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Pollution of Osheepcheon Creek by abandoned coal mine drainage in Dogyae area, eastern part of Samcheok coal field, Kangwon-Do, Korea

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Abstract Osheepcheon Creek running through the Dogyae area is being polluted by the influx of the abandoned coal mine drainage. Generally, the more polluted water has lower pH and Eh and higher conductivity values. The concentrations of Mg, Ca, Fe, SO_4, and some trace elements, such as Cd, Co, Cr, Mo, Ni, Pb, Rb, Sr, U and Zn, are tens to hundreds of times more concentrated in the abandoned coal mine drainage than in the unpolluted streamwater. However, most immobile toxic pollutants from the mine drainage are quickly removed from the streamwater by the precipitation of amorphous Fe hydroxide and sorption on the precipitated Fe hydroxide. The fast removal of the pollutants from the streamwater maintains the water quality of the creek as acceptable at most places along the stream path, except where the abandoned coal mine drainage flows in. However, the creek has the potential of deteriorating quickly if the mine drainage is allowed to be continuously combined with the streams. A function of pH, Eh, and conductivity has been developed with discriminant function analysis for the purpose of easy, fast, and inexpensive measurement of the degrees of pollution of the streams. The estimated pollution of the streams with the discriminant function are consistent with what the chemical compositions of the water samples indicate. The pollution map of the study area was constructed from the calculated scores with the discriminant function. The pollution map suggests that the pollutants mainly come from the west side of Osheepcheon Creek. Thus, the abandoned coal mine drainage from the west side has to be appropriately treated as soon as possible to prevent Osheepcheon Creek from being further polluted. Considering the topography, climate, and the amount of the mine drainage, an active treatment method is recommended.

Key words Abandoned coal mine drainage · Stream pollution · Water quality

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Introduction

The Samcheok coal field is located at the southeastern part of the Kangwon-Do Province, Republic of Korea, covering an area of approximately 424 km^2 from 128°40′E to 129°05′E and from 37°05′N to 37°15′N (Fig. 1). The Samcheok coal field had been one of the most productive coal fields in Korea and once supplied more than 65% of the total domestic coal production. However, coal mining over more than 30 years, starting in 1950s in this area, has depleted near-surface coal and caused more expense to the coal mines as mining progressed to deeper levels. Korean government recognized that sustaining such unprofitable coal mines were too much of a burden on the national budget and began allowing them to close, enforcing the so-called Coal Industry Rationalization Policy from 1980. Since then, more than 80% of the coal mines in the Samcheok coal field have been closed and many others still operating are expected to be closed in the near future.

While the closure of the coal mines has led to more domestic consumption of other energy sources, such as petroleum, natural gas, and nuclear power, it has brought on severe stream pollution problems in the coal fields and the corresponding downstream areas. As the number of abandoned coal mines increases, the streams in the coal fields developed yellow to yellowish red precipitates on the bottoms of the stream channels and most aquatic macroorganisms have disappeared. Lately, these pollution problems have become worse and, hence, should be adequately handled as soon as possible. The Ministry of Environment is now regulating the water quality of the drainage from currently operating mines and the Korea Coal Industry Promotion Board is investigating the overall environmental impacts from both abandoned and operating mines. However, still to be performed is the detailed investigation of stream pollution, which can be useful in preparing an adequate treatment program for already polluted streams and prevent the streams from further pollution in the future.

The purpose of this study is to identify the potential

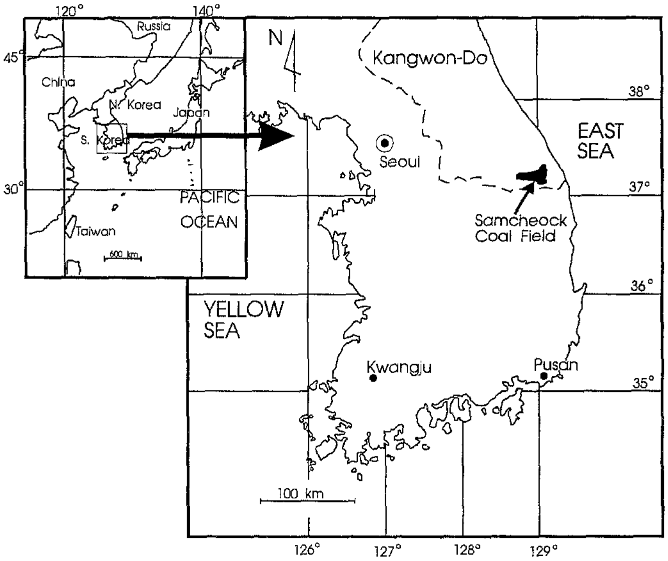


Fig. 1 Location of the Samcheok coal field

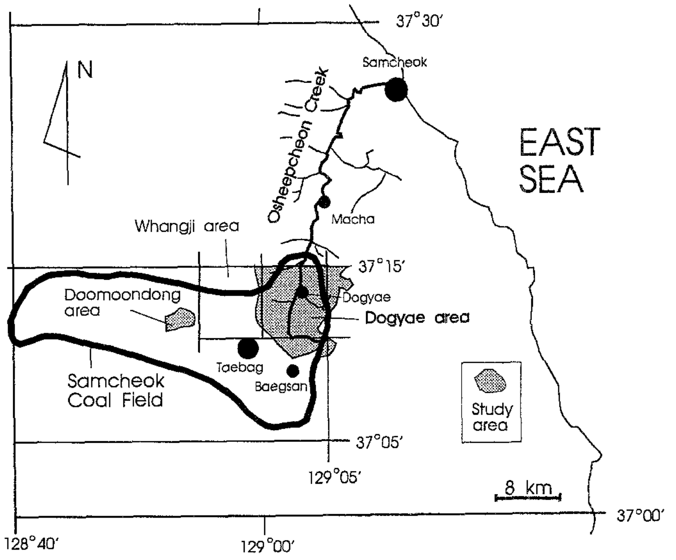


Fig. 2 Location of the study area (shaded)

pollutants from the abandoned coal mine drainage, develop an effective pollution indicator of the streams, and assess the degrees of pollution along the stream pathways with the pollution indicator in the Dogyae area, especially focusing on the Osheepcheon Creek. Dogyae is located at the northeastern part of the Samcheok coal field. Like other parts of the coal field, most of the coal mines once operated in the area have been closed, and only a few mines remain in operation. Osheepcheon Creek is the principal stream of the Dogyae area, which starts at Baegsan, runs through Dogyae, Macha and Samcheok, and finally reaches the East Sea (Fig. 2). After most of the coal mines have been closed, the creek is exposed to potentially severe pollution from abandoned coal mine drainage. Considering that Osheepcheon Creek may be the only water supply to the cities in the area, the pollution of Osheepcheon Creek could be a disaster to both local people and other life forms. It is hoped that the results of this study will help improve the water quality of Osheepcheon Creek, prepare an adequate plan of pollution control, and can be utilized for the investigation of environmental impacts due to the mine drainage in other areas.

Geological setting

The Dogyae area consists of Precambrian metamorphic rocks, Paleozoic and Mesozoic sedimentary formations, and Mesozoic extrusive and intrusive rocks (Fig. 3). Precambrian metamorphic rock, the basement of the area, consists of gneiss and schist polymetamorphosed up to the amphibolite face (Lee and others 1992). Paleozoic sedimentary formations, unconformably overlying the Precambrian basement, are subdivided into Cambro-Ordovician Yangdeog and Great Limestone Group, Carboniferous Manhang and Geumcheon formations, and Permian Jangseong, Hambaegsan, and Dosagog formations. All the Paleozoic sedimentary formations, except those of Great Limestone Group, mainly consist of clastic rocks, such as conglomerate, sandstone, and shale, with minor intercalation of limestone. Both Carboniferous Geumcheon and Permian Jangseong formations are cyclothems (Cheong 1969) and have interbedded coal seams. However, only the coal seams in Jangseong Formation have been mined due to their quality and quantity appropriate for the economic development. Black shales and sandstones are usually associated with the coal seams and include significant amounts of pyrite of lenticular or concretional forms. Most of the Paleozoic clastic rocks show very poor porosity and permeability due to cementation and recrystallization. Mesozoic sedimentary formations are all Cretaceous, consisting of Jeoggagri and Heungjeon formations, which unconformably overlie the Paleozoic strata. The Jeoggagri Formation mainly consists of conglomerates with limestone boulders and the Heungjeon Formation consists of volcaniclastic rocks. After the deposition of all the sedimentary formations, Cretaceous rhyolite extruded and then quartz porphyry intruded.

All the metamorphic and sedimentary formations prior to the Mesozoic Era have been folded and thrusted. The trend of the fold axis and the strike of the thrust plan are variable, but the main trend of the fold axis is in a NS direction and the strike of the thrust plan is mainly in a EW direction. The strike slip faults in the NS direction may be associated with the folding and thrusting. After the intrusion of the Cretaceous quartz porphyry, tensional stresses might be applied to the area and trigger normal faults in various directions.

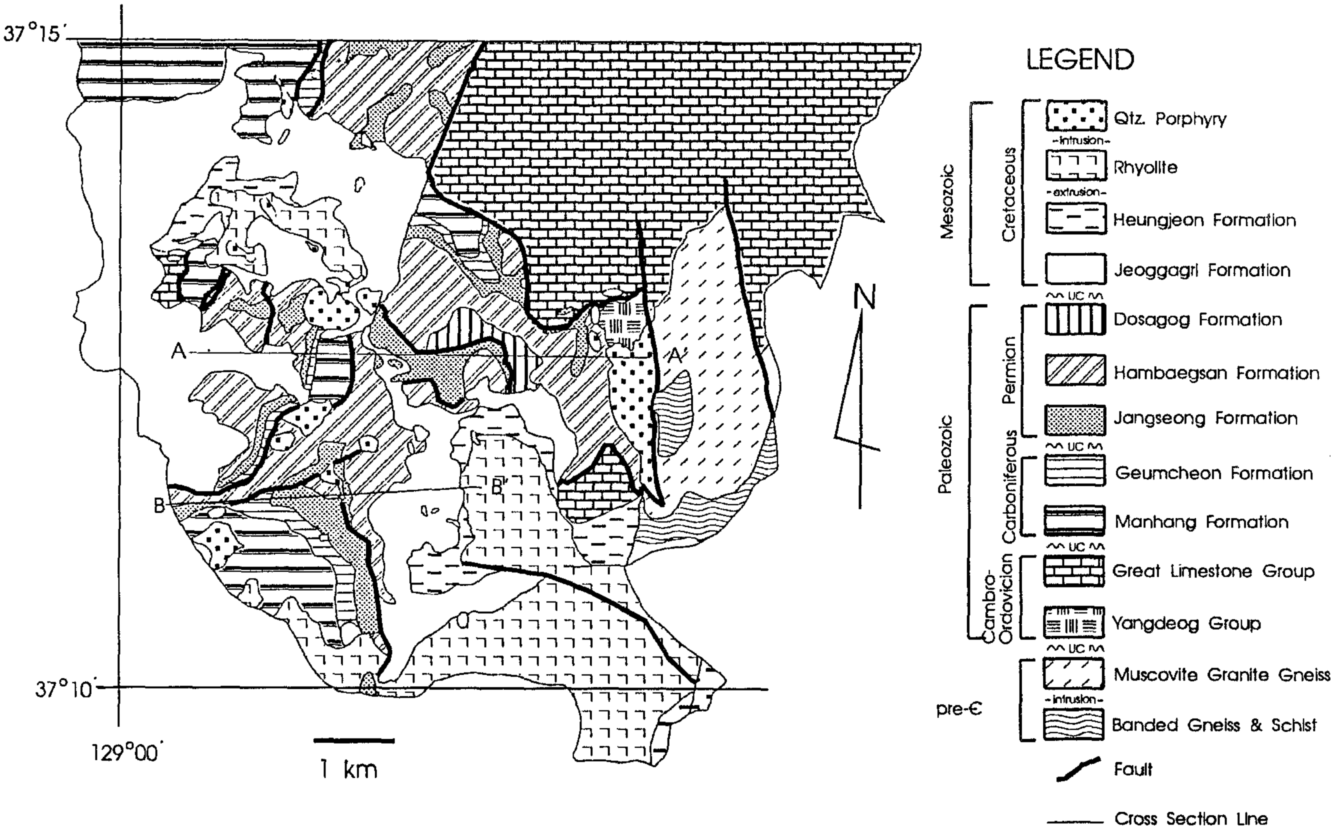


Fig. 3 Geologic map of the Dogyae area

Methods

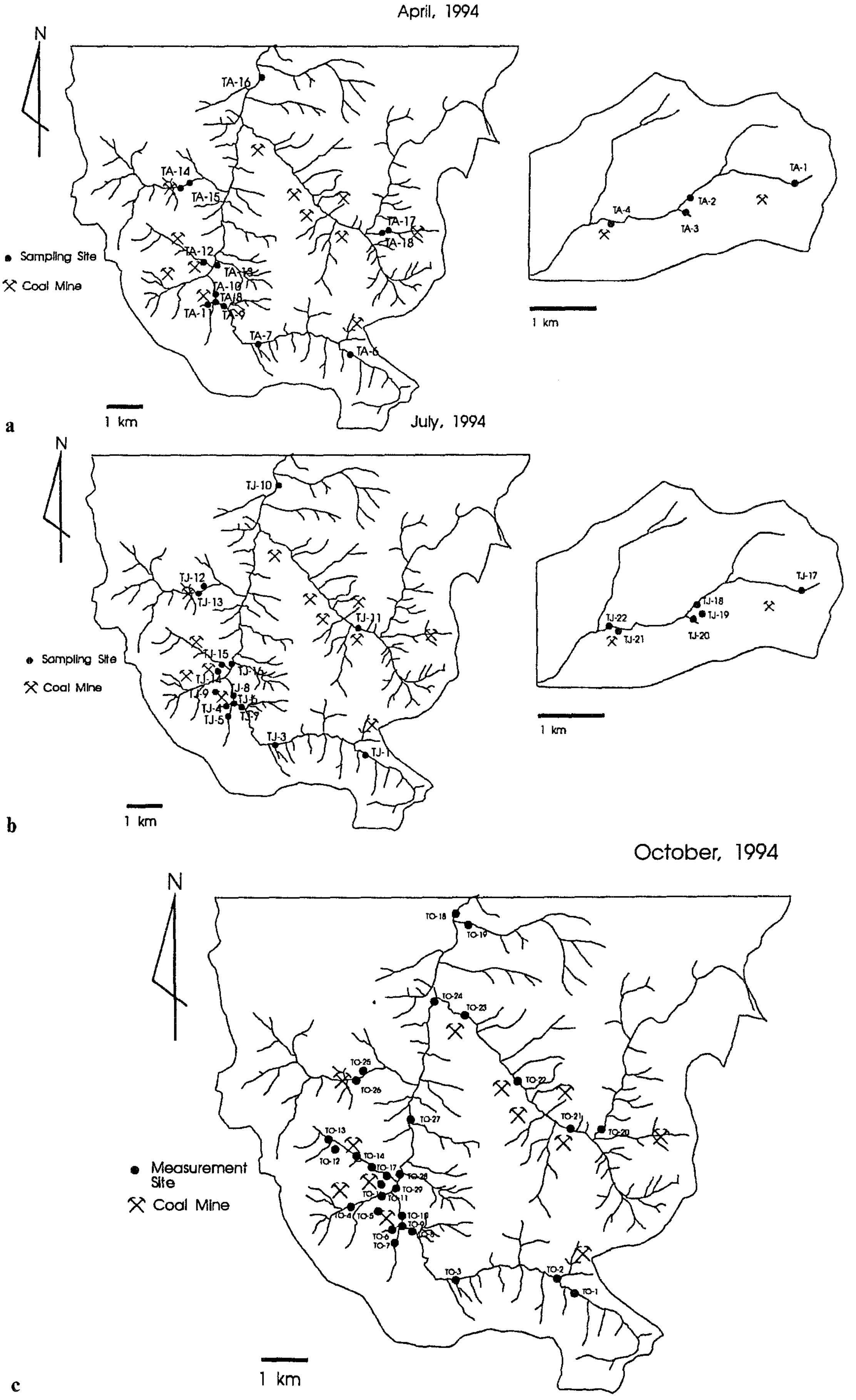
Sample collection and preparation

The water samples of unpolluted and polluted streams as well as coal mine drainage were collected along stream paths in the Dogyae and Doomoondong areas in April and July 1994 (Fig. 4a and 4b). The sample collection in the Doomoondong area, which has bedrock geology very similar to that of the Dogyae area, is done to obtain more unpolluted streamwaters and compare their chemical compositions with those from the Dogyae area. The water samples were divided into two portions: one is filtered only and the other is filtered and acidified. Water sample filtering was performed at each sampling site with a 0.1-μm microporefilter, and acidification was carried out right after the filtering by adding 5 ml 1N HNO_3 to a presoaked 1-l polyethylene bottle (Wood 1976). The filtered samples were used for anionic species analyses, alkalinity and acidity determinations, and SiO_2 analyses. The filtered and acidified water samples were used for the cationic species, including trace element, analyses. All the water samples were stored in a refrigerator at 4°C until later chemical analyses. The precipitate and sediment samples on the bottom of the streams and the typical colliery spoil dump samples were also collected at some of the water sampling sites for their mineral assemblage identification and chemical analyses.

Field measurements and chemical analyses

The pH, Eh, specific conductivity, and temperature of the water were measured in the field right before the streamwater collection in April and July 1994, and then more accurately measured on October 1994 without sampling (Fig. 4c). The acidities and alkalinities of the streamwater samples were determined by titrimetry and the Gran method (APHA and others 1992; Wetzel and Likens 1991). The major cationic constituents of the water and solid (including sediment and colliery-spoil dump) samples were determined with Inductively coupled plasma-atomic emission spectrometer (ICP-AES) and X-Ray fluorescence spectrometer (XRF), respectively. The trace element analyses of all samples were carried out with Inductively coupled plasma-mass spectrometer (ICP-MS). The anionic species in water samples were determined with Ion chromatograph (IC). The mineral compositions of the streambed sediments and colliery spoil dumps were analyzed with X-Ray diffractometer (XRD). All the above chemical analyses, except the analyses with IC, were performed at the Basic Science Research Center at Seoul, Korea. The analyses with XRD and IC were respectively carried out

Fig. 4 Locations of the stream water sampling and field measurement sites: (**a**) April, (**b**) July, and (**c**) October 1994


April, 1994
N
TA-16
TA-14
TA-15
TA-17
TA-18
TA-12
TA-13
TA-10
TA-8
TA-11
TA-9
TA-7
TA-6
● Sampling Site
⚒ Coal Mine
1 km
TA-1
TA-2
TA-3
TA-4
1 km
a
July, 1994
N
TJ-10
TJ-12
TJ-13
TJ-11
TJ-15
TJ-16
TJ-14
TJ-8
TJ-9
TJ-6
TJ-4
TJ-5
TJ-7
TJ-3
TJ-1
● Sampling Site
⚒ Coal Mine
1 km
TJ-17
TJ-18
TJ-19
TJ-20
TJ-22
TJ-21
1 km
b
October, 1994
N
TO-18
TO-19
TO-24
TO-23
TO-25
TO-26
TO-22
TO-27
TO-21
TO-20
TO-13
TO-12
TO-14
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TO-29
TO-11
TO-4
TO-5
TO-10
TO-9
TO-8
TO-6
TO-7
TO-3
TO-2
TO-1
● Measurement Site
⚒ Coal Mine
1 km
c

in the Department of Geology and Department of Chemistry, Kangwon National University.

Results and discussion

Table 1 summarizes the field measurement data for the streams in the study area. The polluted streamwater and coal mine drainage generally show lower pH and Eh and higher conductivity than the unpolluted water. The low pH of the mine drainage has been well recognized as a result of the pyrite oxidation in coal seams and the associated geologic bodies (Sullivan and others 1988b; Powell 1988; Zaihua and others 1991; Uma 1992). The increase of H^+ causes more water–rock interaction and consequently raises the contents of the dissolved species in the water. The high conductivity of the mine drainage indirectly indicates such high contents of the dissolved species. It may be noted that the pH and Eh values of some mine drainages are close to those of unpolluted waters. It indicates that the mine drainage in the study area is often partially neutralized and oxidized after the dissolution of pyrite.

Table 2 compares the major constituent compositions of a typical unpolluted water and a mine drainage sample with that of the world average fresh water (WAF) from Livingstone (1963). Table 2 indicates that the unpolluted water has a similar chemical composition to that of WAF, but the mine drainage has major constituents tens to hundreds of times more concentrated than the unpolluted water. In particular, Fe and SO_4 concentrations are much higher in the mine drainage than in the unpolluted water, which confirms that the oxidation of pyrite plays a principal role in determining the chemical characteristics of the mine drainage. The relatively high content of Ca and Mg in the mine drainage is probably the result of neutralization of the water by carbonate minerals, mainly comprising the intercalated limestone beds in the sedimentary formations. Wiggering (1993) and Webb and Sasowsky (1994) discussed the importance of carbonate minerals in buffering acid mine drainage and controlling its pH.

Table 3 compares the trace element compositions of the unpolluted and mine drainage water with WAF. Again, most of the trace element contents in mine drainage are tens to hundreds of times more concentrated than in the unpolluted water. From comparison of the chemical composition between the unpolluted and mine drainage water, it can be noted that the mine drainage can severely pollute the peripheral streams by inputting Ca, Mg, Fe, Mn, SO_4, and such trace elements as Cd, Co, Cr, Cu, Mo, Ni, Pb, Rb, Sr, U, and Zn. The complete list of the chemical compositions of all the collected water samples is in the Appendix.

Figure 5 schematically shows the variations of SO_4, Fe, and other trace elements in the streamwater along Osheepcheon Creek. The SO_4 content in the streamwater abruptly increases at the influx points of the abandoned coal mine drainage, and then more or less gently decreases but does not reach the local background value as the water moves out of the downstream area. On the other hand, the Fe content in the streamwater also abruptly increases at the influx point of the mine drainage, but quickly decreases to reach the local background value right after the water passes the influx point (Fig. 5a and 5d). The trace elements of relatively low mobility, such as Cr, Cu, Pb and Zn behave similarly to Fe (Fig. 5b and 5e), while those of relatively high mobility such as Rb, Sr, and U follow the pattern as SO_4 (Fig. 5c and 5f). Cd, Co, Mo and Ni, not depicted in Fig. 5, also behave similar to Fe. Figure 5 indicates that, fortunately, most of the toxic heavy metals have relatively low mobilities and are quickly removed with Fe from the water.

Although dilution by the inflow of freshwater from the tributaries contributes to the decrease of the pollutant contents in Osheepcheon Creek, the abrupt decrease of the Fe and other toxic element contents may be a result of their removal through fast precipitation of Fe compounds and the sorption of the toxic metals to the precipitated Fe compounds. The yellow to reddish yellow and sometimes white precipitates are easily observed on the field, especially around the influx points of the abandoned coal mine drainage. The chemical equilibrium analyses of the water samples using MINTEQA2 (Allison and others 1991) suggest that the polluted water is supersaturated with amorphous Fe hydroxide (FeOOH; ferrihydrite), amorphous Al sulfate [$Al_4(OH)_{10}SO_4$], alunite [$KAl_3(SO_4)_2(OH)_6$], diaspore [$AlO(OH)$], gibbsite [$Al(OH)_3$], goethite [α-$FeO(OH)$], hematite (Fe_2O_3), jarosite [$(Na,K,H)Fe_3(SO_4)_2(OH)_6$], maghemite ($\gamma$-$Fe_2O_3$), quartz ($SiO_2$), muscovite [$KAl_2(Al,Si_3)O_{10}(OH)_2$], and other clay minerals, but undersaturated with most of the toxic element compounds. Thus, the fast removal of the toxic elements is certainly not due to the precipitation of their own compounds, but probably due to the sorption of one or more phases listed above. XRD analyses of the yellow and white precipitates show that both of them are amorphous compounds (Fig. 6). The chemical analyses of the precipitates in Table 4 show that the yellow to reddish yellow precipitate (TAS-8) is mainly composed of Fe and the white precipitate (TJS-13) of Al. The results from the XRD, chemical, and equilibrium analyses strongly suggest that the yellow to reddish yellow and white precipitates are, respectively, amorphous Fe hydroxide and amorphous Al sulfate, which is pertinent to other investigators' observations (Anderson and Benjamin 1985; Theobald and others 1963). However, the exact determination of the chemical formulae of the precipitates needs further detailed study. Details of the equilibrium between Al,Fe-compounds and water are discussed in Nordstrom and others (1979), Nordstrom (1982), and Sullivan and others (1988a).

The content of SO_4 in the streamwater seems not to be so significantly affected by the precipitation of Al sulfate as Fe content is the precipitation of Fe hydroxide (Fig. 5a and 5d). The reason for the insignificant effect of Al sulfate precipitation on the variation of SO_4 content in water may be that the amount of Al from the dissolution of the feldspar minerals is much less than the amount of SO_4 from the oxidation of pyrite in the clastic sedimentary rocks.

Table 1 Water quality data of the Osheepcheon Creek measured in April, July, and October 1994

Unpolluted					Polluted					Coal mine drainage				
Sample number	T (°C)	pH	Eh (mV)	K_{25} (µS/cm)	Sample number	T (°C)	pH	Eh (mV)	K_{25} (µS/cm)	Sample number	T (°C)	pH	Eh (mV)	K_{25} (µS/cm)
April, 1994														
TA-1	9.6	7.37	610	71.6	TA-2	14.0	7.69	530	412	TA-4	11.3	3.64	750	926
TA-3	5.7	6.95	560	36.8	TA-8	10.8	7.42	270	818	TA-11	12.5	6.30	300	2190
TA-5	10.1	7.41	580	12.16	TA-9	11.1	8.04	540	317	TA-12	8.8	4.47	650	763
TA-6	7.0	7.35	560	71.8	TA-10	11.4	8.08	420	343	TA-14	15.0	6.61	250	2610
TA-7	12.8	8.32	480	164	TA-13	7.0	7.71	540	645					
					TA-15[a]	8.7	8.89	470	2680					
					TA-16	8.9	7.98	470	1104					
					TA-17	8.1	8.29	520	382					
					TA-18	9.7	8.03	530	451					
Range	5.7–12.8	6.95–8.32	480–610	36.8–121.6		7.0–14.0	7.42–8.29	270–540	317–1104		8.8–15.0	3.64–6.30	250–750	763–2610
Average	9.04	7.48	558	93.16		10.13	7.9	477.5	558.3		11.9	5.26	487.5	1622.3
July, 1994														
TJ-1	20.9	7.18	550	105.7	TJ-5	20.5	8.01	500	449	TJ-4	14.8	6.27	280	1948
TJ-3	22.8	8.08	470	252.0	TJ-6	20.1	6.96	270	1327	TJ-9	15.7	4.65	510	1058
TJ-17	21.7	6.94	270	60.9	TJ-7	25.2	7.78	430	630	TJ-13	22.7	4.63	470	1610
TJ-20	20.3	7.10	520	56.1	TJ-8	25.8	7.81	460	610	TJ-14	13.9	7.08	340	672
					TJ-10	28.1	8.41	470	967	TJ-21	14.6	4.49	600	674
					TJ-11	26.8	8.40	490	337					
					TJ-12[a]	21.6	7.27	370	2000					
					TJ-15	24.3	6.75	390	819					
					TJ-16	23.1	7.52	480	737					
					TJ-18	29.8	4.57	570	684					
					TJ-19	23.1	3.49	740	581					
					TJ-22	27.2	4.33	610	760					
Range	20.3–22.8	6.94–8.08	270–550	56.1–252.2		20.1–29.8	3.49–8.41	270–740	337–1327		13.9–22.7	4.49–7.08	280–600	672–1948
Average	21.43	7.33	452.5	118.68		24.91	6.73	491.8	718.3		16.34	5.42	400	1192.4
October, 1994														
TO-1	10.2	7.32	590	83.7	TO-8	11.6	7.76	430	314	TO-4	12.1	4.99	550	755
TO-2	11.2	7.32	560	130	TO-9	11.8	7.26	250	486	TO-5	13.1	3.37	700	1115
TO-3	10.9	7.48	400	287	TO-10	11.8	7.43	270	369	TO-6	13.3	6.17	330	1394
TO-7	11.6	7.74	390	264	TO-11	12.2	4.93	510	868	TO-12	16.0	3.49	210	884
TO-13	12.2	6.91	550	110	TO-14	13.0	4.16	640	573	TO-16	12.3	6.87	300	699
TO-19	12.6	8.20	480	261	TO-15	12.4	5.87	540	578	TO-26	12.9	4.83	550	835
TO-20	13.0	8.13	470	210	TO-17	12.4	5.92	470	555					
					TO-18	13.5	7.84	480	575					
					TO-21	13.1	7.89	470	239					
					TO-22	13.0	7.85	490	218					
					TO-23	13.3	7.64	490	402					
					TO-24	13.9	7.67	490	710					
					TO-25[a]	18.2	8.69	440	2080					
					TO-27	11.9	7.52	500	398					
					TO-28	11.6	7.23	390	433					
					TO-29	11.3	7.33	320	423					
Range	10.2–13.0	6.91–8.20	390–590	83.7–287		11.3–13.5	4.16–7.89	250–640	218–868		12.1–16.0	3.37–6.87	210–700	699–1394
Average	11.67	7.59	491.4	192.2		12.45	6.95	449.3	476.07		13.28	4.95	431.7	947

[a] Drainage from mine water treatment facility

Table 2 Comparison of major constituents (mg/l) of typical unpolluted and mine drainage water from study area with that of world average freshwater from Livingstone (1963)

Species	WAF[a]	TA-6[b]	TA-14[c]
SiO_2	13.1	15.6	19.1
Al	0.4	0.06	0.16
Fe	0.67	0.05	77.11
Mg	4.1	0.93	248.9
Ca	15.0	7.4	181.7
Na	6.3	2.48	28.00
K	2.3	1.76	15.12
Cl	7.8	5.14	3.42
CO_3	58.4	25.85	59.08
NO_3		12.84	
SO_4	11.2	9.22	1490.8

[a] World average freshwater (Livingstone, 1963)
[b] Unpolluted water
[c] Mine drainage

Table 3 Comparison of trace elements (μg/l) of typical unpolluted and mine drainage water from study area with that of world average freshwater from Livingstone (1963)

Species	WAF	TA-6	TA-14
Cd		0.01	4.94
Co	0.1	0.13	99.56
Cr	1.0	1.67	262.00
Cu	7.0	7.05	171.89
Mo	0.6	0.3	30.71
Ni	0.3	1.31	280.32
Pb	3.0	0.65	33.82
Rb	1.0	6.7	2347.69
Sr	70.0	26.4	9798.57
U	0.04	0.02	5.36
Zn	20.0	23.07	279.42

The pollutant contents, except those of a few highly mobile species, in Osheepcheon Creek are not as high as might be expected; because, as mentioned previously, the precipitation of Fe compounds and the sorption of the toxic metals on the Fe compounds quickly remove the pollutants from water and the fresh tributaries are continuously combined to dilute the polluted water. However, if the influx of the abandoned coal mine drainage continues, the water quality of Osheepcheon Creek will soon deteriorate from the influx points and then to the far downstream areas. Thus, urgently needed are not only the reclamation of already polluted streams but also prevention of further input of the pollutants from abandoned coal mine drainage. During the reclamation and protection of the streams, it is also required to regularly measure the pollution along Osheepcheon Creek to check the water quality of the streams for improvement and possible other influxes of still unrecognized mine drainage.

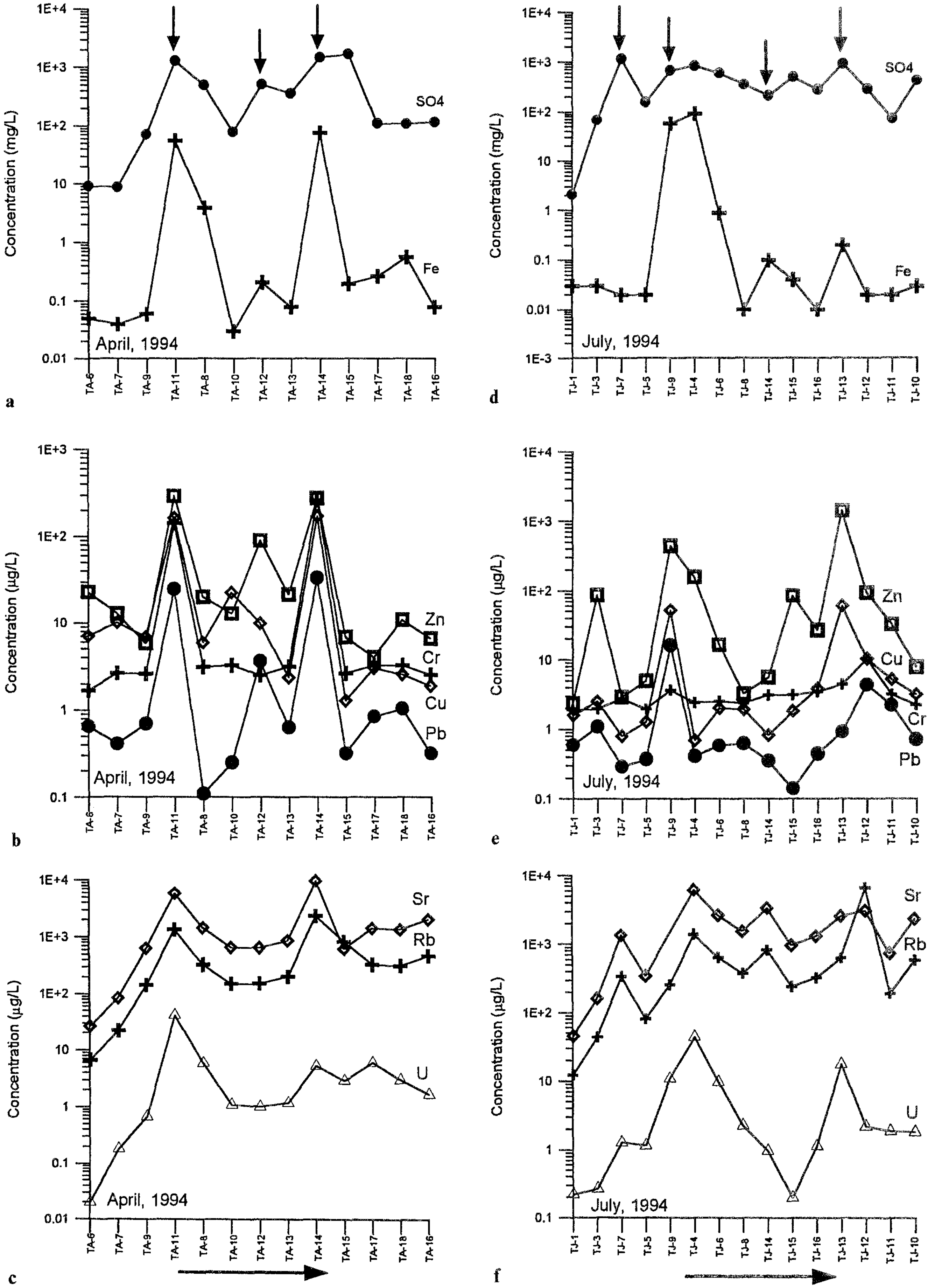
The degrees of pollution of the streams can be represented in several ways. We may directly utilize the concentrations of the pollutants to represent the pollution, but this has a few problems: First, we have to select the pollutants effectively indicating the pollution. If we select an immobile species, its concentration would hardly reflect the actual pollution. Thus, we have to select one or two mobile species, such as SO_4, Rb, or Sr. Secondly, it is very time consuming and expensive to collect water samples and analyze the concentrations of the pollutants in the samples. This problem can be much more serious if we take samples more frequently and cover a relatively large area in detail. Thus, the indicators of the pollution should fulfill the conditions both of effectiveness in pollution indication and convenience in quantity measurement. Such indicators may be pH, Eh, or conductivity, all of which are easy, fast, and inexpensive to measure.

As examined earlier in Table 1, the pollution of streams by abandoned coal mine drainage should be represented not with pH, Eh, or conductivity alone but with a function of their combination. Such functions may be obtained from the statistical discrimination of the severely polluted water samples from unpolluted ones with pH, Eh, and conductivity as variables. The discriminant function analysis requires the samples to be classified first. The classification of the water samples in Table 1 arbitrary and mainly based on field observations and measurements. The water samples can be more objectively classified by cluster analysis with some of the independent compositional variables that may be selected from the R-mode factor analysis of the samples (Davis 1986).

Table 5 shows the factor matrix for the water samples collected in April 1994, obtained by PCA method with Kaiser's varimax rotation. The factor matrix shows that factors I, II, and III are related to the mine drainage and explain more than 70% of the chemical compositional variation among the water samples. Of these factors, pH, Fe, and SO_4 are selected as the independent variables for the cluster analysis. Figures 7 shows the dendrogram resulting from the cluster analysis using the complete linkage method on the basis of Euclidean distance. The dendrogram suggests that TA-1, TA-3, TA-5, and TA-6 are the least polluted and TA-4, TA-11, TA-12, and TA-14 are most polluted, which are pertinent to the field observations. The discrimination function analysis of the two groups gives a canonical discriminant function, $Z = 4.482\,\mathrm{pH} + 20.296\log(\mathrm{Eh}) - 5.973\log(K_{25}) - 69.977$. The scores ($Z$) calculated with the discriminant function for the measured pH, Eh, and conductivity can be utilized to grade the pollution degrees of the streams.

Figure 8 is the stream pollution map of the study area, showing the pollution degrees of the streams in October 1994. The pollution degrees were graded as (1) severely polluted ($Z < -8.0$), (2) highly polluted ($-8.0 \leq Z <$

Fig. 5a–f Variations of the dissolved species concentrations in stream water along Osheepcheon Creek: (**a**) Fe and SO_4 in April, (**b**) relatively immobile trace elements in April, (**c**) relatively mobile trace elements in April, (**d**) Fe and SO_4 in July, (**e**) relatively immobile trace elements in July, and (**f**) relatively mobile trace elements in July 1994. The vertical small arrows represent the influx points of the abandoned coal mine drainage and the horizontal large arrows indicate the direction toward downstream areas


a
1E+4
1E+3
1E+2
10
1
0.1
0.01
Concentration (mg/L)
SO4
Fe
April, 1994
TA-6
TA-7
TA-9
TA-11
TA-8
TA-10
TA-12
TA-13
TA-14
TA-15
TA-17
TA-18
TA-16
d
1E+4
1E+3
1E+2
10
1
0.1
0.01
1E-3
Concentration (mg/L)
SO4
Fe
July, 1994
TJ-1
TJ-3
TJ-7
TJ-5
TJ-9
TJ-4
TJ-6
TJ-8
TJ-14
TJ-15
TJ-16
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TJ-12
TJ-11
TJ-10
b
1E+3
1E+2
10
1
0.1
Concentration (µg/L)
Zn
Cr
Cu
Pb
April, 1994
e
1E+4
1E+3
1E+2
10
1
0.1
Concentration (µg/L)
Zn
Cu
Cr
Pb
July, 1994
c
1E+4
1E+3
1E+2
10
1
0.1
0.01
Concentration (µg/L)
Sr
Rb
U
April, 1994
f
1E+4
1E+3
1E+2
10
1
0.1
Concentration (µg/L)
Sr
Rb
U
July, 1994

-4.0), (3) fairly polluted ($-4.0 \leq Z < 0.0$), (4) moderately polluted ($0.0 \leq Z < 4.0$), (5) slightly polluted ($4.0 \leq Z < 8.0$), and (6) unpolluted ($8.0 \leq Z$) based on the calculated scores with the above discriminant function. Figure 8 indicates that the main pollution sources are located on the west side of the Osheepcheon Creek and the degrees of pollution of most streams, except those very near to the pollution sources, are not as high as expected. The pollution degrees in Figure 8 are consistent with what is suggested by the chemical compositions of the water samples collected in April and July 1994.

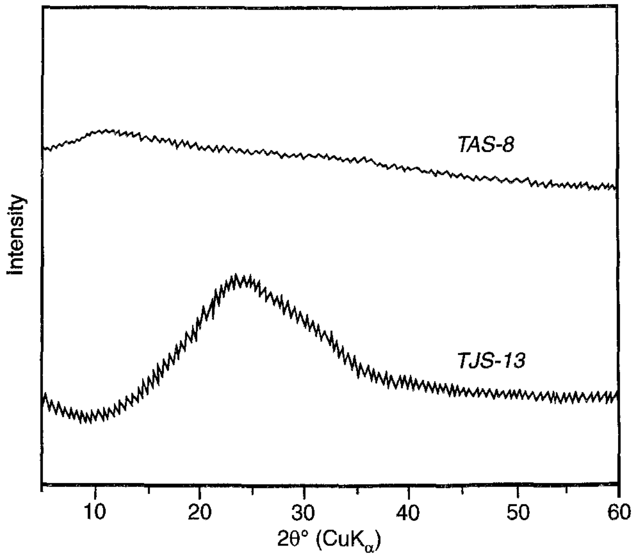


Fig. 6 X-ray diffractogram of the yellow to reddish yellow (TAS-8) and the white (TJS-13) precipitates on the bottom of the stream channel

Table 4 The elemental compositions (wt %) of typical yellowish red (TAS-8) and white (TJS-13) precipitate from study area

	TAS-8[a]	TJS-13
Si	2.43	0.03
Al	1.06	15.51
Fe	55.01	4.76
Mn	0.16	0.02
Ca	1.45	0.31
Mg	0.13	0.30
K	0.04	0.46
Na	0.01	0.08
Cd	0.92×10^{-4}	0.48×10^{-4}
Co	9.83×10^{-3}	3.04×10^{-3}
Cr	1.37×10^{-3}	6.51×10^{-3}
Cu	3.68×10^{-3}	7.51×10^{-4}
Mo	3.60×10^{-4}	5.45×10^{-4}
Ni	1.43×10^{-2}	7.06×10^{-3}
Pb	1.02×10^{-3}	2.05×10^{-3}
Rb	1.09×10^{-2}	6.27×10^{-3}
Sr	4.54×10^{-2}	6.65×10^{-3}
U	1.59×10^{-3}	7.95×10^{-4}
Zn	0.11	2.53×10^{-2}

[a] TAS-8 and TJS-13 were collected at the bottom of the stream channel where TA-8 and TJ-13 were sampled, respectively

The coal mines are densely distributed on both sides of Osheepcheon Creek, but pollutants mainly come out from the west side. The concentration of the pollution source on the west side should be due to other reasons than the simply geological conditions, because the permeability of the geologic formations in the area is generally so poor that groundwater cannot oxidize significant amounts of pyrite and interact enough with the rocks while passing through the grains (D. Cheong, personal communication). Moreover, even if the permeability of the formations is good and the groundwater moves only through the grains or fractures, the groundwater drained into Osheepcheon Creek both from the east and west side must have about the same opportunity to react with the pyrite in Jangseong Formation (Fig. 9). Ahn and others (1990) studied the coal mine discharge in the study area and found that the significant amount of the groundwater from Whangji area, located right beside the west side of the study area (Fig. 2) drains through the mine adits on west side of the Osheepcheon Creek. They suggested that the interconnected mine adits of Dogyae and Whangji areas are the main pathways for the local groundwater, and the groundwater in the higher-level mine adits of Whangji area has to migrate to the lower-level mine adits in the Dogyae area and drains through the openings on the west side of Osheepcheon Creek. The groundwater should have much more opportunity and time to react with pyrite during its migration along the long interconnected mine adits on the west side than along the short separated mine adits on the east side. This is the reason for the concentration of the main pollution sources on the west side of Osheepcheon Creek. To prevent Osheepcheon Creek from being further polluted, the abandoned coal mine drainage from the west side of Osheepcheon Creek should be appropriately treated as soon as possible.

Summary and suggestions

The polluted water of Osheepcheon Creek shows lower pH and Eh, and higher conductivity. The pollution of Osheepcheon Creek is mainly due to the abandoned coal mine drainage, the chemical characteristics of which are mainly determined by the oxidation of the pyrite in Jangseong Formation. Comparing the chemical compositions of the abandoned coal mine drainage and the unpolluted streamwater suggests that the mine drainage can severely pollute Osheepcheon Creek through feeding the pollutants of most major constituents and many toxic trace elements in the peripheral streams. In terms of the field measurement data and inorganic species contents of Osheepcheon Creek, the pollution has not progressed extensively yet, except in those places of mine drainage influx, because of not only the dilution of the pollutants by the joining of fresh tributaries but also the fast removal of

Table 5 Factor matrix for the compositional variables of the water samples collected in the study area

Variable	Factor I	Factor II	Factor III	Factor IV	Factor V	Factor VI
Cr	.98741	.03965	.01743	−.09595	.0288	.07479
Sr	.96187	.10031	−.00426	−.08891	.1961	.07873
Pb	.96059	.02798	.12816	−.09419	.0553	.20067
Fe	.95699	.04028	.15485	−.07519	.0801	.19353
Rb	.91560	.35145	−.02486	−.10806	.1276	.07120
Mo	.88993	.01759	−.06839	−.15271	.2867	.09014
Ni	.86579	.04795	.41276	−.01637	.1091	.23545
Co	.81843	.03831	.51054	.02673	.0896	.16443
Cu	.78324	−.04310	.33366	.22719	−.0658	.40405
Ca	.73403	.51958	.08992	−.07793	.1376	.32222
Li	.67168	.55179	−.02131	−.16559	.2935	.11140
Eh	−.63229	−.15521	.52664	.13956	−.2143	.13995
Na	−.07496	.95854	−.14257	−.05585	.0579	−.09195
CO_3	−.21183	.92116	−.17519	−.09800	−.0191	−.02587
K	.62480	.76072	−.03383	−.02848	.1296	−.05404
SO_4	.60981	.73412	.11470	−.07528	.0098	.17076
K_{25}	.65106	.71416	.10829	−.07637	.0777	.15777
Mg	.68920	.70134	−.03404	−.10365	−.0336	.09374
Al	−.08602	.02571	.96068	.11986	.0613	−.02129
Zn	.34898	.01373	.88151	.17051	.0589	.17112
pH	−.21003	.22652	−.85813	.05894	.2121	−.14657
Cl	−.12607	−.05631	.18697	.86935	.2349	−.20730
As	−.03438	−.16852	.13534	.76549	−.3005	.12406
Se	−.18255	−.22286	−.04997	.70647	−.4919	.26523
SiO_2	.30917	−.37149	.45378	−.47785	.4627	−.11619
Ba	.29610	−.00627	−.00803	−.09616	.8281	.05697
HCO	.08636	.43902	−.47462	−.14470	.6535	.29770
Cd	.54042	−.08692	.02620	.30194	−.0894	.75542
U	.41083	.06339	.27474	−.03281	.3308	.73006
NO_3	−.43054	−.46513	−.01014	.26158	.0386	−.51417
Eigenvalues	14.4222	5.5563	2.8910	2.4153	1.3520	1.1640
% of Var.[a]	48.1	18.5	9.6	8.1	4.5	3.9
Cum. %[b]	48.1	66.6	76.2	84.3	88.8	92.7

[a] % of variation

[b] Cumulative % of variation

most toxic pollutants from water by the sorption on the precipitated amorphous Fe hydroxide.

The pollution of the streams can be effectively estimated with a function of the field measurement data, such as pH, Eh, and conductivity. The method of pollution estimation in this study is easy, fast, and inexpensive and especially useful for the investigation of a large area with relatively frequent measurements of the water quality. The pollution map constructed from the estimated pollution suggests that the pollutants mainly come from the west side of the Osheepcheon Creek. To prevent Osheepcheon Creek from being further polluted, the abandoned coal mine drainage on the west side should be appropriately treated. The Dogyae area is a mountainous region with a temperature range of approximately 20 to −20°C, where a large-scale settling pond or a wetland may not be adequate to treat the mine drainage. Considering the topography, climate, and the amount of mine drainage in the study area, an active treatment method rather than a passive one may be appropriate for the reclamation of the mine drainage. The facilities for the active treatment of the mine drainage should be built on at least two separate places near the main pollution sources labeled A and B in Fig. 8.

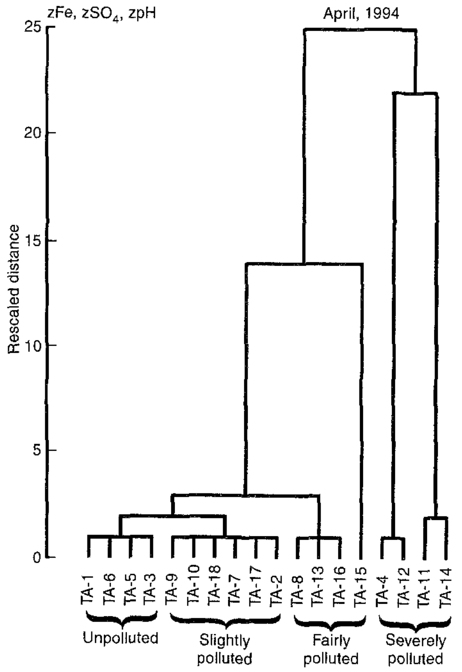


Fig. 7 Dendrogram from the cluster analysis with the standardized pH, Fe, and SO_4 contents in the water samples

Fig. 8 Pollution map of the streams in the Dogyae area, constructed from the estimated pollution degrees based on the calculated scores with the discriminant function. The darker circles represent the more polluted water

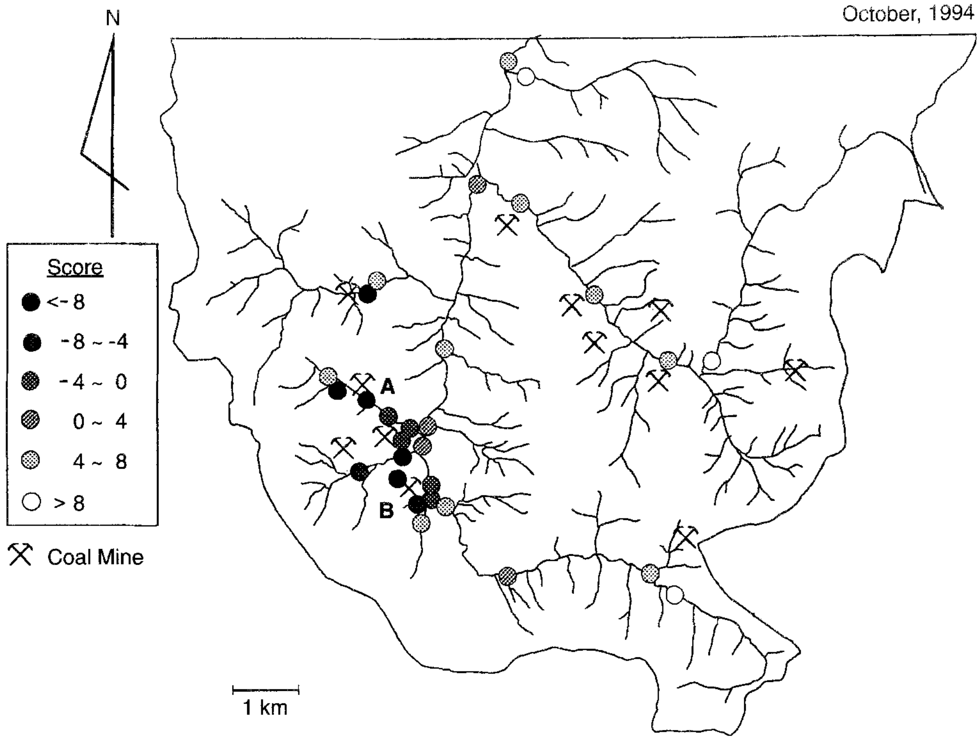
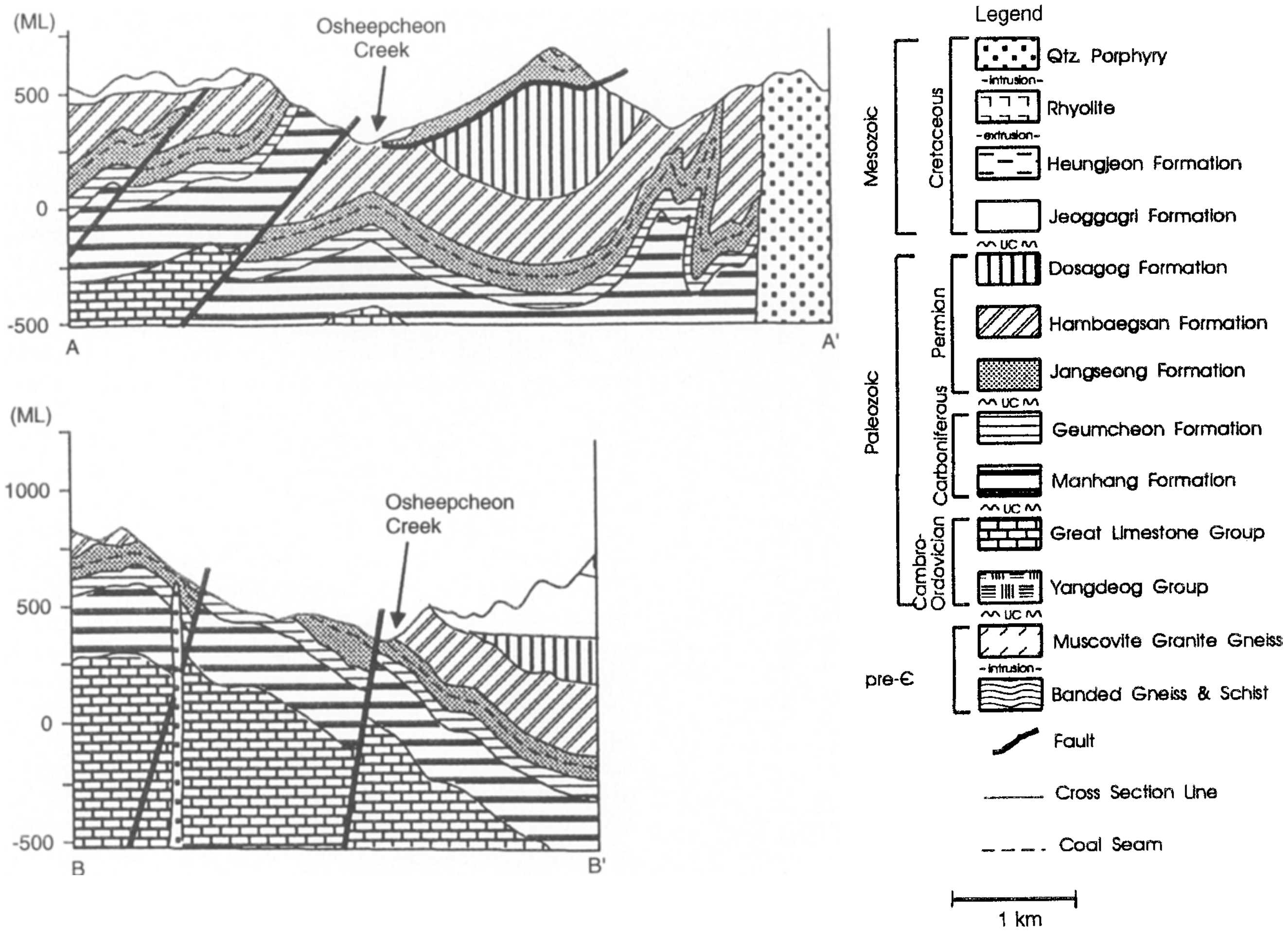


Fig. 9 Geological cross sections along A–A′ and B–B′ in Fig. 3



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Appendix: Chemical compositions of water samples collected in April and July 1994 from Dogyae and Doomoondong

Table A1 Major species concentrations (mg/l) in water samples

Sample	SiO_2	Al	Fe	Ca	Mg	K	Na	SO_4	NO_3	HCO_3[a]	CO_3[a]	Cl	Acid.[b]	Alk.[c]	Hard.[d]
TA-1	3.84	0.09	0.04	7.11	1.58	1.59	1.42	3.12	3.43	16.54	0.04	7.80	13.90	13.60	24.26
TA-2	11.63	0.17	0.02	35.47	10.95	3.68	6.59	136.56	12.22	37.13	0.21	9.46	2.40	30.60	133.66
TA-3	9.63	0.07	0.02	4.04	0.54	1.45	1.20	4.93	12.67	8.28	0.01	2.63	15.20	4.25	12.31
TA-4	19.90	15.14	14.92	59.04	18.88	4.17	7.85	496.90	7.32			8.11	363.00		225.17
TA-5	13.79	0.08	0.08	14.76	1.47	1.68	2.31	7.24	3.76	56.88	0.17	2.77	77.00	45.75	42.91
TA-6	15.58	0.06	0.05	7.40	0.93	1.76	2.48	9.22	12.84	25.85	0.07	5.14	36.50	17.00	22.31
TA-7	18.32	0.03	0.04	13.54	2.82	2.42	6.73	8.96	8.20	53.78	1.27	4.73	18.20	45.05	45.42
TA-8	9.93	0.06	3.92	78.83	45.40	3.97	3.91	495.18	5.19	108.60	0.32	4.41	56.50	54.06	383.80
TA-9	15.91	0.08	0.06	24.47	13.04	3.78	15.87	71.88	7.11	87.18	1.08	4.44	10.25	72.25	114.80
TA-10	14.80	0.10	0.03	26.83	14.44	3.67	13.84	79.34	7.69	82.99	1.13	4.48	41.15	68.85	126.46
TA-11	17.66	0.18	55.94	205.69	162.68	8.63	4.30	1303.7		139.97	0.03	3.62	193.25	114.75	1183.5
TA-12	16.83	2.01	0.21	51.83	46.31	3.17	4.05	517.73	2.74	2.07		2.42	58.80	0.85	320.12
TA-13	13.67	0.12	0.08	46.19	40.25	4.17	12.99	361.23	6.28	79.43	0.46	4.49	47.30	48.13	281.09
TA-14	19.10	0.16	77.11	181.69	248.89	15.12	28.00	1490.8		59.08	0.03	3.42	185.30	48.85	1478.6
TA-15	5.50	0.05	0.20	142.04	238.69	15.08	175.70	1695.6		122.30	10.71	3.15	76.30	107.95	1337.6
TA-16	10.37	0.05	0.08	72.19	76.11	8.34	43.98	686.79	9.00	118.13	1.27	9.96	1.25	97.75	493.68
TA-17	17.44	0.10	0.27	26.54	7.45	3.51	36.96	69.08	6.01	112.92	2.48	4.29	87.15	94.35	101.07
TA-18	16.80	0.16	0.57	27.11	12.02	4.79	42.73	111.83	4.30	110.81	1.34	4.08	64.95	91.80	117.19
TJ-1	4.32	0.04	0.03	18.73	1.38	1.47	3.33	2.10	2.40	54.81		0.08	7.50	45.00	52.45
T1-3	2.62	0.04	0.03	44.85	5.59	2.52	7.79	67.30	5.05	97.64	1.10	2.06	2.50	81.00	135.01
TJ-4	5.01	0.03	91.37	8.14	171.63	7.16	4.60	830.79		117.10		1.20	55.00	96.00	727.10
TJ-5	3.11		0.02	77.46	12.67	1.86	3.50	156.31	6.77	125.01	1.20	1.73	5.00	103.50	245.59
TJ-6	3.36		0.89	202.50	78.97	0.44	3.94	599.54	4.70	117.01	0.10	1.41	7.50	96.00	830.84
TJ-7	3.99	0.04	0.02	75.08	24.12	3.57	19.51	1147.9		129.16	0.73	1.80	2.50	106.50	286.80
TJ-8	3.71	0.07	0.01	88.14	30.05	3.75	19.22	353.08	4.63	89.10	0.77	1.80	2.50	105.00	343.83
TJ-9	9.89	14.06	57.56	141.39	42.12	2.52	2.70	675.40				0.70	177.50		526.50
TJ-10	2.09	0.60	0.03	123.56	69.88	5.99	27.18	425.90	6.02	103.48	2.50	4.53		87.00	596.30
TJ-11	3.61	0.13	0.02	45.06	9.29	3.44	24.27	72.50	4.30	105.33	2.49	1.91		88.50	150.77
TJ-12	2.63	0.06	0.02	32.21	25.65	1.88	50.92	284.69		127.86	0.22	0.94	12.50	105.00	186.06
TJ-13	5.60	24.03	0.20	117.94	172.37	4.02	28.63	915.80	3.72			1.31	132.50		1004.3
TJ-14	4.62	0.10	0.10	106.10	38.11	3.29	5.05	212.10	183.23	159.02	0.18	0.60	10.00	130.50	421.87
TJ-15	5.51	0.05	0.04	102.21	59.06	2.30	3.85	495.00	2.29	14.63		0.85	2.50	12.00	498.43
TJ-16	3.75	0.13	0.01	13.07	49.73	3.54	13.05	278.99	5.05	74.78	0.23	2.87	2.50	61.50	237.42
TJ-17	1.55	0.01	0.02	9.35	1.82	0.17	1.52	3.86	4.97	25.59		0.29	2.50	21.00	30.84
TJ-18	5.74	13.98	1.82	82.66	22.46	0.03	5.60	413.20	8.70			3.47	75.00		298.89
TJ-19	4.47	8.98	8.87	29.77	9.78	1.34	1.28	204.96	3.63			1.05	105.00		114.61
TJ-20	2.27	0.04	0.02	7.76	0.98	0.14	2.22	5.56	7.00	20.10	0.02	1.20	2.50	16.50	23.41
TJ-21	5.56	5.53	0.28	96.00	18.11	2.87	8.90	365.50	7.47			2.86	35.00		314.29
TJ-22	7.56	29.65	0.28	86.05	26.54	0.33	5.45	459.76	6.65			2.52	170.00		324.16

[a] Calculated from the measured alkalinity.

[b] Acid. acidity as mg $CaCO_3$/l, measured with titrimetry.

[c] Alk. alkalinity as mg $CaCO_3$/l, measured with the Gran method.

[d] Hard. hardness as mg $CaCO_3$/l, calculated from the concentrations of Ca and Mg.

Table A2 Trace element concentrations (μg/l) in water samples

Sample no.	Cd	Co	Cr	Cu	Mo	Ni	Pb	Rb	Sr	U	Zn
TA-1	9.17	0.48	2.67	107.27	0.63	2.35	1.10	9.25	29.02	0.01	104.88
TA-2	0.86	26.10	1.70	10.21	0.58	42.10	0.60	60.40	257.83	0.23	49.67
TA-3	1.04	0.47	3.94	8.34	0.62	1.44	0.21	8.54	29.92	0.02	6.58
TA-4	1.65	71.00	6.18	106.85	0.34	156.33	4.60	174.04	724.24	13.22	743.91
TA-5	0.22	0.16	1.67	4.18	0.80	1.13	0.29	12.43	46.94	0.11	2.97
TA-6	0.01	0.13	1.67	7.05	0.30	1.31	0.65	6.70	26.40	0.02	23.07
TA-7	0.41	0.10	2.68	10.21	1.24	1.49	0.41	22.07	84.23	0.18	12.97
TA-8	0.60	18.93	3.15	5.96	0.23	24.09	0.11	330.63	1445.01	5.94	20.31
TA-9	0.48	0.41	2.64	6.90	2.97	3.97	0.70	143.98	635.03	0.67	5.86
TA-10	0.32	1.14	3.28	22.84	1.75	5.03	0.25	151.34	656.82	1.09	13.02
TA-11	13.59	79.31	141.22	164.43	17.94	250.26	24.99	1349.81	5836.29	41.68	293.43
TA-12	0.78	22.93	2.54	9.95	0.04	51.50	3.66	153.36	650.71	1.01	90.33
TA-13	0.58	12.91	3.17	2.39	1.27	22.17	0.64	202.81	863.85	1.19	21.77
TA-14	4.94	99.55	262.00	171.89	30.71	280.32	33.82	2347.69	9798.57	5.36	279.42
TA-15	0.14	3.08	2.67	1.29	0.61	10.21	0.32	830.44	621.04	2.94	6.95
TA-16	0.10	2.30	2.58	1.92	1.26	10.56	0.48	467.23	2029.23	1.68	6.68
TA-17	0.10	1.26	3.28	3.07	9.99	7.32	0.85	328.98	1420.92	6.05	4.08
TA-18	0.29	3.50	3.30	2.60	10.94	9.98	1.05	313.79	1345.76	3.04	10.98
TJ-1	0.11	0.36	1.91	1.59	1.05	1.81	0.59	12.26	45.27	0.22	2.35
TJ-3	0.36	0.36	1.97	2.51	1.00	3.10	1.09	43.70	162.26	0.27	87.07
TJ-4	0.21	85.82	2.42	0.69	0.93	0.41	0.41	1395.06	6201.44	44.27	158.53
TJ-5	0.27	0.83	1.96	1.28	0.59	0.37	0.37	81.50	345.77	1.17	5.01
TJ-6	0.10	36.24	2.53	2.02	0.68	0.58	0.58	646.52	2643.00	9.81	16.51
TJ-7	0.02	0.68	2.76	0.80	3.91	0.29	0.29	339.90	1346.98	1.29	2.94
TJ-8	0.02	2.69	2.38	1.94	2.29	0.62	0.62	378.22	1544.54	2.28	3.24
TJ-9	0.38	198.56	3.64	51.77	0.61	16.18	16.18	256.91	19.06	10.99	442.01
TJ-10	0.02	5.45	2.25	3.18	1.07	0.71	0.71	591.74	2344.48	1.86	7.91
TJ-11	0.12	0.56	3.16	5.22	2.64	2.21	2.21	192.08	734.76	1.91	32.64
TJ-12	0.26	153.64	10.37	10.37	1.23	4.36	4.36	6682.95	3071.61	2.21	93.94
TJ-13	1.77	480.35	4.43	60.13	0.48	0.92	0.92	632.46	2569.76	17.82	1420.51
TJ-14	0.02	5.47	3.12	0.82	1.87	0.35	0.35	826.35	3370.31	0.98	5.66
TJ-15	0.52	35.55	3.12	1.84	0.08	0.14	0.14	241.26	966.37	0.20	85.25
TJ-16	0.21	28.67	3.45	3.83	1.87	0.44	0.44	324.97	1306.84	1.15	26.69
TJ-17	0.20	0.55	3.53	3.89	0.82	0.39	0.39	9.85	36.79	0.02	3.61
TJ-18	1.74	169.05	2.83	112.55	0.15	7.11	7.11	129.59	524.90	9.75	752.93
TJ-19	0.83	104.19	7.45	115.47	0.07	3.60	3.60	123.61	513.02	5.71	483.64
TJ-20	0.11	0.12	2.76	3.33	0.01	0.44	0.44	11.51	45.41	0.02	1.80
TJ-21	0.67	62.98	4.05	36.95	0.07	1.86	1.86	225.59	882.27	3.69	618.42
TJ-22	1.06	235.24	5.06	166.04	0.21	8.19	8.19	175.87	672.04	15.15	189.59

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