameters during construction. Depending on the quality of the borrow deposits, it may be necessary to collect and analyze one sample for every 100 to 500 m^3 of material brought to the site to ensure the materials meet specifications.

- <u>Visual Inspection</u> - The construction engineer should visually inspect materials arriving at the site to ensure they meet baseline quality standards. A great deal of information can be obtained through visual inspection. If the engineer suspects that materials would not meet specifications, the materials should be tested;

- In-place Density Testing - Compaction or in-place density testing is especially critical during installation of low permeability clay layers. The use of portable nuclear density testing equipment is recommended; and

- Site Surveys - The field engineer should consistently measure the thicknesses of the various soil layers. It is critical to the performance of the soil covers that the soil layers be uniform in thickness and meet all design criteria.

(f) Additional Recommendations

17. Additional recommendations for designing and installing capillary barriers or wet covers include the following:

- Investigate low cost alternatives for capillary break materials. Due to the relatively high cost of gravel in the study area, it is recommended that the cost, availability, and suitability of potential low cost alternatives be investigated. Alternatives to gravel may include geofabric drainage materials, crushed sandstone overburden, or screened and washed black shale;

- The sizes of waste disposal cells at active mine sites should be reduced to prevent the onset of ARD. Currently, pyretic wastes are disposed of in huge, monolithic deposits. Due to the size of the deposits, the wastes are left exposed to oxygen and rain water for long periods of time before being covered with simple soil covers. By the time the wastes are covered, the chemical reactions leading to ARD are in the advanced stages making prevention or control much more difficult and costly; and

- Pyretic wastes that are exposed to air and water for more than a few weeks should be treated with bactericides and/or lime to prevent the onset of ARD.

3.2 Designing and Installing "Dry" Soil Cover Systems

18. This section describes the design and installation of dry soil cover systems used in the JICA ARD mitigation plans. Figure C-1-2, Dry Soil Cover System, illustrates the conceptual design of a dry cover system to be used in mitigating ARD within the JICA study area.

(a) Design Objectives

19. Dry soil covers are designed and installed at mining and mineral processing sites to meet the following objectives:

- Significantly reducing infiltration of precipitation into reactive waste dumps by providing a low permeability water barrier, thereby reducing the leaching of pyrite oxidation products and seepage of acidic drainage from the wastes; and

- Facilitating lateral drainage and surface evaporation as additional mechanisms for reducing infiltration.

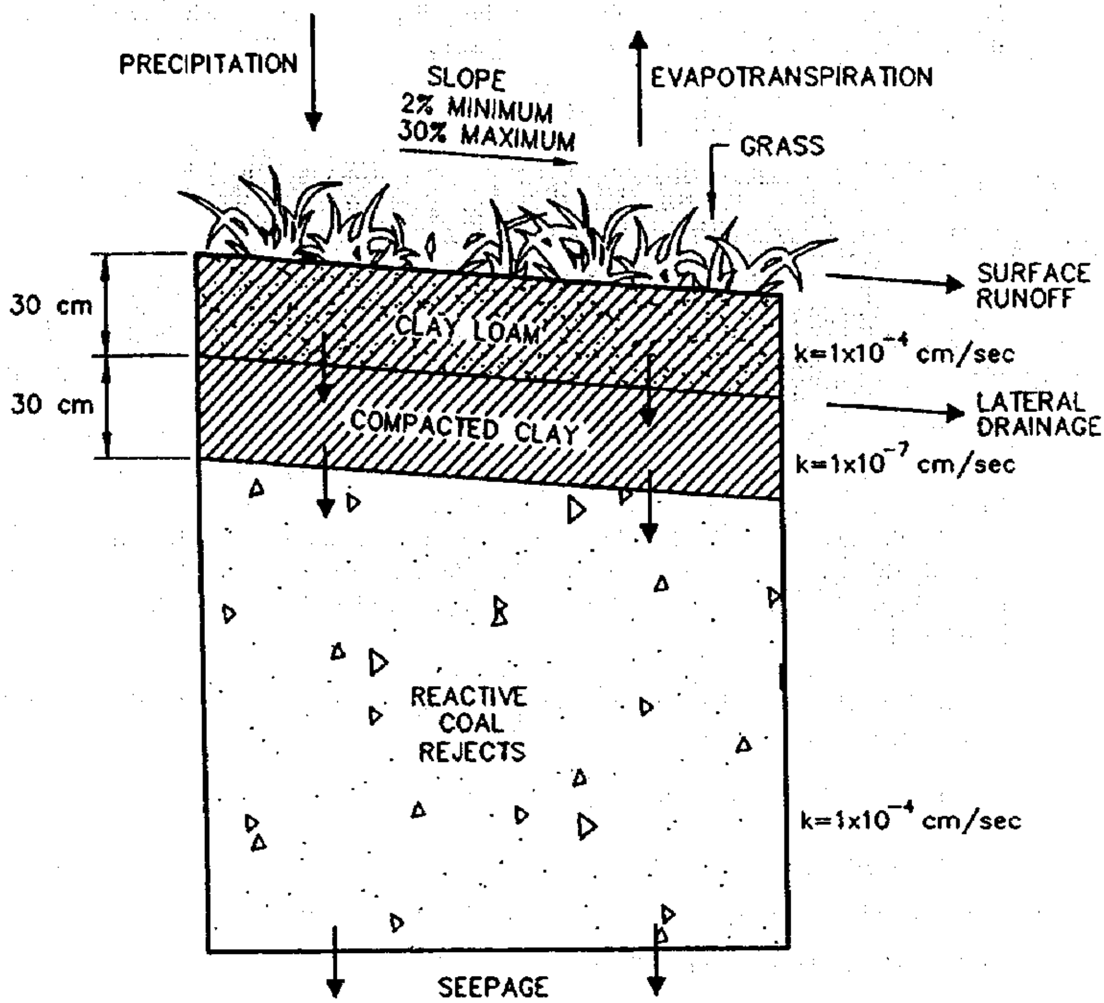

FIGURE C-I-2 DRY SOIL COVER SYSTEM

NOTE:

K = IN-PLACE PERMEABILITY OR HYDRAULIC CONDUCTIVITY

20. Both wet and dry soil covers effectively retard the downward movement of precipitation by providing a low permeability barrier. Unlike wet covers, dry covers are designed to store moisture during wet seasons and release moisture during dry seasons. Hence, dry covers are somewhat less effective as oxygen barriers and may be subject to desiccation cracking of the compacted clay layer during dry seasons.

(b) Anticipated Effectiveness

21. Properly designed and installed dry covers are expected to reduce ARD from pyretic waste dumps by 70 to 75 percent compared with uncovered waste dumps. Hence, dry cover systems are effective for reducing acid loads to surface and ground water, but are somewhat less effective than wet covers. As with wet covers, a high level of quality assurance testing and inspection is needed during construction to ensure the effectiveness of dry cover systems. Because of their lower effectiveness, dry covers are considered applicable for use at sites where there is little or no ARD impact on surface or ground waters.

22. To achieve a 70 to 75 percent load reduction, a double layer dry cover system, such as shown in Figure C-I-2, is recommended. However, a single layer of clay could also be used if the cost of a double layer system is prohibitive. If only a single clay layer is used, the top part of the clay should be amended with organic matter and nutrients to facilitate the establishment of a vegetative cover.

(c) Design Details and Criteria

23. In detail, dry covers are the same as wet covers or capillary barriers except that dry covers do not include the capillary break layer. Hence, the design details and criteria for dry covers are the same as those presented in Section 3.1 (d) for wet covers, except that the capillary break is missing.

(d) Construction Quality Assurance

24. The same construction quality assurance procedures specified in Section 3.1 (e) for the wet cover systems should also be performed during construction of any dry cover systems.

3.3 Designing and Installing Passive Anaerobic Wetland Treatment Systems

25. This section describes the design and installation details for the passive anaerobic treatment systems recommended for use in treating acidic waters within the JICA study area.

(a) Design Objectives

26. Passive anaerobic treatment systems (PATS) consist of artificial ponds or wetlands designed and constructed to neutralize acidic water by adding alkalinity from both inorganic and biologically-

derived sources. Hence, the sole objective of installing PATS at the JICA study area is to add bicarbonate alkalinity for the purpose of neutralizing acidity in site mine waters. The addition of alkalinity is necessary to raise the pH and provide the conditions needed for subsequent removal of metals such as iron, manganese, and aluminum in aerobic wetlands.

27. PATS are applicable for treating drainage from active or abandoned mines or seepage from pyretic waste dumps. These systems are passive because they are designed to require little or no operator attention after construction, thereby greatly reducing long-term treatment costs compared to active chemical neutralization. However, PATS require relatively large land areas compared to active chemical treatment systems.

28. PATS are designed to add alkalinity by two methods, by dissolution of limestone and through the production of bicarbonate ions as a byproduct of bacterial sulfate reduction. These systems are termed "anaerobic" because they are designed to operate in the complete absence of oxygen. The absence of oxygen is a critical environmental requirement of the sulfate reducing bacteria (SRBs) that are responsible for the production of bicarbonate alkalinity. Further, the strongly reduced conditions present in the PATS prevent the formation of ferric iron (Fe^{+3}) precipitates that could armor the limestone and decrease its solubility. Any dissolved iron in the system is maintained in the ferrous (Fe^{+2}) state which is highly soluble at pH less than about 8 or 9.

(b) Anticipated Effectiveness

29. Acidic seeps draining from abandoned sites contain acidity in concentrations ranging between 100 to 600 milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$). Acidity in waters from some active mines and coal washing facilities ranges up to 2,500 mg/L as $CaCO_3$. PATS can be designed to neutralize up to 90 percent of this acidity. Also, if greater neutralization efficiencies are needed, additional PATS can be linked in series with aerobic wetlands. The key to achieving highly efficient PATS is to design them to add alkalinity in concentrations equal to or greater than the total acidity of the treatment system influent, as described in the following subsection.

(c) Design Details and Criteria

30. Figure C-I-3A, Passive Anaerobic and Aerobic Wetland Treatment Systems, represents the generalized design of a PATS for use in treating ARD within the JICA study area. The PATS illustrated in this figure consists of deep, open-water ponds with a substrate rich in biodegradable organic matter underlain by a layer of limestone, underdrains, and hydraulic control structures. The various components illustrated in Figure C-I-3A serve the following functions:

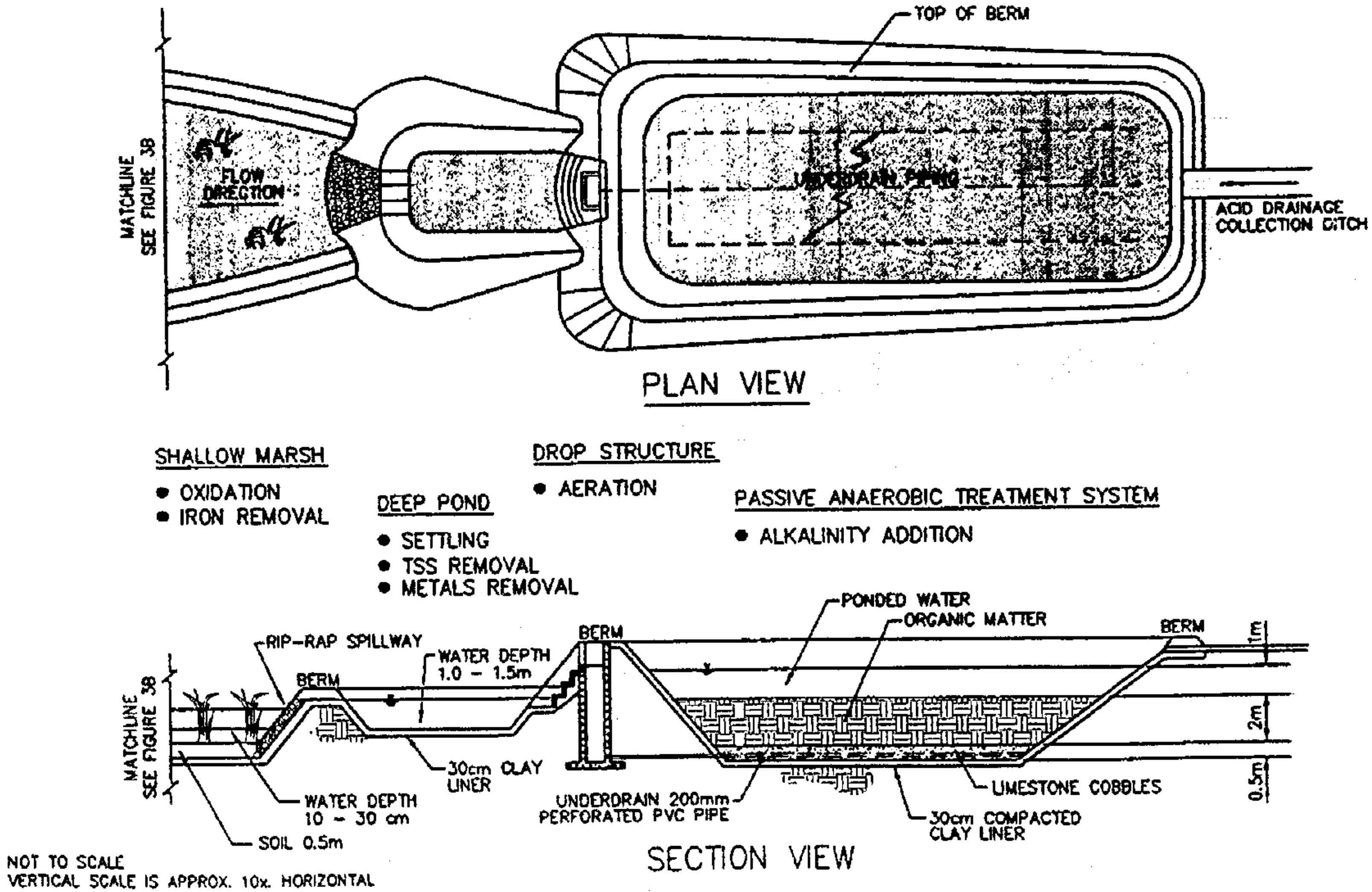

FIGURE C-I-3A

PASSIVE ANAEROBIC AND AEROBIC WETLAND TREATMENT SYSTEM

31. **Deep Water Ponds** - Water in the PATS is maintained at a minimum depth of 1 meter to prevent the diffusion of atmospheric oxygen into the organic substrate layer at the bottom of the pond. The water depth is maintained by an earthen dike and hydraulic control structure at the outlet of the pond. The flow of water in the pond is downward. It is critical to the performance of the PATS that oxygen be prevented from diffusing into the organic substrate layer because the SRBs are most active in the substrate layer. Also, the deeper the water, the higher the equilibrium partial pressure of CO_2 will be in the limestone layers. Maintaining a high CO_2 partial pressure raises the $CaCO_3$ solubility, thereby increasing the alkalinity contributed by the limestone. Finally, the impounded water provides the hydraulic head needed to force the water downward through the underlying substrate and limestone layers (Figure C-I-3A).

32. **Organic Substrate Layer** - The organic substrate layer in Figure C-3A consists of 2 meters of composted animal and plant wastes. However, the thickness of the organic layer can be varied from 0.5 to 2 meters. The key design requirement is to provide a volume of organic matter sufficiently large to neutralize the influent acidity. The purpose of the organic layer is to consume dissolved oxygen creating a reduced, anaerobic environment and provide a food and energy source for the SRBs. A by-product of biological sulfate reduction reactions is the production of excess bicarbonate ions, as illustrated in the following equation.

$$2CH_2O + SO_4^{2-} = H_2S + 2HCO_3^-$$

33. The reaction represented by this equation is responsible for producing approximately half the alkalinity generated in the PATS. Because the presence of any dissolved oxygen would prevent SRB activity, it is critical that the organic substrate layer exert sufficient biochemical oxygen demand (BOD) to consume any dissolved oxygen in the water. Otherwise the biological alkalinity production would cease.

34. Due to the production of excess bicarbonate, the pH of the water flowing through the organic layer is typically neutral, even though the influent pH may be as low as 2.5. However, the oxidation and precipitation reactions that would normally occur rapidly at neutral pH are prevented from occurring due to the absence of dissolved oxygen. Therefore, precipitation of ferric iron is not a threat to system performance.

35. Empirical design criteria have been developed by Wildeman et al. (1993). Experience at mining sites in the U.S. and Canada indicate that SRBs and produce approximately 0.6 moles of bicarbonate alkalinity per day from each m^3 of organic matter. This relationship is the best design criteria available for estimating the volume of organic matter needed to neutralize a given concentration of acidity using PATS. To estimate the volume of required organic matter, the daily acidity load is determined, as followed:

$$\text{Acidity Load (moles/day)} = \frac{\text{Total Acidity (mg/L as } CaCO_3\text{)} \times \text{Flow Rate (L/day)}}{\text{Molecular Weight of } CaCO_3 \text{ (mg/mole)}}$$

Then the volume of organic matter is estimated, as follows:

$$\text{Volume of Organic Matter } (m^3) = \text{Acidity Load (moles/day)} / 0.6 \text{ moles/m}^3\text{/day}$$

36. **Organic Materials Selection** - A mixture of soluble and insoluble organic materials are needed to provide short-term and long-term organic carbon source for the SRBs. Locally available materials in Santa Catarina include chicken litter, saw dust, swine wastes, and rice processing wastes. Typically, mixtures are developed in the field using locally available materials. Hence, there are no strict guidelines on the selection of organic materials. Typical mixtures contain approximately 1/3 soluble and 2/3 insoluble organic materials, such as the following:

- Animal wastes such as pig, sheep, cattle, or poultry manures to provide readily available organic carbon and to act as the source of SRBs;
- Moderately soluble organic materials such as plant material, including grass hay, wheat straw, or rice straw; or food processing wastes, including spent mushroom compost, rice hulls, etc.; and
- Insoluble organic materials such as wood chips or saw dust.

37. **Limestone Layer** - A layer of high quality limestone cobbles is placed under the organic substrate layer. The limestone contributes to the total alkalinity produced by the PATS in addition to functioning as a hydraulic drainage layer. Given sufficient residence time, equilibrium conditions will be established between the bicarbonate produced through biological sulfate reduction and the solid $CaCO_3$ contained in the limestone. If the concentration of bicarbonate from sulfate reduction is less than the equilibrium concentration, some limestone will dissolve to make up the difference. Also, the decomposition of the organic substrate results in elevated partial pressures of CO_2 which increases the equilibrium concentrations of dissolved carbonate and bicarbonate. Kepler and McCleary (1994) indicate that alkalinity additions ranging from about 75 mg/L to over 300 mg/L are possible using PATS. In warm climates, about half the alkalinity produced by PATS results from sulfate reduction and half from limestone dissolution (Kepler and McCleary, 1994). The volume of limestone needed to neutralize half the acidity is estimated by an empirical formula developed by Hedin et al. (1994).

38. **Underdrains and Hydraulic Controls** - The underdrains and hydraulic control system is designed to facilitate vertical downward flow through the organic substrate and limestone layer. The drains consist of large diameter, perforated PVC pipe. The drains penetrate the earthen dike and exit inside the concrete hydraulic control structure. Many different types of control structures are possible, such as low cost concrete weir illustrated in Figure C-3A in which the water level is controlled by simple, stop-logs.

39. Clay Liner System - A clay liner is placed on the bottoms and sides of the anaerobic pond to prevent leakage. The clay liner consists of 30 cm of compacted clay with an in-place permeability of 10^{-7} cm/sec or less. The liner is needed to ensure that the water level in the ponds remains at the desired static level during low flow periods. If excessive leakage occurs, the water level could drop, potentially exposing the organic layer to oxygen.

40. Criteria used in the design of the PATS illustrated in Figure C-1-3A are summarized in Table C-1-4.

TABLE C-1-4

SUMMARY OF DESIGN CRITERIA FOR PASSIVE ANAEROBIC TREATMENT SYSTEMS

Criterion Description	Recommended Design Value
Design Life Cycle	20 to 30 years
Hydraulic Loading Rate	20 m^2/L/sec
Hydraulic Retention Time - Organic Layer	60 to 120 hours
Hydraulic Retention Time - Limestone Layer	24 hours
Acidity Loading Rate - Organic Layer	0.6 moles/ m^3/day
Acidity Loading Rate - Limestone Layer	See Appendix B
Depth of Standing Water	1.0 meter minimum
Depth of Organic Layer	0.5 to 2.0 meters
Depth of Limestone Layer	0.5 to 1.0 meters
Type of Organic Matter	See above discussion
Limestone Quality	90 percent $CaCO_3$ minimum
Limestone Size	75 to 200 mm
Underdrain Piping	200 mm perforated PVC or HDPE
Pond Liner	30 cm compacted clay

(d) Additional Recommendations

41. This section presents recommendations for additional investigations for optimizing the design and operation of PATS for the JICA study area. These recommendations include the following:

- Conduct pilot-scale demonstrations to develop site-specific design criteria. These pilot-scale systems should be used to test different organic substrates and should be monitored over long time frame. The monitoring data should be used to prepare mass balances of the key reactants and products of biological sulfate reduction and limestone dissolution; and

- Investigate the feasibility of using swine wastes as a component of the organic substrate. Wastes from the production of swine is readily available in southern Santa Catarina. In fact, treatment and disposal of swine wastes is a serious environmental problem within the study area. Swine wastes are typically available as a liquids and are too soluble to be used without some kind of pretreatment. Also, swine wastes are capable of transmitting human pathogens, so extreme caution should be exercised during preparation. These problems could potentially be overcome by composting the liquid swine wastes to other types of organic matter, such as saw dust, to create a more stable, solid substrate.

42. If feasible, swine wastes could prove to be the lowest-cost source of organic matter for construction of PATS within the JICA study area. Also, the beneficial use of swine wastes would help mitigate the significant environmental impacts caused by the swine production facilities.

3.4 Designing and Installing Passive Aerobic Wetland Treatment Systems

43. This section describes the design and installation of passive aerobic wetland treatment systems.

(a) Design Objectives

44. The objectives of designing and constructing passive aerobic wetland treatment systems in the JICA study area include the following:

- Removing dissolved metals, including iron, manganese, and aluminum by facilitating a wide variety of abiotic and biologically mediated chemical reactions; and
- Removing precipitated metals and suspended solids to improve water quality.

45. Aerobic wetlands are applicable for treating water that contains more alkalinity than acidity. At the JICA sites, only waters previously treated with PATS are expected to be net-alkaline. In the eastern US coal producing regions, constructed aerobic wetlands have proven effective in reducing mineral acidity and dissolved metals in coal mine drainage. Aerobic wetlands are capable of facilitating a wide variety of abiotic and biologically mediated chemical reactions and treatment processes, including aeration, oxidation, precipitation, chelation, adsorption, complexation, sedimentation, filtration, bacterially catalyzed oxidation, and plant uptake.

(b) Anticipated Effectiveness

46. If sufficient land area is available for construction, aerobic wetlands are capable of removing greater than 90 percent of the iron, manganese, and aluminum in coal mine drainage. Aerobic wetlands are considered potentially effective and applicable for conditions at the JICA FS sites assuming the water is pretreated by anaerobic systems or is naturally net-alkaline. The presence of many natural wetlands and ponds at some of the sites provides excellent opportunities for use of aerobic wetland treatment. However, because most acidic water needing treatment at the sites is strongly acidic, the effectiveness of aerobic wetlands is expected to be greatly enhanced by the addition of alkalinity through passive chemical or biological mechanisms.

(c) Design Details and Criteria

47. For net-alkaline ARD, simply providing aerobic wetlands with the retention time needed for metal removal reactions to occur is sufficient to effect treatment. Wetlands should also be constructed to act as sedimentation basins so that precipitated metals are effectively removed from the water and retained in the treatment system. Net-acidic ARD can also be effectively treated to removal metals using aerobic wetlands. However, significant decreases in pH must be anticipated and prevented by combining the aerobic systems with alkalinity-producing systems, such as PATS.

48. As most of the ARD within JICA FS sites is expected to be net-acidic, it is anticipated that aerobic wetlands will typically be installed downstream of PATS to add alkalinity. Hence, aerobic wetlands are generally considered one component of complete aerobic and anaerobic treatment systems for removing metals and acidity. The aerobic component of these systems could consist of enhancements to the many existing deep ponds or natural wetlands. At sites without existing wetlands, artificial wetlands consisting of constructed deep and shallow marshes, deep ponds, and aerobic rock filters could be constructed.

49. Figure C-I-3B, Passive Anaerobic and Aerobic Wetland Treatment Systems, illustrates the design of a generalized passive aerobic wetland treatment system for use in conjunction with a PATS. The features incorporated into this generalized design for removing metals and acidity include the following:

- Mechanical Aeration - Hydraulic drop structures and artificial riffles to provide mechanical aeration;
- Oxidation Ponds - Shallow marshes with water depths between 10 and 30 cm to provide large surface areas for diffusion of atmospheric oxygen. Also, wetland ecosystems consisting of aquatic plant species, such as cattails, reeds, and rushes will be used to oxygenate the shallow water zones and provide sites for bacterial oxidation processes, and filter suspended sediments;
- Deep Ponds - Deep water zones to provide ample residence time for metal precipitation and sedimentation. The deep ponds are designed with variable depths ranging from 30 to 200 cm;
- Aerobic Rock Filters - Aerobic rock filters consist of shallow ponds filled with cobbles and small boulders to facilitate biological manganese removal. The submerged boulders and cobbles support the growth of filamentous bacteria that biologically oxidize manganese;
- Hydraulic Control Structures - Hydraulic controls include rip-rap channels and spillways to prevent damage during storm runoff events and water level control structures to maintain desired water depths during wet and dry seasons; and
- Clay Liner System - A clay liner is placed on the bottoms and sides of the aerobic ponds to prevent leakage. The clay liner consists of 30 cm of compacted clay with an in-place permeability of 10^{-7} cm/sec or less. The liner is needed to ensure that the water level in the ponds remains at the desired static level during low flow periods.

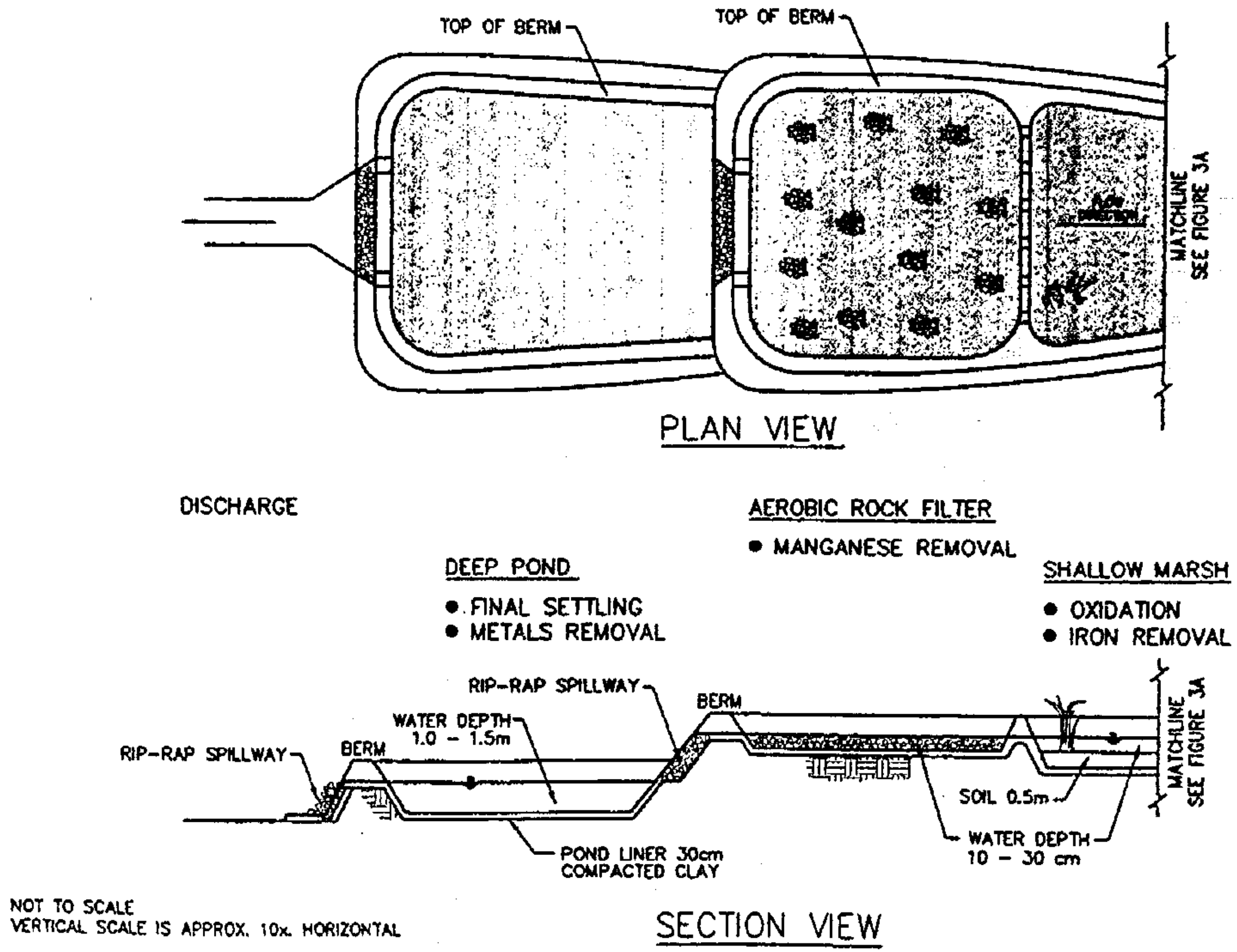

FIGURE C-I-3B

PASSIVE ANAEROBIC AND AEROBIC WETLAND TREATMENT SYSTEMS

50. Critical design criteria for metal removal processes in the aerobic wetland systems include the following:

- Metal Loading Rate - Metal loading rates for use in design of effective aerobic wetland treatment systems have been developed by the US Bureau of Mines (BOM) (Hedin et al., 1994) and the Tennessee Valley Authority (TVA) (Brodie, 1995). To achieve compliance with US iron and manganese compliance levels, work performed by these agencies indicate aerobic wetlands should be sized to provide between 0.05 and 0.1 square meters of surface area for each gram of iron per day that enters the system, or 1 to 2 square meters per gram of dissolved manganese per day. Stated differently, the metal loading criteria used successfully by the US BOM and the TVA are 10 to 20 grams of iron per day per square meter (g/d/m^2) and 0.5 to 1.0 g/d/m^2 manganese;

- Dissolved Oxygen Concentration - Lack of sufficient dissolved oxygen can limit the effectiveness of aerobic wetland treatment systems. Research performed by Hedin, et al (1994) and Brodie (1995) indicates that aeration only provides enough dissolved oxygen to oxidize about 50 mg/L of Fe^{2+}. Therefore, effective aerobic wetland designs incorporate one aeration zone for each 50 mg/L iron present in the ARD;

- Hydraulic Retention Time - TVA recommends constructing the shallow oxidation ponds to provide a minimum of 24 hours of retention time to facilitate the oxidation and precipitation of dissolved iron. Aerobic rock filters should be designed to provide approximately 16 hours retention time. Deep ponds should be designed to provide approximately 24 hours retention time. Hence, hydraulic retention time for whole aerobic wetland should be designed to provide a minimum of 64 hours retention time;

- Wetland Cell Configuration - Scientifically designed aerobic wetlands typically include a variety of compartments or cells designed to perform the functions needed to achieve treatment. Features of aerobic cell designs include the following:

  -Variable flow velocities to promote both oxidation and settling processes;
  -Variable water depths to promote a variety of removal processes;
  -Intercell connections that serve as aeration devices; and
  -Deep settling zones that provide a minimum of 1 meter freeboard for accumulation of metal sludges; and

TABLE C-I-5

SUMMARY OF DESIGN CRITERIA FOR PASSIVE AEROBIC WETLAND TREATMENT SYSTEMS

Design Criterion	Design Value
Iron Loading Rate	10 to 20 (gram/day/m^2)
Manganese Loading Rate	0.5 to 1.0 (gram/day/m^2)
Hydraulic Retention Time - Oxidation Ponds	24 hours
Hydraulic Retention Time - Deep Ponds	24 hours
Hydraulic Retention Time - Aerobic Rock Filter	16 hours
Static Water Depth - Oxidation Ponds	10 to 30 cm
Static Water Depth - Deep Ponds	30 to 200 cm
Static Water Depth - Rock Filters	10 to 30 cm
Pond Liner Material	Compacted Clay
Liner Thickness	30 cm
Number of Oxidation Cells	One per 50 mg/L dissolved iron

- Hydraulic Controls - Water level and flow control is critical to the proper functioning of wetland systems. Hydraulic control structures such as earthen dikes, berms, rock head-walls, small concrete dams, etc. need to be carefully analyzed and designed into wetland treatment systems to ensure continued effectiveness. The hydrology of each site needs to be analyzed and site-specific hydraulic design must be developed.

51 Table C-I-5 summarizes the design criteria for aerobic wetland treatment systems presented above.

3.5 Designing and Installing Surface Erosion Controls

52. This section summarizes the design and installation details for surface erosion controls prescribed in the site-wide ARD mitigation plans in the JICA study area. Surface erosion controls refer to engineering methods of preventing soil transport caused by surface-water runoff during precipitation events. Erosion controls are not designed to directly mitigate ARD, but are essential for protecting the soil cover systems that are key to the control of ARD. Effective erosion controls also serve to promote surface evaporation and runoff, thereby reducing infiltration into the soil covers and buried wastes.

53. An effective vegetative cover is the first line of defense for soil covers in the control of surface erosion. A dense mat of vegetation holds the soil in place by binding the upper most soil layer together in a tangle of plant roots. Ideal species for re-vegetating soil covers are discussed in detail in Section II-G of this Main Text and in Section 4 of the ZETA/IESA report. In summary, soil covers should be planted with a mixture of shallow rooted, annual and perennial grasses and forbs. Deep rooted trees and shrubs should not be planted. Also, adequate preparation of the cover soil is critical to the successful establishment of a suitable vegetative cover. Soil preparation includes the following tasks:

- Adding chemical fertilizers to provide essential plant nutrients;
- Adding organic matter to improve soil texture and moisture retention qualities;
- Adjusting soil pH by adding lime; and
- Improving the cation exchange capacity by adding calcium and magnesium, if needed.

54. In addition to establishing an effective vegetation cover, providing surface runoff collection and drainage channels is critical to the protection of the soil covers. Without drainage channels to collect and safely convey storm water off of the covers, erosion channels would quickly develop and could begin cutting into the soil layers. Figure C-I-4, Surface Erosion Control and Drainage Design Details, and Figure C-I-5, Surface Drainage System Details, illustrate typical surface drainage systems designed to collect and convey precipitation off of constructed soil cover systems without causing

significant soil erosion.

55. As illustrated in Figure C-I-4, the capped waste piles should be terraced to prevent the creation of excessively long slopes and provide collection points for rainfall running off the slopes. Lateral drainage channels are installed on each terrace. These lateral drains convey the runoff to main channels designed to convey the water down the face slopes. Figure C-I-5 depicts the design of the main center drains.

3.6 Designing and Installing Clean Water Diversions

56. This section describes the design and installation of clean water diversions prescribed in the site-wide ARD mitigation plans. Diverting uncontaminated water around or safely through deposits of potentially acid generating materials is an effective method of controlling ARD, especially in locations where acid generating wastes have been deposited in historic stream channels. The purpose of these diversions is to prevent direct contact between acid generating materials and clean surface waters. By diverting streams around the waste piles, uncontaminated water can remain clean, thereby reducing the overall acid and metal loads in receiving streams.

57. Stream diversion structures include all available methods of diverting, collecting, and transporting surface waters, such as the following:

- Small earthen and rock dams;
- Cast-in-place or pre-cast concrete collection boxes;
- Open, trapezoidal concrete channels;
- Corrugated metal or plastic culverts and flumes; and
- Concrete box culverts.

58. Clean water diversions designs are site-specific. Therefore, providing specific design details is beyond the scope of this conceptual planning document. However, designs of standard water diversion, collection, and conveyance structures are presented in Section II-D of Main Text.

3.7 Designing and Installing Stream and River Channel Erosion Controls

59. Often at abandoned mining sites, acid producing materials were placed in stream or river channels where they are subject to erosion and transport during intense thunderstorms. Erosion and downstream transport disperses the wastes over large areas making it difficult or impossible to mitigate the associated negative environmental impacts. Controlling erosion in stream channels can reduce the suspended load during rainstorms and prevent the deposition of wastes in downstream areas where they continue to generate acidity and dissolved metal loads.

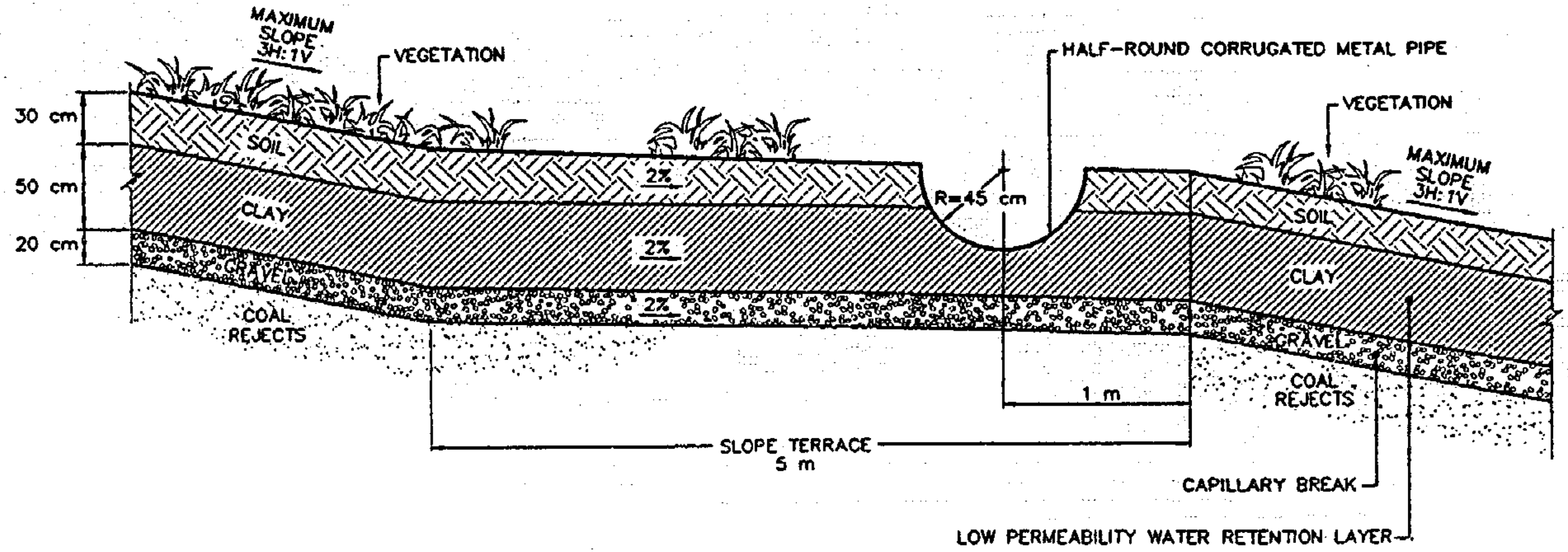

FIGURE C-I-4

SURFACE EROSION CONTROLE AND DRAINAGE DESIGN DETAILS

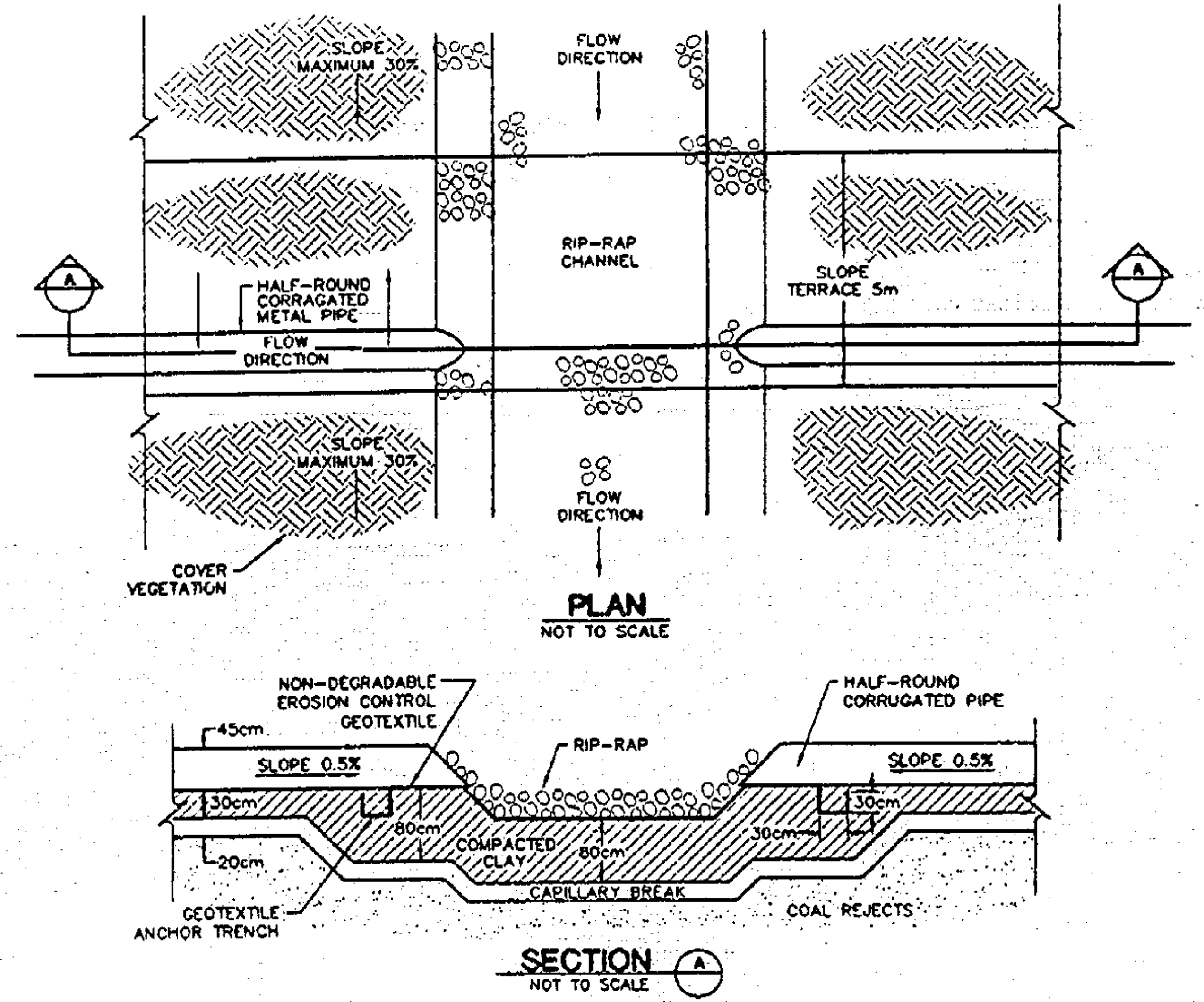

FIGURE C-I-5 SURFACE DRAINAGE DESIGN DETAILS

60. Channel erosion controls refer to engineering methods of preventing the erosion and transport of these acid producing materials. These engineering controls may consist of cast-in-place concrete revetment walls, masonry revetment walls or bank stabilizers, open concrete channels, gabion walls, and rip-rap lined channels. Design of channel erosion controls is site-specific because each site may require a variety of different approaches. Elaborating the details of these designs is beyond the scope of this report. However, design details for standard revetment walls and channels are presented in Section II-D of this Main Text.

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C. ACID WATER TREATMENT

C-II FS SITES STUDY

1. Characteristics of Pollution

1. The feasibility study (FS) region is located north and west of the City of Criciuma, Santa Catarina. This area was mined extensively for coal in the 1970s resulting in acidification of numerous streams at the headwaters of three river basins. The affected river basins include the Rio Tubarão, Rio Urussanga and Rio Araranguá which has two major affected tributaries, i.e. the Rio Mãe Luzia and Rio Sangão. The pH of their waters ranges from 2 to 4. Farther upstream beyond or isolated from the coal mining areas, however, river water is clean showing 6 to 7 in pH. The pollution is not limited to low pH levels, but also due to high metal concentrations in the water. For example, a lead concentration exceeds several times existing Brazilian environmental standards; it is 10 times higher for manganese, several to 10^3 times for iron and aluminum. As a result, several municipalities could not use the water for consumption and to rely on water sources in the neighborhood.

1.1 Descriptions of FS Sites

2. Four FS sites have been selected by JICA and are representative of the different types of conditions requiring remediation throughout the region. They are as follows:

- ➪ Fiorita FS Site - an example of an abandoned open-pit mine in the Rio Araranguá basin, located upstream in the municipality of Siderópolis;
- ➪ Rocinha FS Site - an example of an extensive valley fill deposit of coarse rejects from coal washing in the Rio Tubarão basin, located upstream in the municipality of Lauro Müller;
- ➪ Carvão FS Site - an example of a flowing from an abandoned underground mine discharging to the Rio Urussanga basin, located upstream in the municipality of Urussanga; and
- ➪ Capivari FS Site - an example of a large settling pond for an abandoned coal washing facility at the Eletrosul Power Station in the Rio Tubarão basin, located downstream in the municipality of Capivari de Baixo.

(a) Fiorita FS site

3. The Fiorita FS site is approximately 230 ha in area, where the Barro Branco coal seam was mined by dragline methods along the axis of the valley presumably beginning from outcrops in the banks of the Rio Fiorita (Figure III-3 of Summary). Mining proceeded both north and south of the Rio Fiorita into the surrounding valley sides until the overburden thickness became too great to mine economically. The final north and south highwalls define the boundary of the mined area. At the highwalls, lateritic overburden soils on sandstone can be seen. In unflooded sections, the weathered Barro Branco seam is

also exposed.

4. Due to no reclamation during and after mining activities, the dragline mining method resulted in deposition of large conical piles of coarse bouldery sandstone waste throughout the site, leaving a disturbed area of about 160 ha, with 27 million m^3 of overburden waste and a total 16 ha of ponds and lakes sporadically located along the north and south highwalls or surrounded by overburden wastes. A few roads are maintained through the piles to provide access to the old working faces. Along those roads or in shallow streams in the site, black shale wastes or wash plant rejects, estimated at approximately 766,000 m^3, were dumped. Those black wastes are presumably brought in from somewhere else outside the FS site for illegal disposal, since there were no coal washing facilities during mining operations in the site.

5. There are two main types of waste at Rio Fiorita: shale and sandstone. The shale contains high sulfur concentrations comparable to coarse rejects at Rio Rocinha and Capivari. Shale wastes and bedrock at the site have high sulfur concentrations and are only slightly oxidized. This material is the source of poor quality water. Sandstone wastes have very low sulfur concentrations and also negligible neutralization potential. These wastes are not a source of poor quality leachate but would be suitable for construction purposes. Loadings to the Rio Fiorita are greatest along the south highwall in the middle of the FS site, possibly as the result of leaching of pyretic shale covered with sandstone waste. Given the significance of this loading source, and the possibility that other areas of buried shale may exist, any effort to remedy acid producing shale needs to consider not only exposed but buried waste shale deposits. The highest priority for this site is remediation of areas of waste pyretic shale. Exposure of bedrock also needs to be minimized. The pH of water coming into the FS site is a neutral 7 but in the course of running through the site, it is reduced to between 3 and 4.

(b) Rocinha FS site

6. The Rocinha FS site is approximately 71 ha in area, straddling the Rio Rocinha, which used to be the site of several coal washing plants (Figure III-9 of Summary). About 3 km upstream, coal was extracted from several underground openings entirely on the north bank of the Rio Rocinha and all of it was hauled to the FS site for washing between 1975 and 1990. Coarse rejects were deposited extensively as valley fill and side hill dumps mainly on the north bank of the Rio Rocinha until they became a flat elevated terrace. Wash plant fines were apparently discharged directly into the Rio Rocinha. Fines were also deposited in numerous settling basins or impoundments. Currently, coarse rejects are being excavated and re-washed to recuperate coal. The coarse rejects from this process are being returned to the dumps or sometimes dumped on the hillside in the FS site.

7. In the course of valley filling, the water of the Rio Pazza Dez, a tributary of the Rio Rocinha,

was blocked to the Rio Rocinha by the dumped rejects, estimated at 3.6 million m^3 of waste in total, over original extensive cobble and gravel depositions, and a short cut tributary to the Rio Rocinha was artificially created. The greatest unknown is the detailed pre-operational topography. Extensive valley filling as occurred at the coal washing area resulted in obliteration of the original valley trace of the Rio Pazza Dez.

8. The coarse rejects at the former preparation plant contain high concentrations of sulfur. On average, about 50% of the sulfur is oxidized. These wastes, in particular, have potential for very long term acid generation. Any remediation measure that results in saturation of the waste would also lead to release of acidity and leaching of iron, aluminum, manganese and probably zinc. In terms of volume of material and impact, these materials represent the highest priority for remediation. The Rio Pazza Dez at its discharge to the Rio Rochina is the greatest contributor of load to the Rio Rochina from the Rio Rochina FS site. Materials whose leachate flows into the Rio Pazza Dez represent the highest priority for remediation. The shaley wastes in the upper part of the site are very well-oxidized (approaching 100%) and contain much lower sulfur. These wastes have a very low priority for remediation due to exhaustion of the ability of oxidization any more. The pH of water coming into the FS site is almost 7 but it is reduced to between 3 and 4 mainly by the water from the original Rio Pazza Dez.

(c) Carvão FS site

9. The main feature of the Carvão FS site is the flowing from the abandoned Mina Santana's decline portal (Figure III-14of Summary). The decline, which ran in an approximately NNW direction for about 2 km, accessed extensive room and pillar chambers in Plano II before the Barro Branco seam is cut off by a fault. The downthrown seam to the north was accessed by a different decline (Plano XV). Mina Santana was operated from the 1970s to 1984 by Cia Carbonifera Urussanga and was closed following the death of 32 miners in an explosion.

10. The portal opens onto an area (less than 2 ha) filled with coarse rejects and an abandoned wash plant. This was the site of a former small open pit mine operated by Carbonifera Treviso from 1969 to 1977. Currently, the discharge from the decline portal enters a small, unnamed surface stream flowing across a waste shale area. In July 1996, this area was flooded and connected to a settling pond. Sometime in early 1997, the shale wastes were covered with soil and planted in eucalyptus trees, and the pond was mostly filled. The surface stream drains into an unnamed rock channel which flows into a 100 m culvert. The culvert drains into an incised valley which joins the Rio Carvão. The data obtained by the JICA team indicate the volumetric flow rate from the portal varies from 4.3 to 20 m^3/min. The pH of the water is relatively high, about 4.5 standard units.

11. The mine drainage from Mina Santana, however, is not the major sources of pollution. Drainage from the massive coal reject dumps located upstream of the unnamed stream contributes 50 percent of the acidity load, 89 percent of the aluminum load, and 75 percent of the iron load immediately downstream of the confluence of this stream and the Rio Carvão because the reject is currently being actively re-washed to recover part of the residual coal content. Despite this large load contribution, the waste piles were not included in the Rio Carvão FS site.

(d) Capivari FS site

12. This site consists of waste deposits from coal washing operated by CSN adjacent to the nearby coal burning plant operated by Eletrosul (Figure III-18 of Summary). Since the mid-1940s, uncontrolled disposal of wastes occurred in the marshy flats surrounding the Rio Estiva dos Pregos. Extensive waste materials were transported by railway and disposed of in a low-lying area of peaty soils. A large, 80 ha acid lake (pH 3) was created by gravity, because those soils are extremely soft and was unable to sustain weight of the dumped wastes and sank together with the wastes. Subsequently, dykes were constructed to contain the wastes in the current location. Exposed deposits of coarse rejects remain in the northern part of the site near abandoned wash plant structures, with which CSN re-washed those wastes. Between 1986 and 1992, they were washed again by a private company or a current land owner. Also extensive deposits of settling pond fines were presented in the southern, downgradient part of the site. The areas required for remediation total 240 ha, i.e. 80 ha of the acid lake, 80 ha of exposed waste and 80 ha of undisturbed but polluted area south and southeast of the lake.

13. The Rio Estiva do Pregos has been diverted into two ditches upstream of the site and north of the major Brazilian highway, BR-101 and both enter the site. The western branch passes under BR-101 and is immediately diverted east by a dike along the northern boundary of the waste disposal area. This branch joins the eastern branch in the northeastern corner of the site. The combined flow then runs around the main east dyke. The Rio Estiva dos Pregos then leaves the dyke in a northeast flowing ditch. Seepage from the large Capivari impoundment occurs through the southern and southeastern dykes. There is no surface water discharge from the acid lake to the river. Groundwater is shallow in the waste deposits (< 3m deep) generally varying with the waste topography. Very little seepage into the Rio Estiva dos Pregos occurs along the northern and northeastern dykes. The river appears to be slightly above the water of the acid lake along the northern boundary since the quantity of water flow is significantly decreased in the course of flowing from the northern boundary down to the south while the pH of the water is changing from 6 to 3.

1.2 Geochemical Assessment

14. The following subsections summarize the geochemical characterization of mining wastes at the JICA FS sites.

(a) Objective

15. The objective of the geochemical characterization of mining wastes was to gather relevant chemical data needed to develop effective plans for mitigating the effects of ARD from abandoned and active coal mining sites in southern Santa Catarina.

(b) Methods

16. Solid waste samples were collected from each of the four FS sites using a Case 580H backhoe. The work took place on October 28, 29, 30 and 31 and November 4, 5, 6 and 7, 1996. Test pits were dug to a maximum depth of 4 m. Each pit was logged (material types, depth to water table, pH and EC of water, final depth of pit) and samples collected according to waste types, coloration, mineralogy and degree of saturation. A total of 152 samples were collected and shipped to FUCRI/UNESC for analysis.

17. A subset of these samples were analyzed for total metals and leachable metals using United States Environmental Protection Agency (US EPA) Method 1312. Total metal determinations (item 5) are used to evaluate mineralogy of the samples and the total quantity of metals that is potentially available for leaching. Leachable metals (item 6) indicate the quantity of metals that could potentially released by the waste if placed in water or exposed to precipitation. An Acid/Base Accounting (ABA) program based on guidelines provided in the US EPA Document EPA 600/2-78-054 methods, was also performed on selected samples, as described below.

(c) Geochemical characteristics of mine waste

18. The results of the total and leachable metals analyses and the ABA tests performed on mine waste samples collected at the JICA FS sites are summarized in this section.

19. Most samples contained high concentrations of sulfur in both non-oxidized and oxidized form. All but one sample indicated negligible neutralization potential. All but a few samples exhibited negative neutralization potential which indicates the materials will produce acidity on exposure to air and water. Total concentrations of Al, Ca, Fe, Mn, Cr and Zn were above detection levels but lower than crustal averages. Concentrations of As, Cd, Cu, Pb and Hg were close to or at the detection limits. Leachates from the EPA 1312 procedure contained detectable concentrations of Al, Ca, Cu, Cr, Fe, Mn and Zn. Total and leachable metal concentrations are mostly weakly correlated. Leachable metal concentrations are correlated with the leachate pH. Expected relationships are observed.

(d) Geochemical implications of ARD mitigation

20. The geochemical characterization of the JICA team FS sites are described below in terms of their relevance to ARD control strategies.

21. *Rio Fiorita*: Test pit locations are illustrated in Figure C-II-1. There are two main types of waste at Rio Fiorita: shale and sandstone. The shale contains high sulfur concentrations comparable to coarse rejects at Rio Rocinha and Capivari. Shale wastes and bedrock at the site have high sulfur concentrations and are only slightly oxidized. This material is the source of poor quality water. Sandstone wastes have very low sulfur concentrations and also negligible neutralization potential. These wastes are not a source of poor quality leachate but would be suitable for construction purposes. Loadings to the Rio Fiorita are greatest between sites FS-09 and FS-07, possibly as the result of leaching of pyretic shale covered with sandstone waste. Given the significance of this loading source, and the possibility that other areas of buried shale may exist, any effort to remedy acid producing shale needs to consider not only exposed but buried waste shale deposits. The highest priority for this site is remediation of areas of waste pyretic shale. Exposure of bedrock also needs to be minimized.

22. *Rio Rocinha*: Wastes at two parts of the FS sites were sampled as shown in Figure C-II--2. The coarse rejects at the former preparation plant contain high concentrations of sulfur. On average, about 50% of the sulfur is oxidized. These wastes, in particular, have potential for very long term acid generation. Any remediation measure that results in saturation of the waste would also lead to release of acidity and leaching of iron, aluminum, manganese and probably zinc. In terms of volume of material and impact, these materials represent the highest priority for remediation. The Rio Pazza Dez at its discharge to the Rio Rochina is the greatest contributor of load to the Rio Rochina from the Rio Rochina FS site. Materials whose leachate flows into the Rio Pazza Dez represent the highest priority for remediation. The Shelly wastes in the upper part of the site are very well-oxidized (approaching 100%) and contain much lower sulfur. These wastes have a very low priority for remediation.

23. *Rio Carvão*: Sampling at Carvão was limited (Figure C-II-3). The few samples indicated that coarse rejects (shale waste rock) deposited near the portal have high sulfur content and are only weakly oxidized. Loadings from the coarse rejects below the mine portal are a significantly larger contributor of load to the Rio Carvão than the mine portal. The coarse rejects appear to contribute approximately 40 times the load to the Rio Carvão than does the mine portal discharge. The results confirmed that the priority for remediation at this site is the coarse rejects. The mine drainage is probably a limited concern.

24. *Capivari*: Test pit locations are given in Figure III-18 of Summary. Both tailings and coarse rejects are present. Characteristics of these materials are comparable to Rio Rocinha though

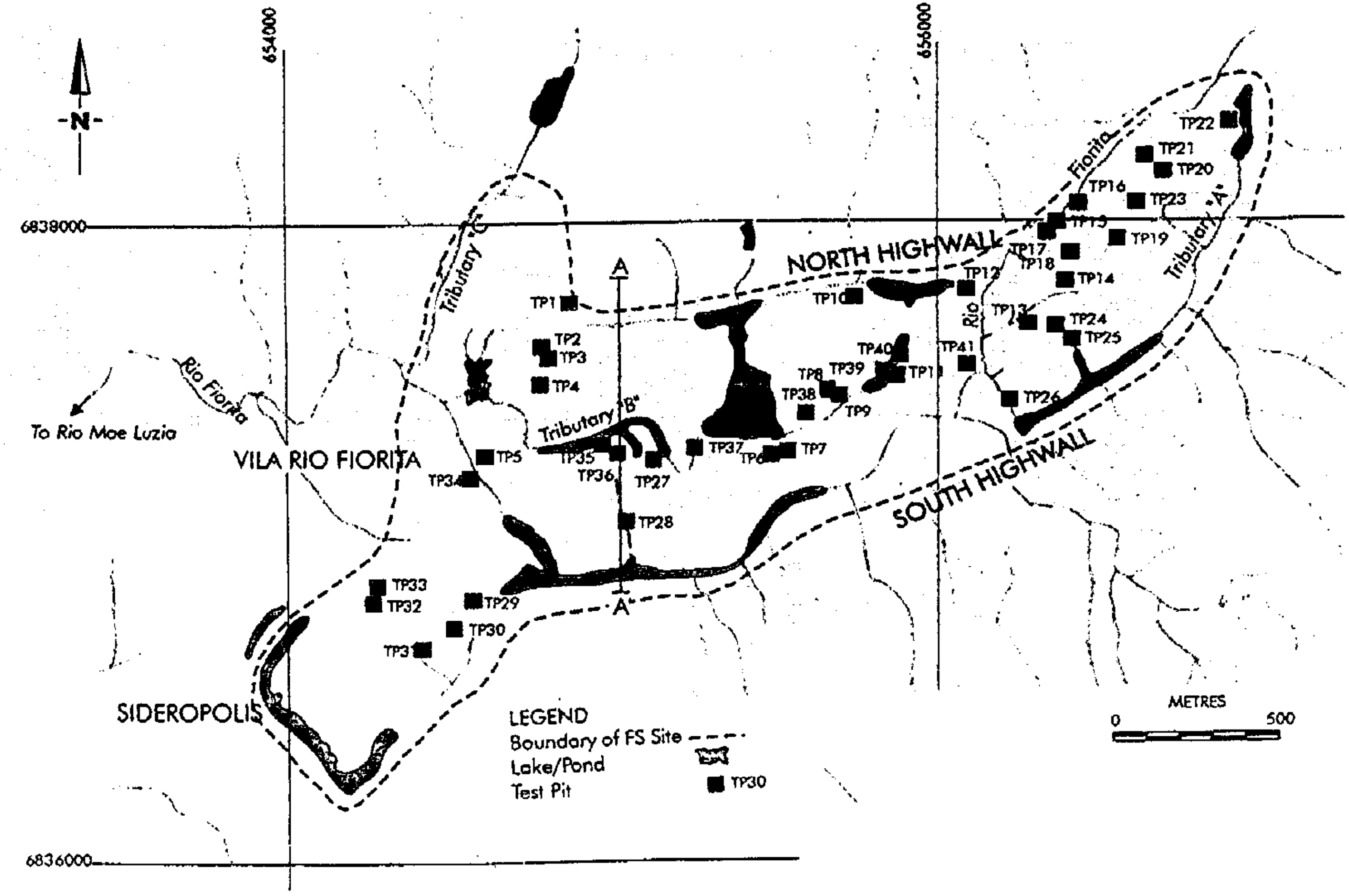

FIGURE C-II-1 TEST PIT LOCATIONS IN THE FIORITA FS SITE

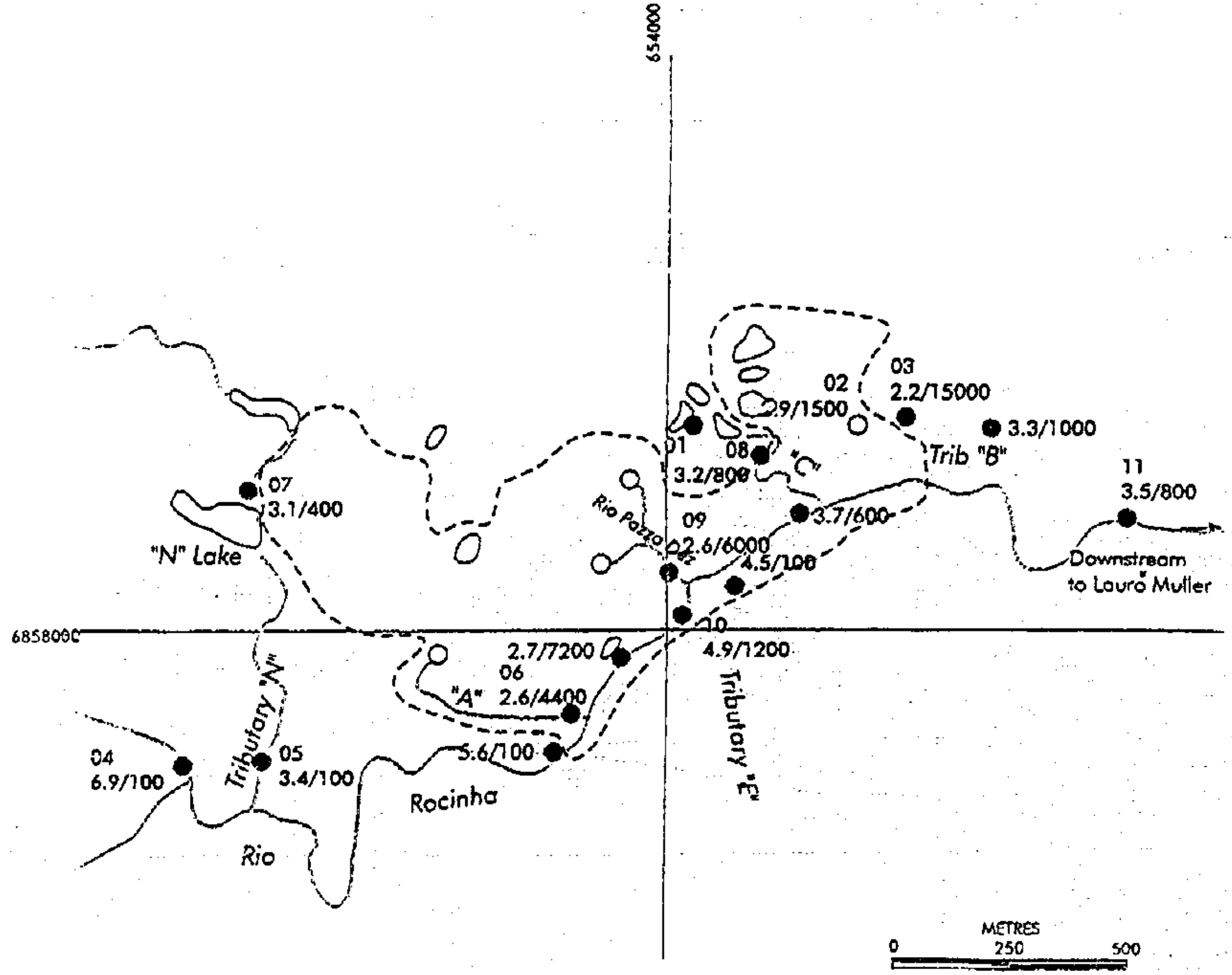

FIGURE C-II-2 TEST PIT LOCATIONS IN THE ROCINHA FS SITE

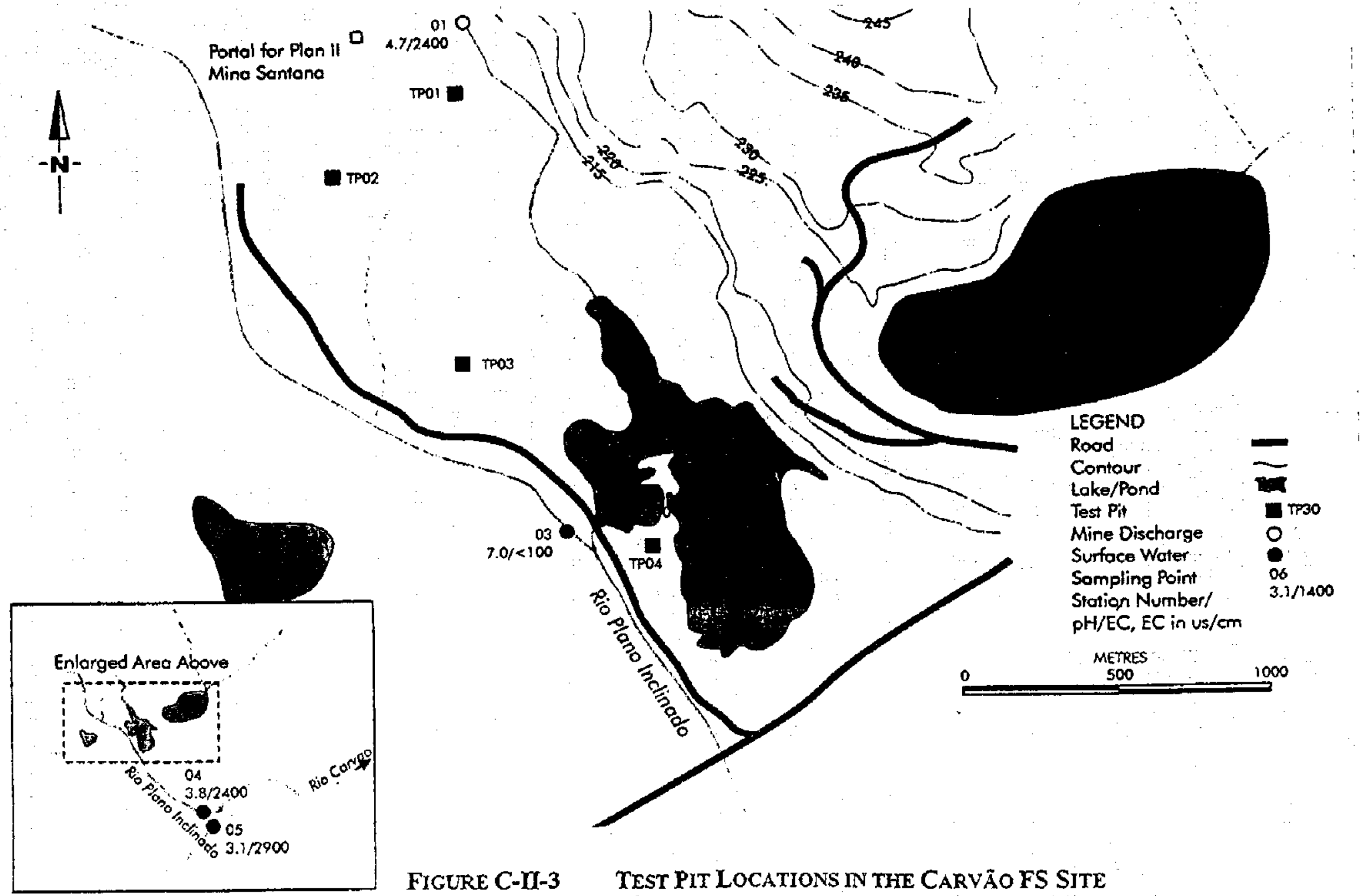

FIGURE C-II-3 TEST PIT LOCATIONS IN THE CARVÃO FS SITE the wastes are less oxidized. Similar considerations exist for remediation as at Rio Rocinha. The remediation priority is also the same.

1.3 Treatability Test Results

25. This section summarizes the results of treatability tests performed as part of the ARD feasibility study. During February and March of 1997, bench-scale treatability tests were performed at the Environmental Research Center at FUCRI/UNESC. Treatability studies described in this section include waste neutralization tests, biocide treatment of acidic mine wastes, acid water neutralization and precipitation tests, and passive biological treatment tests. These bench-scale tests were conducted under the supervision of JICA team members in accordance with the Acid Water Neutralization Specifications presented in the JICA Team's contract with FUCRI/UNESC. The results of these treatability tests are discussed in the subsections that follow.

(a) Waste neutralization test results

26. Waste neutralization tests were performed as part of the geochemical characterization of solid mine wastes and acid/base accounting procedures described in para. 17 of this report. Through this procedure, the net neutralization potential (NNP) of the sample material was determined. The NNP values can be interpreted as the amount of calcium carbonate ($CaCO_3$) needed to neutralize the total amount of acid the waste is capable of generating. Therefore, these results can be used to evaluate the feasibility of chemically neutralizing the wastes as a method of preventing or controlling ARD.

27. The NNP values represent the amount of calcium carbonate in kilograms per ton of waste (kg/ton) needed to neutralize the acid generated by oxidation of all the sulfur contained in the sample. The results indicate that only a few samples were non-acid forming. For the samples of saturated and unsaturated coarse rejects, the NNP ranged between -15.9 kg/ton and -317 kg/ton. The average NNP for the coarse rejects was -170 kg/ton. These data indicate that on average 170 kg of calcium carbonate would need to be added to each ton of waste to prevent or control the production of acid.

28. In operating mines, waste materials exhibiting a positive NNP are typically blended with acid generating materials to prevent ARD. At abandoned mine sites, surface application of limestone or other alkaline materials can be used to control ARD. The evaluation of this technology is presented below.

(b) Biocide treatability test results

29. A column leach test was performed to evaluate the feasibility of using an anionic surfactant bactericide to control acid production in pyretic mine wastes. The specific surfactant used during this

test was sodium lauryl sulfate (SLS). The samples used for this bench-scale test were obtained from the Rio Rocinha FS site in November of 1996. Five 15-kg samples of the test material were placed in PVC columns. Four of the columns were leached for 10 weeks with aqueous solutions containing various concentrations of SLS. SLS solutions with concentrations of 60 mg/L, 120 mg/L, 120 mg/L, and 240 mg/L were applied to columns 1, 2, 3, and 4, respectively. The fifth column was leached with clean water containing no surfactant as an experimental control column.

30. The test results indicate large reductions in acidity, iron, sulfate, and sodium concentrations occurred in all columns during the 10 week leaching test, including the control column. In general, reductions of all parameters were proportional to SLS dosage. However, the differences between the columns, including the control, were insignificant for pH, iron, sulfate, and sodium. The pH of the column leachate samples changed only slightly, from 1.5 to 2.2 during the test period. Acidity reductions ranged from approximately 98 percent to greater than 99 percent in columns 1 through 4, respectively; whereas a 77 percent reduction in acidity was observed in the test column. The reductions in iron concentrations ranged from 98 percent in the control column to greater than 99 percent for column 4.

31. In conclusion, these column test results indicate that rinsing the waste with clean water would be nearly as effective as applying the biocide solutions. Further, despite large reductions in the concentrations of all constituents, the leachate from all columns still exceeded water quality standards for pH, iron, and sulfate after 10 weeks of leaching. Based on these bench-scale results, application of biocide solutions appears ineffective in controlling acid drainage from samples of pyretic coal rejects.

(c) Acid water neutralization test results

32. During the active treatment bench testing program, FUCRI/UNESC personnel performed the following specific tests:

- Acid neutralization tests using three different reagents on several acid water samples from each of the FS sites. The specific reagents tested during this investigation included caustic soda ($NaOH$), soda ash (Na_2CO_3), and hydrated lime ($Ca(OH)_2$);
- Oxidation tests using two reagents, calcium hypochlorite and potassium permanganate, to evaluate the potential benefits of oxidizing the metals prior to the metals removal tests;
- Metals removal tests using the three reagents to identify the optimal reagents, pH, and dosages for removal of aluminum, copper, iron, manganese, and zinc in water samples from the FS sites; and
- Analysis of the volume of treatment sludges produced and the settling characteristics of the sludge.

33. ***Acid water neutralization test results***: The results of this test indicate hydrated lime is the most effective reagent for raising the pH of acid water samples from the FS sites. First, the tabulated

results show that less reagent is required to raise the pH to 7.5 when lime is used than either caustic or soda ash. Second, acid waters that were neutralized using lime were more resistant to reacidification. Finally, lime costs considerably less than either caustic or soda ash.

34. *Metal oxidation test results*: The metal oxidation test results were highly variable depending on the initial acidity and metals concentrations of the sample. Qualitatively, it appears calcium hydrochlorite was slightly more effective as an aid in reducing iron concentrations than potassium permanganate. However, addition of oxidizing agents had no significant effect on the removal of aluminum.

35. *Metals removal test results*: The removal efficiencies for aluminum, copper, iron, manganese, and zinc were tested. For all metals, the removal efficiencies ranged from 95 to 99.9 percent, depending on the initial concentrations. In almost all cases, metals concentrations after treatment to pH 10.5 were below the water quality goals for the JICA team FS sites. The bench-scale metals removal efficiencies suggest that active treatment would be highly effective in reducing metals concentrations in site surface waters.

36. *Sludge production and characterization test results*: The sludge production test results indicate the volume of sludge produced when the pH is raised to 10.5 is highly variable but appears to be inversely proportional to the initial pH. Neutralization of mildly acid waters, such as the samples from FS-09 and PT-14, generated very little treatment sludge, i.e. less than 15 ml/L. However, neutralization of strongly acidic waters, such as the samples from FS-01, RS-09, and CAS-04, generated copious amounts of treatment sludges, including 246 ml/L, 329 ml/L, and 321 ml/L, respectively. These results indicate that sludge would comprise from 1.5 percent to 30 percent of the volume of the treated water. Without significantly reducing the sludge volume, the quantity of sludge requiring disposal would be an insurmountable problem that would preclude the use of active treatment for all but the smallest and weakly acidic seeps and streams.

37. *Passive biological treatment tests*: The possible use of sulfate-reducing bacteria (SRB) for treatment of ARD was investigated by the Team. The addition of carbon energy sources such as vegetable cellulose under anaerobic conditions is known to result in the generation of excess sulfide ions through SRB activity. These microorganisms can be used under the appropriate conditions to remove metals and add alkalinity to acidic mine water. During the treatability studies, water treatment effects of various carbon sources under pH 4 conditions were compared using the concentrations of sulfate and total iron as indicators for treatment effectiveness. Organic materials tested included soils, cattle manure, and river bottom sediments. The results of the experiments indicate that cow manure and river sediments contained populations of SRBs and organic carbon sufficient to reduce both the sulfate and

total iron concentrations. These results show that low-cost treatment systems using readily available organic matter, such as agricultural wastes, can be used to neutralize and remove metals from ARD. More detailed discussions of these test results are presented in Section II-G of this Main Text.

2. Remedial Alternative for FS Sites

38. Three alternatives for each FS site were developed by creating three distinct groupings of remedial actions for acid water treatment. Since overburden waste dumps exist only in the Fiorita FS site, the reclamation of overburden waste dumps was included only in this site, resulting in six remedial alternatives for the Fiorita FS site.

2.1 Fiorita Remedial Alternatives

(a) Alternative descriptions

39. *Alternative 1*: The features of this alternative are source removal, on-site disposal, passive treatment and overburden waste dump reclamation. Black reject material and exposed pyretic shales are thought to be the primary source of acidity and metal contamination to the Rio Fiorita. Those source materials would be excavated and disposed of by either placing them under a minimum of one meter water in one of several existing on-site ponds or placing them in an engineered on-site waste repository which is covered with a wet cover or capillary barrier system. Following removal of the pyretic shales, the excavated areas would be recontoured, regraded and covered with an oxygen limiting vegetated cover system to prevent the oxidation of any pyretic shales in the foot wall of the pit that may have been exposed during excavation. Small acidic seeps and streams entering the Rio Fiorita would be treated through passive biological treatment systems in constructed aerobic or anaerobic wetlands. Overburden waste dumps would be recontoured, regraded and covered with grass seeded clay (single layer dry cover). The remedial actions are as follows:

i.) Excavation and on-site disposal of exposed reactive waste;
ii.) Subaqueous disposal in existing on-site ponds;
iii.) Construction of an on-site waste repository;
iv.) Construction of passive wetland systems;
v.) Control of channel erosion and installation of aeration drop structures;
vi.) Diversion of clean water; and
vii.) Overburden reclamation.

40. *Alternative 2*: The features of this alternative are source containment under wet cover systems, passive treatment and overburden waste dump reclamation. A major difference from Alternative 1 is source material disposal. Black reject material and pyretic shales would be left in place and capped with a wet cover system. However, limited reactive wastes, those located in water courses and in the area with the potential for water levels to fluctuate through the wastes and the threat of damage to a

cover system during floods. The wet cover would significantly decrease infiltration of rainfall through the wastes, thereby retarding or eliminating the transport of oxidation products from the wastes to site surface waters and groundwater. Passive wetland, channel, aeration drop structures, clean water diversion and overburden waste dumps reclamation are identical with Alternative 1. The remedial actions are as follows:

i.) Covering of reactive wastes with an wet cover system;
ii.) Limited excavation and on-site disposal of exposed reactive wastes;
iii.) Construction of passive wetland systems;
iv.) Control of channel erosion and installation of aeration drop structures;
v.) Diversion of clean water; and
vi.) Overburden reclamation.

41. *Alternative 3*: The features of this alternative are source control, passive treatment and overburden waste dump reclamation. A major difference with Alternative 2 is a reactive waste covering system. Black reject material and pyretic shales would be left in place and capped with a dry cover. The procedure of limited excavation and on-site disposal of exposed reactive wastes is identical with Alternative 2 except for the covering system. The dry cover system would consist of two separate soil layers, an uncompacted soil layer supporting a vegetated cover of native grasses and a low-permeability-compacted clay layer. Passive wetland and overburden waste dumps reclamation are identical with Alternative 1 and 2. The remedial actions are as follows:

i.) Covering of reactive wastes with dry soil cover systems;
ii.) Limited excavation and on-site disposal of exposed reactive wastes;
iii.) Construction of passive wetland systems;
iv.) Control of channel erosion and installation of aeration drop structures;
v.) Diversion of clean water; and
vi.) Overburden reclamation.

42. *Other alternatives*: Alternatives 4, 5 and 6 eliminate overburden dumps reclamation from Alternatives 1, 2 and 3, respectively.

(b) Rio Fiorita alternative evaluations

43. *Effectiveness evaluations*: Since there are no difference between Alternatives 1 and 4, Alternatives 2 and 5, and Alternatives 3 and 6, the first three Alternatives are described. Effectiveness evaluations of the Rio Fiorita remedial alternatives are presented below:

- *Alternative 1*: This alternative is the most effective of the three alternatives for the Rio Fiorita Site. Following implementation of the Alternative 1, the pH and metals concentrations in site surface waters are expected to meet water quality goals for the site. Metals and acidity concentrations are expected to be reduced by as much as 90 to 98 percent. Iron and aluminum concentrations would be at or below background levels. However, removal of the exposed waste would not eliminate all sources of acidity and metals contamination because an unknown quantity of reactive wastes are believed to be buried beneath the mounds of sandstone overburden that cover most of the surface of the site;

- *Alternative 2*: Covering exposed reactive wastes with an oxygen-limiting wet cover is expected to result in a net decrease in the acidity and metals loads to the Rio Fiorita of approximately 60 to 70 percent at the site boundary. This estimated load reduction indicates capping the wastes in place and is anticipated to be less effective than excavating and removing the wastes, as prescribed under Alternative 1. Acidity and metals concentrations are still expected to meet water quality standards despite the decrease in load reductions compared with Alternative 1; and

- *Alternative 3*: Covering reactive waste with a dry soil cover system, as prescribed under Alternative 3, is expected to result in only a 20 to 40 percent reduction in the surface water metal and acid loads. The effectiveness of the passive treatment systems would be diminished due to an increase in metal and acid loading from the capped wastes. Water quality goals are not expected to be met at the site boundary under this alternative.

44 ***Implementability evaluation***: The evaluation of Rio Fiorita remedial alternatives with respect to their anticipated implementability is summarized below. All three alternatives are expected to be readily implementable. With only minor expectations, most of the proposed facilities can be constructed using conventional earthmoving and concrete construction techniques. Specialized technical oversight would be needed to ensure the proper design and construction of the prescribed passive wetland treatment systems. The existing local force of professional and construction labor possesses most of the skills needed to design and install the Alternative 1 facilities. However, personnel with experience in the construction of effective wetland treatment systems are not widely available, and technical assistance from outside the local area may be needed.

45. ***Investment Costs***: Investment costs were estimated in Section II-D of Main Text in detail. Water quality simulation for the FS sites are presented in Section II-B of Main Text in detail. Together with those results, cost estimates are summarized below.

TABLE C-II-1

FIORITA REMEDIAL COST AND EFFECTIVENESS

	Estimated Loads Reduction(%)	pH [a/]	Cost (RS million)
Alternative 1	90 - 98	4.6 - 5.0	12.4
Alternative 2	60 - 70	3.8 - 4.0	11.2
Alternative 3	20 - 40	3.5 - 3.7	8.4
Alternative 4	90 - 98	4.5 - 5.0	7.3
Alternative 5	60 - 70	3.8 - 4.0	5.6
Alternative 6	20 - 40	3.5 - 3.7	2.8

a/ Estimated at the downstream boundary of the FS site (Current pH = 3.5).

46. In the most effective alternative (Alternative 1), metals and acidity concentrations are expected to be reduced by as much as 90 to 98 percent. In spite of the greatest reductions, it would not meet the existing Brazilian surface water quality norms. Since the current estimation do not count on the effect of overburden waste reclamation, by which loadings supplied from probably buried reactive

wastes beneath the overburden dumps could be significantly reduced, there is no difference between Alternatives 1, 2, 3 and Alternatives 4, 5, 6 in terms of pH, respectively.

2.2 Rocinha Remedial Alternatives

(a) Alternative descriptions

47. *Alternative 1*: The features of this alternative are source containment, passive treatment and erosion controls. Pyretic black reject dumps would be left in place and capped with a wet cover or capillary barrier. Prior to capping, the waste dumps would be re-graded and re-contoured. Surface drainage channels would also be installed to collect and transport runoff away from the capped areas to reduce erosion during intense rainfall events. The purpose of re-contouring the slopes is to reduce the slope lengths by installing periodic terraces, alleviate excessive slope grades to reduce runoff kinetic energy, and provide low gradient lateral drainage channels to safely convey runoff off the slopes. Lime would be also applied to the surface of reactive waste piles prior to capping (10 to 15 kg/m^2). Existing surface ponds would be drained and filled to prevent seepage into the underlying wastes. The drained ponds would be re-graded to conform to the final topography of the terraced waste piles and then capped with wet covers. Several acidic seeps and streams would be treated through passive biological treatment systems, including both anaerobic and aerobic wetlands. Clean water in the Rio Pazza Dez above the FS site would be intercepted and diverted to the Rio Rocinha in a concrete-lined channel. A potion of the flow from the Rio Pazza Rez is believed to currently flow underground through reactive wastes then discharges into the channel at RS-9. The remedial actions are as follows:

i.) Covering of reactive wastes with an oxygen-limiting wet cover system;
ii.) Applying lime to reactive waste dumps;
iii.) Limited excavation and on-site disposal of exposed reactive wastes;
iv.) Draining and filling surface water impoundments;
v.) Construction of passive wetland systems;
vi.) Control of channel erosion and installation of aeration drop structures;
vii.) Diversion of clean water; and
viii.) Stabilizing the Rio Rocinha river channel.

48. *Alternative 2*: The features of this alternative are source containment, passive treatment and erosion controls. Differences are reactive waste covering systems, using a dry soil cover instead of a wet soil cover system used in Alternative 1, and no application of lime to the waste surfaces in this alternative. The remedial actions are as follows:

i.) Covering of reactive wastes with a dry cover system;
ii.) Limited excavation and on-site disposal of exposed reactive wastes;
iii.) Draining and filling surface water impoundments;
iv.) Construction of passive wetland systems;
v.) Control of channel erosion and installation of aeration drop structures;
vi.) Diversion of clean water; and

vii.) Stabilizing the Rio Rocinha river channel.

49. *Alternative 3*: The features of this alternative are source containment and erosion controls. A difference is that the passive wetland treatment systems described under Alternatives 1 and 2 are omitted from this Alternative 3. The remedial actions are as follows:

i.) Covering of reactive wastes with a dry cover system;
ii.) Limited excavation and on-site disposal of exposed reactive wastes;
iii.) Draining and filling surface water impoundments;
iv.) Control of channel erosion and installation of aeration drop structures;
v.) Diversion of clean water; and
vi.) Stabilizing the Rio Rocinha river channel.

(b) Rio Rocinha alternative evaluations

50. The Rio Rocinha FS site is an example of a valley-fill waste deposit. Mitigation of the effects of acid drainage are severely constrained by the valley topography, the volume of waste present at the site, and limited area for construction of mitigation facilities. Most wastes have been placed on the steep northern side slopes of the Rio Rocinha canyon. Some waste deposits extend to the river channel itself and are in contact with river water. Further, several side canyons contain waste dumps that are severely impacted by erosion from the stream channels. The effectiveness of all the remedial alternatives is constrained by the method of waste deposition and the steepness of the terrain.

51. *Effectiveness Evaluation*: There are few opportunities to utilize natural wetlands for passive treatment. The effectiveness of any remedial plans for the Rio Rocinha site depends on ending the current practice of rewashing the coal rejects at the site. Current rewashing activities would restrict remedial activities to less than half the area of the site and would disturb remedied areas with vehicle traffic and ongoing waste deposition:

- *Alternative 1*: Following implementation of the Alternative 1, the pH and metals concentrations in the Rio Rocinha at monitoring point RS-11 are not expected to meet water quality goals for all metals. Despite estimated reductions in metals and acidity concentrations of up to 95 percent, aluminum and iron concentrations would still exceed the water quality goals in the Rio Rocinha at RS-11. However, the water quality goals for all metals except aluminum would be met at monitoring point PT-02. Greater reductions in metals concentrations are probably not possible because 95 percent is expected to be the upper limit of removal efficiency for the available mitigation methods. Acidity, aluminum, iron, and manganese concentrations would not be reduced to background levels by the actions planned under Alternative 1 because of the heavy loads entering the Rio Rocinha in the reach between RS-10 and RS-11;

- *Alternative 2*: Changing the design from a wet to a dry cover system could reduce the overall effectiveness of the remedial actions at the site from approximately 90 to 95 percent under Alternative 1 to 60 to 70 percent under Alternative 2. The decreased effectiveness would result from the possible failure of the dry cover to effectively exclude oxygen from the waste materials and from a possible increase in the amount of infiltration seeping into the waste. Because of the high initial acid and metal loads, the estimated 60 to 70 percent removal efficiency achieved under

Alternative 2 would result in acidity and metals concentrations exceeding water quality goals at the site boundary (RS-11), as well as downstream at PT-02; and

- *Alternative 3*: The overall effectiveness of Alternative 3 is expected to be much lower than the previous two alternatives due to the absence of the wetland treatment systems. Without the benefit of passive treatment, groundwater migrating through the capped waste piles would seep unabated into the Rio Rocinha. Under Alternative 3, acidity and metals concentrations at the site boundary are expected to be reduced by only 25 to 30 percent.

52. ***Implementability evaluation***: The evaluation of Rio Fiorita remedial alternatives with respect to their anticipated implementability is summarized below.. All three alternatives would be difficult to implement because of a possible shortage of cover and wetland construction materials and the existence of the current reprocessing of coal rejects at the site. Clay materials needed to construct the soil cover systems are available locally. However, soils suitable for constructing the vegetative layer are not locally available in sufficient quantities to complete the cover systems, as designed. Successful implementation of these alternatives depends on ending the current practice of rewashing the coarse rejects at the site. The alternative could not be implemented under current conditions due to the continued excavation, rewashing, and redepositing of coal rejects. Most of the proposed facilities can be constructed using conventional earthmoving and concrete construction techniques. Specialized technical oversight would be needed to ensure the proper design and construction of the prescribed passive wetland treatment systems. The constructability of the proposed wetland treatment systems located along the Rio Rocinha above RS-11 is questionable due to potential geotechnical engineering, groundwater hydraulic, and flood protection issues.

53. *Investment Costs*: Investment costs were estimated in Section II-D of Main Text in detail. Water quality simulation for the FS sites are presented in Section II-B of Main Text in detail. Together with those results, cost estimates are summarized below.

TABLE C-II-2

ROCINHA REMEDIAL COST AND EFFECTIVENESS

	Estimated Loads Reduction(%)	pH [a/]	Cost (R$ million)
Alternative 1	up to 95	less than 4.5	8.1
Alternative 2	60 - 70	3.6 - 3.8	5.1
Alternative 3	25 - 30	less than 3.5	3.5

a/ Estimated at the monitoring point (RS-11) slightly downstream of the FS site boundary (Current pH = 3.1)

54. In the most effective alternative (Alternative 1), metals and acidity concentrations are expected to be reduced by up to 95 percent. In spite of the greatest reductions, it would not meet the existing Brazilian surface water quality norms.