TAO, Vol. 16, No. 4, 745-762, October 2005

Hydrochemical Changes in Spring Waters in Taiwan: Implications for Evaluating Sites for Earthquake Precursory Monitoring

Sheng-Rong Song[1,*], Yaw-Lin Chen[1], Chia-Mei Liu[1], Wei-Yi Ku[1], Huei-Fen Chen[1], Ya-Jiun Liu[1], Li-Wei Kuo[1], Tsanyao Frank Yang[1], Cheng-Hong Chen[1], Tsung-Kwei Liu[1] and Ming Lee[2]

(Manuscript received 16 January 2005, in final form 21 July 2005)

ABSTRACT

To evaluate potential monitoring sites as well as useful ions which are capable of serving as earthquake precursors, ten subsurface water bodies in different tectonic domains in southwestern, northern and northeastern Taiwan were selected. They included the deep circulation of hot springs, shallower artesian springs and groundwater. Most of the hot springs clearly show chemical anomalies which correlate with earthquake events during the monitoring periods. Against this, the groundwater does not correspond to any events. Hot springs from deeper reservoirs are superior to artesian springs and groundwater from shallower reservoirs. The artesian spring from the smaller subsurface water body is superior to the groundwater from larger reservoirs. Aside from this, anions, especially chloride, outperform cations as geochemical precursors for earthquake monitoring. It is unambiguous that the major factors that determine the usefulness of chemical anomalies in the waters for earthquake precursory monitoring are the kinds, the depths and the size of reservoirs and the ion species of the subsurface water bodies.

(Key words: Earthquake precursory, Taiwan, Hydrochemistry, Hot spring, Artesian spring)

1. INTRODUCTION

Besides being the most unpredictable events known to mankind, earthquakes are undeniably the most destructive hazards in nature. Identifying useful short-term precursors of

[1] Department of Geosciences, National Taiwan University, Taipei, Taiwan, ROC
[2] Central Geological Survey, MOEA
[*] *Corresponding author address:* Dr. Sheng-Rong Song, Department of Geosciences, National Taiwan University, Taipei, Taiwan, ROC; E-mail: srsong@ntu.edu.tw

earthquakes, therefore, has long been a major goal of geoscientists. In the past, substantive evidence in support of many diverse kinds of precursors, including hydrological and chemical changes in subsurface fluids prior to or at the same time as a large earthquake, has been found. Among these are valuable, insightful precursory changes in gases involved in both hydrothermal processes, like Rn, He, CO_2, CH_4, H_2, Ar and N_2, and in water chemistry, like Cl^-, F^-, NO_3^- and SO_4^{2-} (Hauksson 1981; King 1986; Tsunogai and Wakita 1995, 1996; Sugisaki et al. 1996; Toutain et al. 1997; Chyi et al. 2005; Italiano et al. 2005; Ramirez-Guzman et al. 2005; Walia et al. 2005; Yang et al. 2005). Such geochemical anomalies are generally associated with changes in a subsurface water circulating system in the process of earthquake generation (Thomas 1988; Rojstaczer and Wolf 1992; Muir-Wood and King 1993; Rojstaczer et al. 1995; Sugisaki et al. 1996). In a broad sense, in countries with high seismicity, to monitor data on cations, anions and transitional metals in groundwater is to frequently obtain highly constructive information for earthquake prediction (Barsukov et al. 1984/1985; Guiru et al. 1984/1985; Koizumi et al. 1985; Tsunogai and Wakita 1995, 1996; Toutain et al. 1997; Satake et al. 2002; Song et al. 2003, 2005; Claesson et al. 2004). Such solid evidence notwithstanding, it is not always the rule that chemical anomalies are sensitive enough to serve as earthquake precursors at monitoring sites. What is necessary to bear in mind, therefore, is that the choice of the best working sites and the most useful ions underpins the effectiveness of earthquake precursory monitoring.

The highly destructive 1999 Chi-Chi earthquake (magnitude M_L = 7.3) with surface ruptures totaling about 80 - 90 km in length along the Chelungpu fault and with the largest measured vertical offsets extending as long as 5 - 8 m occurred near the town of Chi-Chi in Nantou County in west-central Taiwan. The epicenter was located about 15 km east of the surface trace of the thrust fault at 120.82°E and 23.85°N, while the hypocenter depth was roughly 12 km (Chung and Shin 1999; Kao and Chen 2000). One of the largest inland events in the past century in Taiwan, the Chi-Chi earthquake caused the death of some 2400, injured another 10000 and destroyed more than 100000 buildings.

After the Chi-Chi earthquake, a large-scale research program to monitor active faults and identify earthquake precursors was jointly initiated in 2000 by the Central Geological Survey, the MOEA-ROC and the Institute of Geosciences, National Taiwan University. In one subprogram, over the past five years, weekly measurements of cation and anion concentrations were made in both hot and artesian springs and groundwater in Taiwan in an effort to both establish background concentrations and identify earthquake-related anomalies. The purpose was to evaluate potential sites that would be the most valuable for setting up regular monitoring systems in the future. This paper presents the results from the 5-year evaluation of potential sites with hot and artesian springs and groundwater wells in southwestern, northern and northeastern Taiwan. It also suggests guidelines as to the best way to choose such monitoring sites.

2. SAMPLING AND ANALYSES

To evaluate the potential of chemical ions and subsurface water bodies to serve as earthquake precursors, nine sites with ten hot and artesian springs and groundwater with different depths in southwestern, northern and northeastern Taiwan (Fig. 1) had been selected for regular sampling on the basis of their geological conditions, the water species and their accessibility for long-term sampling. These sites are in locations with different geological and structural conditions, namely, the Pre-Miocene metamorphic terrain, i.e., the Yuanshan hot spring; the Miocene sedimentary formations in the Western Foothills, i.e., the Kuantzeling hot and artesian springs, the two deep wells at Chingshan and the Tapu hot springs; and the recent fluvial deposits, i.e., the Meinong, Tashu, Chaochou and Yuanshan groundwater. Sampling was done once every three days for the duration of at least one year, thereby covering different seasons, including the dry and rainy ones (Table 1).

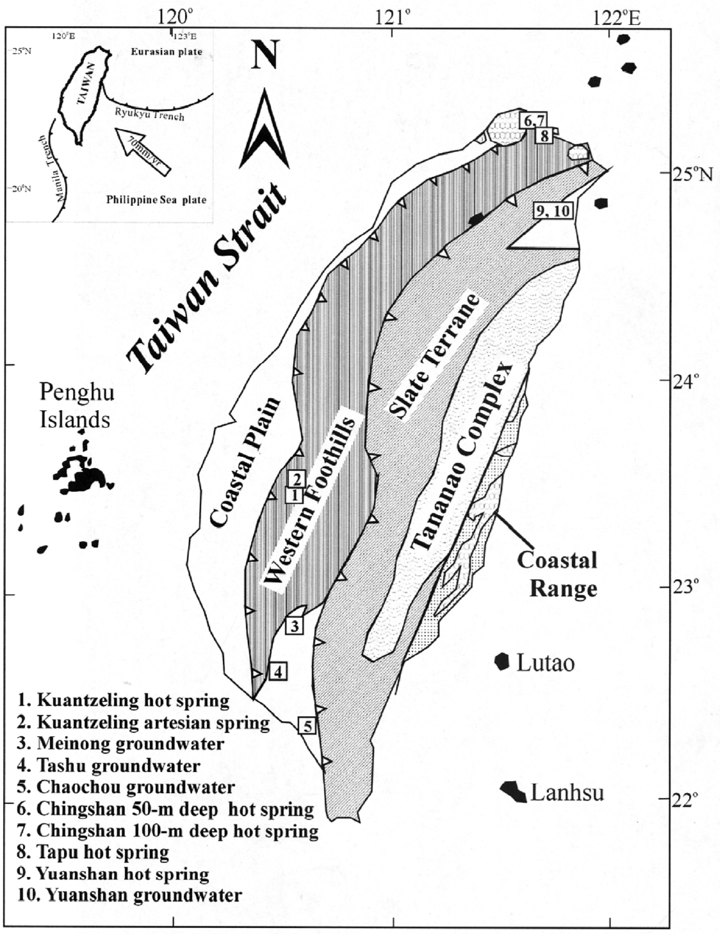

Fig. 1. Geological map of Taiwan with the locations of the monitoring sites marked 1 - 10. Inset map shows the tectonics in the vicinity of Taiwan (modified from Ho 1986).

Table 1. Monitoring period, sampling interval, numbers of sample and correlated to earthquake events of ten monitoring sites.

Site	Monitoring period	Sampling interval	Number of samples	Earthquake events of M_L*				
				Date	Longitude (E)	Latitude (N)	Magnitude	Intensity
Kuantzeling hot spring	1999/07/15~ 2001/08/01	3 days	210	1999/09/21	120.85 °	23.61 °	7.3	5
				1999/10/22	120.40 °	23.51 °	6.4	6
				1999/11/15	120.51 °	23.49 °	5.2	5
				2000/04/12	120.54 °	23.50 °	4.1	4
				2000/06/11	121.11 °	23.89 °	6.7	5
				2000/11/01	120.49 °	23.43 °	4.1	4
				2001/02/09	120.63 °	23.42 °	4.9	4
				2001/04/24	120.46 °	23.46 °	4.0	4
Chingshan-50 m hot spring	2002/01/11~ 2003/10/23	3 days	174	2003/09/07	122.82 °	24.56°	4.3	2
				2003/10/09	121.96 °	24.04 °	4.6	3
Chingshan-100 m hot spring	2002/01/11~ 2003/10/23	3 days	174	2002/09/08	121.68 °	24.45 °	5.7	3
				2002/10/18	121.76 °	24.24 °	4.9	4
				2002/11/02	121.92 °	24.42 °	4.7	3
				2002/12/17	121.89 °	24.45 °	3.9	4
				2003/04/02	121.79 °	24.30 °	4.1	3
Tapu hot spring	2002/01/11~ 2003/10/23	3 days	207	2002/12/17	121.89 °	24.45 °	3.9	4
Yuanshan hot spring	2003/03/01~ 2003/10/20	3 days	77	2003/05/26	121.69°	24.70 °	4.9	2
				2003/10/01	121.77°	24.47 °	3.4	3
Kuantzeling artesian spring	2000/01/07~ 2001/08/29	3 days	174	2000/04/12	120.54 °	23.50 °	4.1	4
				2000/06/11	121.11 °	23.89 °	6.7	5
				2000/07/16	122.29°	20.16 °	7.0	2
Meinong groundwater	2000/01/05~ 2001/01/18	3 days	69	--	--	--	--	--
Tashu groundwater	1999/11/26~ 2001/01/04	3 days	63	--	--	--	--	--
Chaochou groundwater	2000/01/08~ 2001/01/17	3 days	104	--	--	--	--	--
Yuanshan groundwater	2003/02/27~ 2003/10/20	3 days	85	--	--	--	--	--

*: Data from the Central Weather Bureau of Taiwan (CWBT) (2004).
--: non-correlated earthquake events.

Dissolved anions (F^-, Cl^-, Br^-, NO_3^-, PO_4^{3-}, SO_4^{2-}) and cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Si^{4+}) were measured with an ion chromatographer (IC, Type Dionex DX-100) and an inductively coupled plasma-atomic emission spectrometer (ICP-AES, Type Jobin-Yvon JY-38plus), respectively. Samples from the same spring were measured in duplicate to confirm the precision of the measurements. Analytical uncertainties in the absolute concentrations were less than 3% for all of the anions and less than 5% for all of the cations.

3. TEMPORAL VARIATIONS IN THE CHEMICAL COMPOSITION

3.1 Hot springs

Four sites which comprised five hot springs were chosen for regular sampling for earthquake precursory monitoring. They are the Kuantzeling hot spring in the SW Taiwan, the two deep wells at the Chingshan hot spring with the depth of 50 and 100 m and the 40-m deep well at the Tapu hot spring in the N Taiwan, and the Yuanshan hot spring in the NE Taiwan. The sampling periods roughly spanned from one to two years.

The temporal variations for the Cl^- and SO_4^{2-} concentrations of the water samples in these five hot springs are shown in Figs. 2 - 6, respectively. The average concentration and the two-sigma relative standard deviations (2σ) were calculated for each of the samples from the hot springs and are also plotted in the same figures and listed in Table 2. The 2σ domains can be considered representative of the background values of the hot spring waters, values which may have resulted from water-rock interactions in the deep circulation of the subsurface reservoirs, from sampling heterogeneity or from analytical uncertainties. Values higher than 2σ, thus identified as anomalies, occurred during the sampling periods. Except for the chloride and sulfate ions, all of the cations and anions in these five hot springs varied within the 2σ domains during the entire sampling period.

The chloride ion is the major anion in the Kuantzeling hot spring, with its average concentration reaching 2201 ± 264 ppm. The average concentration of the sulfate ion is 33.6 ± 12.4 ppm. The two-sigma relative standard deviation (2σ) of the two ions is 30.9% (Cl^-) and 18.0% (SO_4^{2-}). Except for a few periods, the concentration of chloride in the different samples is, by and large, almost always constant, unlike that for sulfates, which has greater fluctuations particularly in two periods, i.e., from March 2000 to June 2000 and from December 2000 to February 2001 (Figs. 2A, B). Chloride anomalies occur around September 20, October 1 and

Table 2. The average concentrations (ppm) of anions and cations of subsurface waters from ten monitoring sites.

Site	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	Si^{4+}
Kuantzeling hot spring	2201±264	8.16±2.96	33.6±12.4	5302±766	146.0±88.4	bdl	7.16±4.36	16.3±12.6
Chingshan-50 m hot spring	618.0±28.4	bdl	186.0±19.8	191.0±17.2	46.7±7.1	192.0±21.0	bdl	35.4±4.8
Chingshan-100 m hot spring	304.0±99.8	bdl	71.1±19.1	146.0±34.0	46.4±6.7	80.0±28. 6	bdl	34.5±11.0
Tapu hot spring	6048±1656	bdl	2471±512	2249±332	285.0±16.4	305.0±14.4	255.0±31.6	101.0±10.4
Yuanshan hot spring	56.0±17.3	bdl	6.95±1.25	165.0±10.0	bdl	25.4±5.2	bdl	14.8±1.4
Kuantzeling artesian spring	2.70±0.82	bdl	25.4±4.5	11.6±8.7	bdl	107.0±58.8	50.6±15.9	7.26±4.60
Meinong groundwater	11.4±1.8	14.80±4.66	80.8±17.3	43.0±9.1	bdl	81.6±11.5	25.4±2.8	3.53±0.47
Tashu groundwater	13.6±2.5	bdl	58.5±10.1	28.7±3.1	bdl	37.4±4.0	36.2±3.2	4.43±0.79
Chaochou groundwater	2.80±0.60	15.70±3.76	48.9±4.1	12.3±2.7	bdl	63.6±2.5	14.2±0.7	3.10±0.19
Yuanshan groundwater	3.73±2.66	bdl	16.0±2.7	5.06±1.09	bdl	bdl	bdl	7.53±0.90

bdl: Below the detection limits.

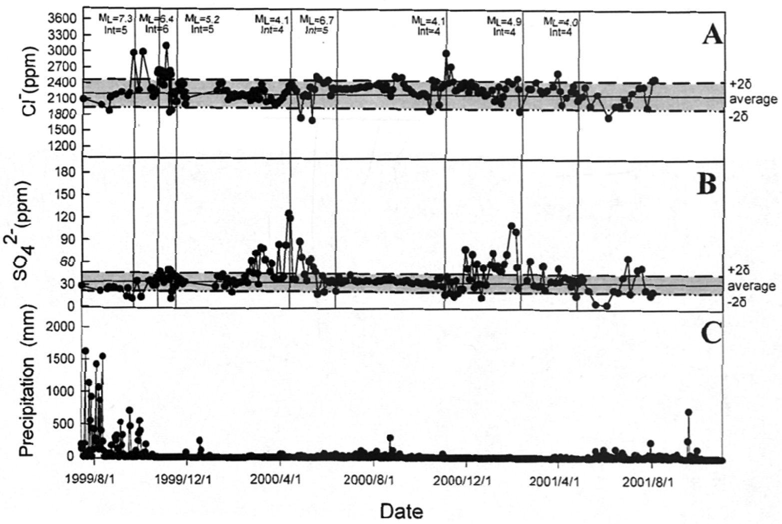

Fig. 2. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Kuantzeling hot spring. The vertical lines represent chemical anomalies which correlate with earthquake events that occurred in this area. (C) Daily precipitation obtained in the Kuantzeling rain gauge station (data from the CWBT).

October 21 of 1999; April 25 and November 1 of 2000; and February 23 of 2001, and the duration of the anomalies range from a few to over twenty days. As for the sulfate concentration, two major anomalous events are detected around April 1, 2000 and January 27, 2001, and the duration is from just a few days to up to one month. Based on the date of earthquake occurred and intensity recorded in the seismic station near the monitoring site, those chemical anomalous events can be well correlated to the earthquakes (Figs. 2A, B). The epicenters of the earthquakes having probably induced the chemical anomalies were predominantly located in central Taiwan which is very near the monitoring site (Fig. 7). Furthermore, the Kuantzeling hot spring has recorded the chemical anomaly to respond the event of Chi-Chi earthquake and we have reported it in another paper (Song et al. 2005).

The chloride ion is also the major anion in both the 50-m and the 100-m deep Chingshan hot springs, and the respective average concentration at these sites reaches 618.0 ± 28.4 ppm and 304.0 ± 99.8 ppm; contrast this with the respective average concentration of the sulfate ion which is 186.0 ± 19.8 ppm and 71.1 ± 19.1 ppm. The two-sigma relative standard deviation (2σ) in these two hot springs is respectively 4.6% and 32.8% for Cl^-, and 26.9% and 10.6% for SO_4^{2-}. For the most part, the concentration of chloride and sulfate in each of these samples was almost constant, except during a few periods (Figs. 3A, B and 4A, B). The chloride anomalies occur around September 9, October 15, November 1 and December 9 of 2002, and March 28 and October 4 of 2003, while the sulfate anomalies occur around December 9 of 2002, and April 14, September 5 and October 4 of 2003, and these anomalies just last a few

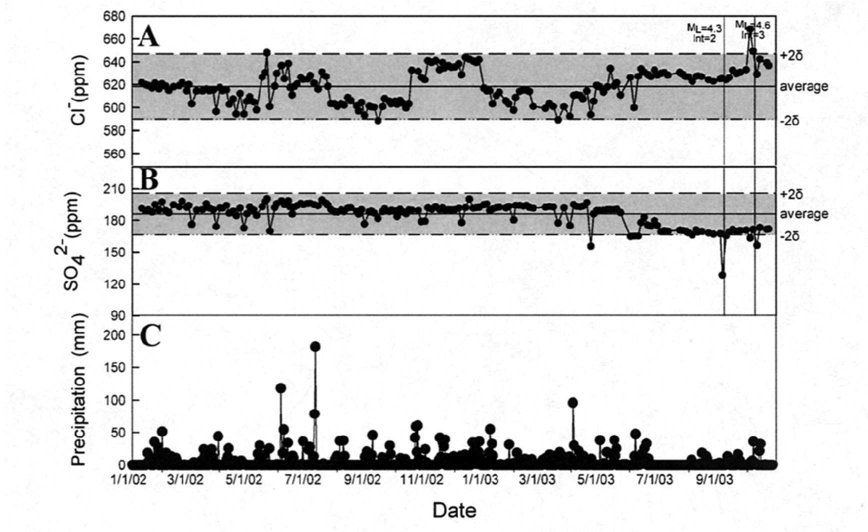

Fig. 3. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the 50-m deep Chingshan hot spring. The vertical lines represent the same as Fig. 2. (C) Daily precipitation recorded in the Chingshan rain gauge station (data from the CWBT).

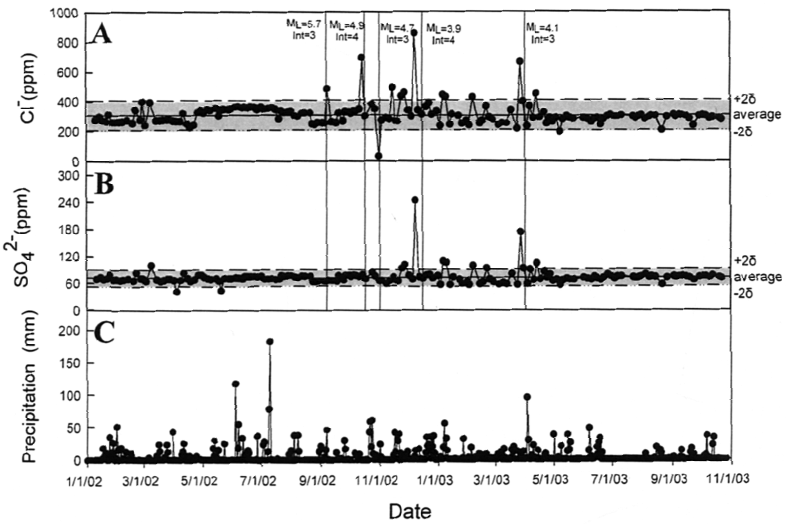

Fig. 4. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the 100-m deep Chingshan hot spring. The vertical lines represent the same as Fig. 2. (C) Daily precipitation record is the same as Fig. 3.

days. Most of the epicenters of the earthquakes that could have induced the chemical anomalies were predominantly in the inland of northeast Taiwan, while few in the offshore (Fig. 7).

The chloride and sulfate ions are again the major anions in the Tapu hot spring, and their average concentration reaches 6048 ± 1656 ppm and 2471 ± 512 ppm, respectively. The two-sigma relative standard deviation (2σ) is 27.4% for Cl^- and 20.7% for SO_4^{2-}. As a rule, the respective concentration in the samples from this site is almost constant, except during one period (Figs. 5A, B). Only one chloride and one sulfate anomaly is identified, and both occur almost simultaneously around December 11, 2002, with a duration of just a few days. The

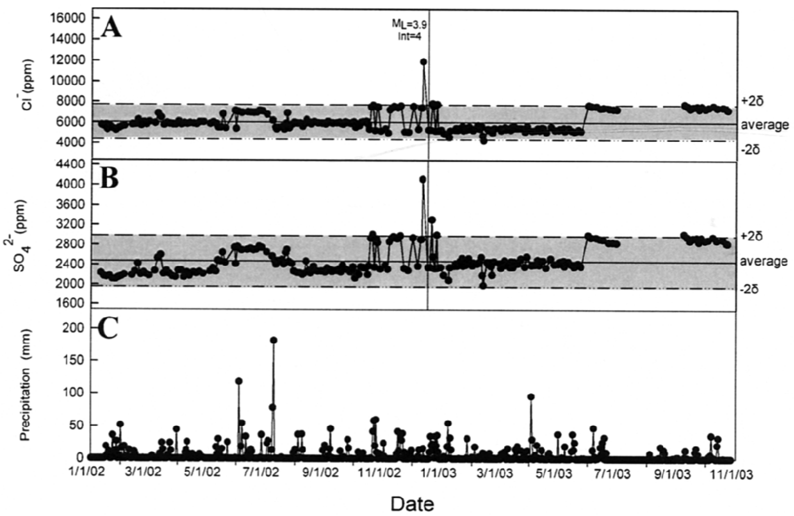

Fig. 5. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Tapu hot spring. The vertical lines represent the same as Fig. 2. (C) Daily precipitation record is the same as Fig. 3.

epicenter of the earthquake that likely induced the two chemical anomalies was the same as one of those at the Chingshan hot springs and was located in northeast Taiwan (Fig. 7).

Again, the chloride and sulfate ions are also the major anions in the Yuanshan hot spring, and their average concentration reaches 56.0 ± 17.3 ppm and 6.95 ± 1.25 ppm, respectively. The two-sigma relative standard deviation (2σ) is 30.9% (Cl^-) and 18.0% (SO_4^{2-}). In general, the respective concentration in the sets of samples of each is almost constant, except during two periods (Figs. 6A, B). Two chloride anomalies and one sulfate anomaly is detected in the Yuanshan hot springs. They occur around May 18 and September 30, 2003 for chloride, and September 26, 2003 for sulfate, for an approximate duration of a few days each. Both epicenters of the earthquakes that must have induced the chemical anomalies were predominantly located very near the monitoring site in the Ilan Plain of northeast Taiwan (Fig. 7).

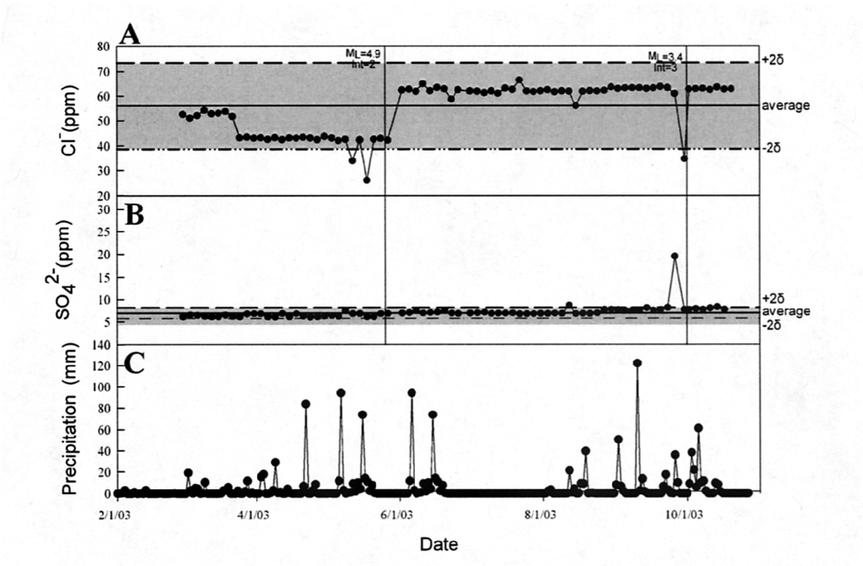

Fig. 6. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Yuangshan hot spring. The vertical lines represent the same as Fig. 2. (C) Daily precipitation recorded in the Ilan rain gauge station (data from the CWBT).

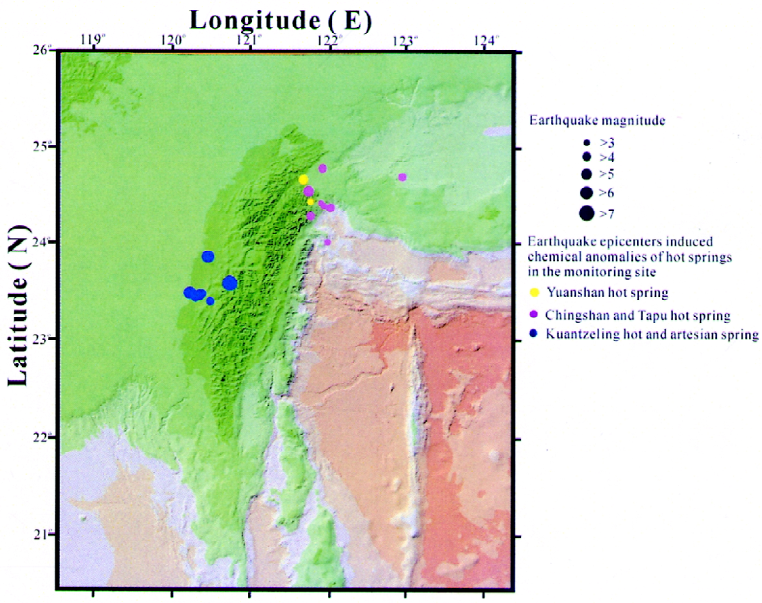

Fig. 7. Distribution of earthquake epicenters which induced the hydrochemical anomalies in the springs at the monitoring sites.

3.2 Artesian Spring

One artesian spring, the Kuantzeling, was chosen for regular sampling in this study of earthquake precursors. Temporal variations in the concentration of Cl^- and SO_4^{2-} in the water samples in the January 2000 to September 2001 period are shown in Figs. 8A, B, respectively. Here, the sulfate ion is the major anion in the spring water, with an average concentration of 25.4 ± 4.5 ppm compared with an average concentration of 2.70 ± 0.82 ppm for the chloride ion (Table 2). The chloride and sulfate concentrations are fairly constant in all samples during the sampling periods. Similarly, the 2σ relative standard deviation is 30.4% (Cl^-) and 17.9% (SO_4^{2-}). In essence, these 2σ domains can be taken as representative of the spring water background values, and they may be attributed to annual fluctuations in groundwater chemistry, changes which are mainly a consequence of rainfall, other superficial phenomena, heterogeneity in the sampling and analytical uncertainties (Toutain et al. 1997). Except for the chloride and sulfate ions, all of the cations and anions vary within the 2σ domains throughout all of the sampling periods. Figure 8 shows that given the sharp increases in the three periods, the Cl^- and SO_4^{2-} concentrations do indeed have anomalies. The anomalies occur almost simultaneously for both elements around April 12 - 15, June 10 - 13 and July 16 of 2000 for durations of just a few to ten days. The epicenters of the earthquakes that probably induced the chemical anomalies were same as those at the Kuantzeling hot springs and were predominantly located in central Taiwan very near the monitoring site (Fig. 7). The exception is the epicenter of the earthquake of July 16, 2000 which located in offshore SE Taiwan (Table 1).

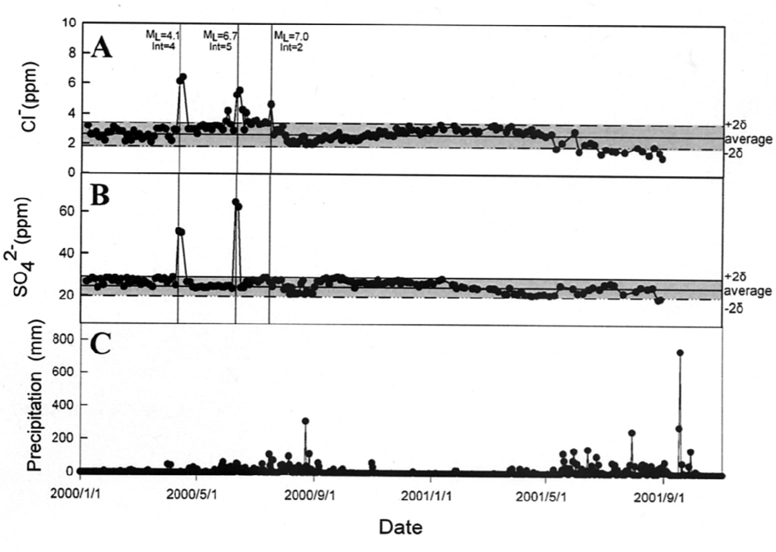

Fig. 8. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Kuantzeling artesian spring. The vertical lines represent the same with Fig. 2. (C) Daily precipitation record is the same as Fig. 2.

3.3 Groundwater

Four sites with groundwater were chosen for regular sampling to evaluate their potential for the monitoring of earthquake precursors. They are located in Meinong, Tashu and Chaochou in southwest Taiwan, and Yuanshan in the northeast. Their depths range from several tens to 250 m. Sampling periods for each site was one year.

Temporal variations in the Cl^- and SO_4^{2-} concentrations in the water samples from these four groundwater sites are shown in Figs. 9 - 12, respectively. The average concentration and the two-sigma relative standard deviation (2σ) were calculated and are also plotted in the same figures and listed in Table 2. The 2σ domains can be taken as representative of the groundwater background values which may be considered the product of annual fluctuations in groundwater chemistry, these mainly being a consequence of rainfall, other superficial phenomena, heterogeneity in the sampling and analytical uncertainties (Toutain et al. 1997).

The sulfate ion with average concentrations of 80.8 ± 17.3 ppm, 58.5 ± 10.1 ppm and 48.9 ± 4.1 ppm in the Meinong, Tashu and Chaochou groundwater, respectively, is the major anion; this compares with the average concentrations of 11.4 ± 1.8 ppm, 13.6 ± 2.5 ppm and 2.8 ± 0.6 ppm for the chloride ion in the same water samples. The 2σ relative standard deviation is 15.8% (Cl^-) and 21.4% (SO_4^{2-}) for the Meinong groundwater, 18.4% (Cl^-) and 17.3% (SO_4^{2-}) for the Tashu groundwater and 21.4% (Cl^-) and 8.4% (SO_4^{2-}) for the Chaochou groundwater.

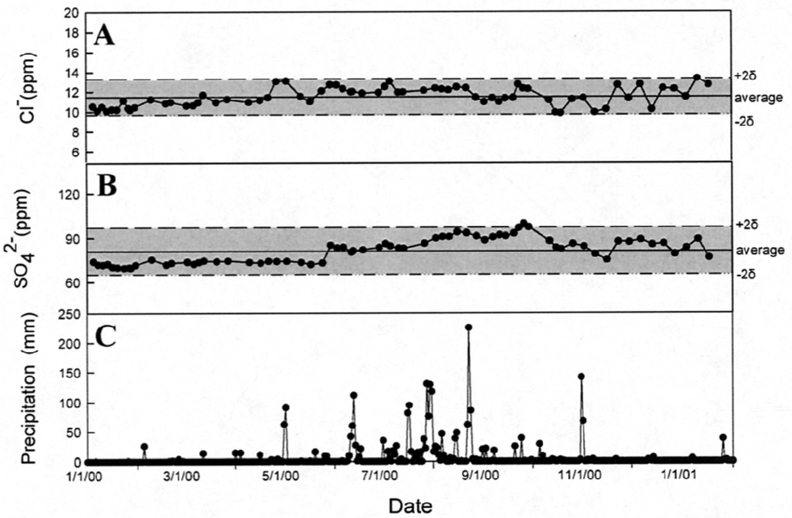

Fig. 9. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Meinong groundwater. (C) Daily precipitation recorded in the Chaochou rain gauge station (data from the CWBT).

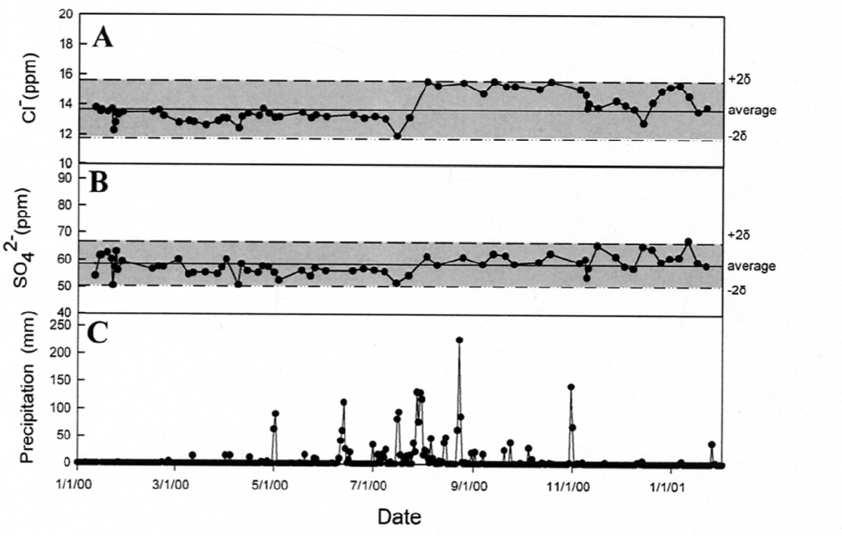

Fig. 10. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Tashu groundwater. (C) Daily precipitation record is the same as Fig. 9.

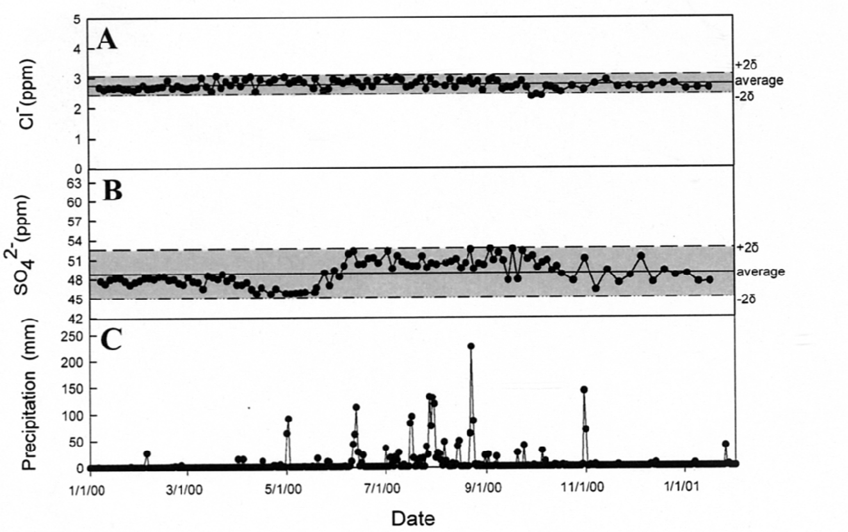

Fig. 11. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Chaochou groundwater. (C) Daily precipitation record is the same as Fig. 9.

Turning to Yuanshan in the northeast, the respective concentration of the chloride and sulfate ions in groundwater is low at 3.73 ± 2.66 and 16.0 ± 2.7 ppm, and the 2σ relative standard deviation is 71.3% (Cl^-) and 16.9% (SO_4^{2-}).

In all four of these groundwater sites, the concentration of Cl^- and that of SO_4^{2-} in all of the samples is fairly constant, though there are variations in the 2σ domains throughout the sampling periods (Figs. 9 - 12). All other cations and anions also vary within the 2σ domains during the same periods.

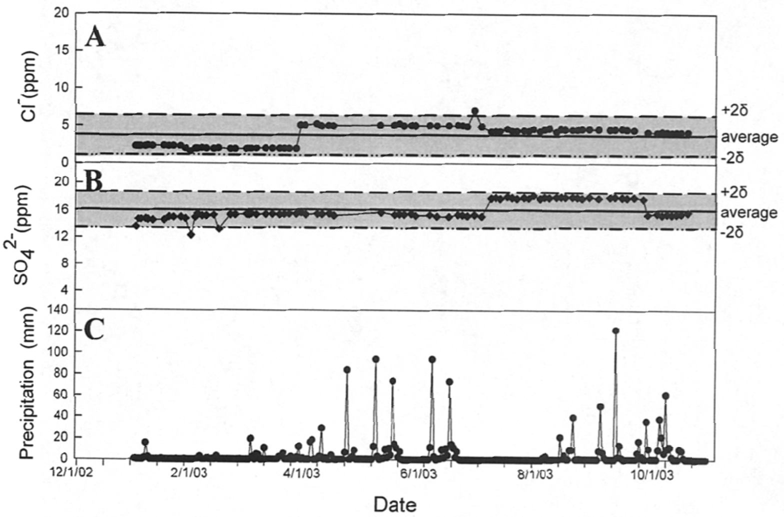

Fig. 12. Temporal variations of (A) Cl^- and (B) SO_4^{2-} concentrations in the Yuanshan groundwater. (C) Daily precipitation record is the same as Fig. 6.

4. DISCUSSIONS

The respective chemical composition of the hot springs and artesian spring and groundwater do indeed tend to change, and this can be attributed to several factors. These include, but are not limited to, varying compositions of groundwater recharge, water-rock interactions (Domenico and Schwartz 1990; Langmuir 1997), the mixing of different water compositions and artificial pollutants. Among all of the factors capable of causing the observed temporal variations in the concentrations Cl^- and SO_4^{2-} for relatively short durations (Figs. 2 - 6 and 8), the mixing of different water compositions (King et al. 1981; Thomas 1988) and artificial pollutants are the only two that cannot flatly be ruled out. Most of the monitoring sites are located in industry-free, sparsely populated countryside or mountainous areas. Besides this, a medium, like meteoric water, is required to carry pollutant solutes down into the subsurface water system. However, lacking here is any evidence of correlated relationships among the anomalies of the ions in the temporal variations and in the daily amounts of precipitation throughout the entire sampling period (Figs. 2 - 6 and 8). Pertinent here are the results of the analysis of tritium (^3H), where it is clear that the concentration of ^3H in the hot springs is less than 0.2 TU (tritium unit) (Liu, unpublished data), strongly suggesting that the hot springs came from older subsurface water bodies, the ages of which may be well over 50 years. This observation is a strong sign that the observed temporal variations in the Cl^- and SO_4^{2-} concentrations have not, in fact, been induced by recent meteoric water flowing down into the circulation system of the subsurface water system. On the weight of this evidence, it is reasonable to conclude that the abrupt changes we witness in the temporal variations in the Cl^- and SO_4^{2-} concentrations cannot be attributed to artifact pollutants.

The mixing of different water compositions in a subsurface water body can be induced in three ways: by the mixing of meteoric and formation waters, the mixing of groundwater and brines or pore waters, and by the mixing of different aquifers or reservoirs with different chemical compositions (Domenico and Schwartz 1990). Of these, the first two processes may gradually change the temporary chemical composition of water and eventually result in a permanent change, or at least a change that lasts a considerably long period of time; with the third process, although the mixing of different aquifers or reservoirs with different chemical compositions can quickly occur, the chemical changes more than likely disappear within a relatively short period of time. Figures 2 - 6 and 8 clearly illustrate that the chemical changes in these springs are abrupt and that the dates correlate well with the occurrence of earthquakes. Thus, it seems justifiable to attribute the factor that causes the rapid temporal chemical variations in the hot springs and the artesian spring and in the groundwater at these monitoring sites to the mixing of different aquifers or reservoirs. It should be equally reasonable to make the claim that the factors which led to the rapid temporal chemical variations must have been induced by those earthquakes.

Worth bearing in mind, the steps that take place during an earthquake cycle are fivefold: 1) strain accumulation; 2) the occurrence of micro-cracks; 3) fluid injection; 4) the occurrence of an earthquake; and 5) a drop in stress (Bolt 1999). The mixing of two individual subsurface water bodies occurs in steps 2 and 3 of the earthquake cycle. More to the point, the chemical compositions of subsurface water systems are normally quite stable, but when the monitoring of a reservoir shows chemical anomalies from mixing, there should, of course, be different chemical compositions among these subsurface water bodies. Based on the temporal variations shown in the water composition of ten monitoring sites (Figs. 2 - 6, 8 - 12), all of the hot springs as well as the artesian spring showed chemical anomalies which could serve as earthquake precursors in certain periods. However, the groundwater clearly did not (Figs. 9 - 12).

A hot spring is composed of thermal water which circulates from the deep. Well known from silica geothermometry is that the silica temperature (T_{SiO_2}) of most hot springs that have been monitored is over 100°C (Song et al., unpublished data), and taking the geothermal gradient as 30 - 50°C km^{-1} in Taiwan (Lee and Cheng 1986), this indicates that hot springs come from a subsurface reservoir which is at least more than 2 km deep. And yet, because there are probably many shallow reservoirs with different chemical compositions above the hot springs, these shallow reservoirs have more opportunity to mix with other reservoirs with different compositions as they circulate upward to the surface during step 2 in the earthquake process when micro-cracks occur before an earthquake. For this vary reason, the fact that all of the hot springs at the monitoring sites show chemical anomalies in response to earthquake events cab be explained.

Artesian springs and groundwater are in saturated zones and circulate in the shallow which is derived from rainfall and infiltration within the normal hydrological cycle. The Kuantzeling artesian spring is located in fine-grained rocks, shale or siltstones of the Tertiary sedimentary rocks in the Western foothills. Based on regional geology and the usage patterns of local people, the reservoir of this spring is small, and the permeability is also low, which means the chemicals are easily affected by water percolating from other reservoirs with different compositions. It would not be surprising, therefore, that in the present study, several anomalies are identified as earthquake precursors during the monitoring periods. However, the Meinong, Tashu and Chaochou groundwater sites are located on the Pintung Plain which is a fluvial apron predominantly composed of gravels with sandy and silty layers. Accordingly, the reservoirs of groundwater in the area of the Pintung Plain are very large, and the permeability may be also high, highly indicative that the chemicals were not significantly affected by mixing from other reservoirs with different compositions. Thus, the temporal variations in these three monitoring sites were quite stable and did not appear to have responded in any way to any earthquake events.

The correlations between the earthquake epicenters and chemical anomalous events in the springs of the Kuantzeling, Chingshan and Yuanshan areas show that the seismic events induced fluid mixing in the subsurface water systems and that this occurred in very restricted regions (Fig. 7). The monitoring sites— for example, those located in the Chiayi area— were only affected by the earthquakes that occurred in central Taiwan. In contrast, those located in the Chingshan and Ilan areas were only affected by the earthquakes that occurred in northeast Taiwan. Taiwan is located within the complexity of the oblique collision zone of the Eurasian continental plate and the Philippine oceanic plate. Presently, rapid crustal movement and widely distributed active structures are the geological characteristics of this young tectonic entity (Yu et al. 1997, 1999; Chang et al. 1998). Hence, in terms of tectonic activity, seven and four neotectonic domains, respectively, can be identified in western and eastern Taiwan, and what's more, each domain is bound by its own distinct active structure (Shyu et al. 2005). Beyond this, each may have its own response to stress accumulation and faulting. This active structural complexity may very well be the dominant factor that controls the hydrochemical changes which are, with no doubt, in response to earthquakes, thus attesting to their capability to serve as earthquake precursors at monitoring sites. However, the results from this study can not explain why the duration changes of chemical anomaly responding to earthquakes in the same monitoring site are different and why some earthquakes induce chemical anomalies in subsurface water body, but some don't (Figs. 2 - 6 and 8). It needs further studies in collecting more data to statistically analyze.

5. CONCLUSIONS

Located as it is in an orogenic belt with highly active seismicity, Taiwan has often been struck by major devastating earthquakes, such as the 1999 Chi-Chi earthquake, which caused a huge number of fatalities as well as the destruction of countless buildings. Nonetheless, this has also given rise to numerous opportunities to investigate potential hydrological monitoring sites which might serve as geochemical precursors of earthquakes in Taiwan. Ten subsurface water bodies in southwestern, northern and northeastern Taiwan were chosen to evaluate the best working sites and the most useful ions for monitoring earthquake precursors in different tectonic domains. The results are convincing: the factors strictly controlling the chemical anomalies that are considered as precursors of an earthquake in subsurface waters are the kinds, the depths and the size of a reservoir as well as the ion species of the water body. Hot springs from deeper zones are, by far, superior to artesian springs and groundwater from shallower reservoirs. Artesian springs from smaller water bodies are also superior to groundwater from larger reservoirs. The anion, especially chloride, is substantially a better precursor than is the cation.

Acknowledgements The authors would like to thank many research assistants and students for their assistance with field sampling and the partial IC and ICP-AES analyses. Thanks are also due to two referees and Dr. C. Y. Lan whose suggestions and valuable reviews greatly improved the manuscript. This research was supported by the Central Geological Survey, Ministry of Economic Affairs and partly by the National Science Council, Republic of China under grants NSC 91-2116-M-002-020 and 92-2116-M-002-014.

REFERENCES

Barsukov, V. L., G. M. Varshal, and N. S. Zamokina, 1984/1985: Recent results of hydrogeochemical studies for earthquake prediction in the USSR. *Pure Appl. Geophys.*, **122**, 143-156.

Bolt, B. A., 1999: Earthquakes. W. H. Freeman and Company, New York, 331 pp.

Chang, H. C., C. W. Lin, M. M. Chen, and S. T. Lu, 1998: An introduction to the active faults of Taiwan: Explanatory text for the active fault of Taiwan, scale 1:500000. Spec. publ. Cent. Geol. Surv., Taiwan. 10, 103 pp. (In Chinese with English abstract)

Central Weather Bureau of Taiwan, 2004: CWBT climate and earthquake report. http:// www.cwb.gov.tw/V4/index.htm/climate data.

Chyi, L. L., T. J. Quick, T. F. Yang, and C. H. Chen, 2005: Soil gas radon spectra and earthquakes. *Terr. Atmos. Ocean. Sci.*, **16**, 763-774.

Claesson, L., A. Skelton, C. Graham, C. Dietl, M. Morth, P. Torssander, and I. Kockum, 2004: Hydrogeochemical changes before and after a major earthquake. *Geology*, **32**, 641-644.

Chung, J. K., and T. C. Shin, 1999: Implications of the rupture process from the displacement distribution of strong ground motions recorded during the 21 September 1999 Chi-Chi Taiwan earthquake. *Terr. Atmos. Ocean. Sci.*, **10**, 777-786.

Domenico, P. A. and F. W. Schwartz, 1990: Physical and chemical hydrogeology. John Wiley & Sons, Singapore, 824 pp.

Guiru, L., W. Fongliang, W. Jihua, and Z. Peiren, 1984/1985: Preliminary results of seismogeochemical research in China. *Pure Appl. Geophys.*, **122**, 218-230.

Hauksson, E., 1981: Radon contents of groundwater as an earthquake precursor: evaluation of worldwide data and physical basis. *J. Geophys. Res.*, **86**, 9397-9410.

Ho, C. S. 1986: An introduction to the geology of Taiwan: Explanatory text of the geologic map of Taiwan. Cent. Geol. Surv., Taiwan, 163 pp.

Italiano, F., A. Caracausi, R. Favara, P. Innocenzi, and G. Martinelli, 2005: Geochemical monitoring of cold waters during seismicity: Implications for earthquake-induced modification in shallow aquifers. *Terr. Atmos. Ocean. Sci.*, **16**, 709-729.

Kao, H., and W. P. Chen, 2000: The Chi-Chi earthquake sequence: active out-of-sequence thrust faulting in Taiwan. *Science*, **288**, 2346-2349.

King, C. Y. 1986: Gas geochemistry applied to earthquake prediction. An overview, *J. Geophys. Res.*, **91**, 12269-12281.

King, C. Y., Evans, W. C., Presser, T., and Husk, R., 1981: Anomalous chemical changes in well waters and possible relation to earthquakes. *Geophys. Res. Lett.*, **8**, 425-428.

Koizumi, N., R. Yoshioka, and Y. Kishimoto, 1985: Earthquake prediction by means of change of chemical composition in mineral spring water. *Geophys. Res. Lett.*, **12**, 510-513.

Langmuir, D., 1997: Aqueous environmental geochemistry. Prentice-Hall, New Jersey, 540 pp.

Lee, C. R., and W. T. Cheng, 1986: Preliminary heat flow measurements in Taiwan. Abs. Fourth Circum-Pacific Energy Mineral Res. Conf., Singapore.

Muir-Wood, R., and G. C. P. King, 1993: Hydrological signatures of earthquake strain. *J. Geophys. Res.*, **98**, 22035-22068.

Ramirez-Guzman, A., Y. A. Taran, R. Bernard, E. Cienfuegos, and P. Morales, 2005: Variations in the Cl, SO_4, δD and δ^{18}O in water from thermal springs near Acapulco, Guerrero, Mexico, related to seismic activity. *Terr. Atmos. Ocean. Sci.*, **16**, 731-743.

Rojstaczer, S., and S. Wolf, 1992: Permeability changes associated with large earthquakes: an example from Loma Prieta, California. *Geology*, **20**, 211-214.

Rojstaczer, S., S. Wolf, and R. Michel, 1995: Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes. *Nature*, **373**, 237-239.

Satake, H., M. Murata, and H. Hayashi, 2002: Chemical characteristics of groundwater around the Mozumbi-Sukenobu fault and the implication for fault activity. *Geophy. Res. Lett.*, **29**, 1-4.

Shyu, J. B. H., K. Sieh, Y. G. Chen, and C. S. Liu, 2005: The neotectonic architecture of Taiwan and its implications for future large earthquakes. *J. Geophy. Res.,* **110**, B08402, doi:10.1029/2004JB003251.

Song, S. R., W. Y. Ku, Y. L. Chen, I. C. Lin. C. M. Liu, L. W. Kuo, T. F. Yang, and H. J. Lo, 2003: Groundwater chemical anomaly before and after the Chi-Chi Earthquake in Taiwan. *Terr. Atmos. Ocean. Sci.*, **14**, 311-320.

Song, S. R., W. Y. Ku, Y. L. Chen, W. Y. Yu, C. M. Liu, Y. G. Chen, T. F. Yang, C. H. Chen, T. K. Liu, and M. Lee, 2005: Hydrogeochemical anomaly in springs in the Chaiyi area, southern Taiwan and its possible relation to earthquakes. *Pure Appl. Geophys.*. (in review)

Sugisaki, R., K. Ito, K. Nagamine, and I. Kawabe, 1996: Gas geochemical changes at mineral springs associated with the 1995 southern Hyogo earthquake (M = 7.2), Japan. *Earth Planet. Sci. Lett.*, **139**, 239-249.

Thomas, D. 1988: Geochemical precursors to seismic activity. *Pure Appl. Geophys.*, **126**, 241-265.

Toutain, J. P., M. Munoz, F. Poitrasson, and A. C. Lienard, 1997: Springwater chloride ion anomaly prior to a M_L = 5.2 Pyrenean earthquake. *Earth Planet. Sci. Lett.*, **149**, 113-119.

Tsunogai, U., and H. Wakita, 1995: Precursory chemical changes in ground water: Kobe earthquake, Japan. *Science*, **269**, 61-63.

Tsunogai, U., and H. Wakita, 1996: Anomalous change in groundwater chemistry- possible precursors of the 1995 Hyogo-ken Nanbu Earthquake, Japan. *J. Phys. Earth*, **44**, 381-390.

Walia, V., H. S. Virk, T. F. Yang, S. Mahajan, M. Walia, and B. S. Bajwa, 2005: Earthquake prediction studies using radon as a precursor in N-W Himalayas, India: A case study. *Terr. Atmos. Ocean. Sci.*, **16**, 775-804.

Yang, T. F., V. Walia, L. L. Chyi, C. C. Fu, C. H. Chen, T. K. Liu, S. R. Song, C. Y. Lee, and M. Lee, 2005: Variations of soil radon and thoron concentrations in a fault zone and prospective earthquakes in SW Taiwan. *Radiat. Meas.*, **40**, 496-502.

Yu, S. B., H. Y. Chen, and L. C. Kuo, 1997: Velociety field of GPS stations in the Taiwan area. *Tectonophy.*, **274**, 41-59.

Yu, S. B., L. C. Kuo, R. S. Punongbayan, and E. G. Ramos, 1999: GPS observation of crystal deformation in the Taiwan-Luzon region. *Geophys. Res. Lett.*, **26**, 923-926.

Appendix 1: The Cl^- and SO_4^{2-} concentrations (ppm) of the Kuantzeling hot spring

Date	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**
7/15/1999	2093	28.1	11/8/1999	2200	11.8	2/19/2000	2132	46.6
8/8/1999	1983	21.7	11/9/1999	2233	20.5	2/22/2000	2272	72.8
8/18/1999	1875	23.5	11/10/1999	2193	44.5	2/25/2000	2102	45.7
8/20/1999	2123	25.4	11/11/1999	2237	40.3	2/28/2000	2123	31.1
8/27/1999	2178	25.8	11/12/1999	2043	41.0	3/1/2000	2385	80.3
9/3/1999	2219	23.7	11/13/1999	2242	40.5	3/2/2000	2272	78.6
9/12/1999	2153	14.1	11/14/1999	2054	27.5	3/5/2000	2055	63.6
9/14/1999	2215	24.7	11/15/1999	2263	41.0	3/8/2000	2141	48.2
9/19/1999	2970	11.7	11/16/1999	2388	39.9	3/11/2000	2057	59.0
9/26/1999	2268	34.1	11/17/1999	2406	37.7	3/17/2000	1994	40.3
10/1/1999	2988	13.5	11/18/1999	2260	31.9	3/20/2000	2022	38.1
10/11/1999	2284	34.4	11/19/1999	2259	38.0	3/23/2000	2089	84.6
10/12/1999	2306	34.6	11/20/1999	2425	33.1	3/26/2000	2133	38.3
10/13/1999	2287	35.5	11/21/1999	2237	33.2	3/29/2000	2220	41.3
10/14/1999	2285	33.9	11/22/1999	2382	35.6	4/1/2000	2258	83.8
10/15/1999	2136	33.8	11/23/1999	2145	30.7	4/4/2000	2359	126.6
10/16/1999	2234	29.3	11/24/1999	2226	32.5	4/7/2000	2398	119.7
10/17/1999	2184	28.3	11/25/1999	2000	32.9	4/10/2000	2320	38.8
10/18/1999	2236	34.8	11/26/1999	2112	33.7	4/13/2000	2266	38.1
10/19/1999	2211	35.4	11/27/1999	2263	27.5	4/16/2000	1764	88.4
10/20/1999	2593	29.8	1/6/2000	2388	41.0	4/19/2000	2168	67.2
10/21/1999	2635	39.4	1/9/2000	2406	39.9	4/25/2000	2196	44.8
10/22/1999	2646	39.9	1/12/2000	2260	44.5	4/28/2000	2164	36.5
10/24/1999	2399	38.6	1/15/2000	2259	27.4	5/1/2000	2340	61.7
10/25/1999	2627	47.4	1/18/2000	2085	38.0	5/4/2000	1714	65.3
10/26/1999	2489	43.8	1/21/2000	2177	33.1	5/7/2000	2299	55.0
10/27/1999	2585	40.8	1/24/2000	2123	20.3	5/10/2000	2534	48.6
10/28/1999	2361	37.5	1/27/2000	2200	35.6	5/13/2000	2485	17.9
10/29/1999	2497	40.9	1/29/2000	2150	30.7	5/16/2000	2413	43.0
10/30/1999	2553	39.1	2/1/2000	2150	32.5	5/19/2000	2426	20.6
10/31/1999	3107	32.4	2/4/2000	2204	32.9	5/25/2000	2464	36.1
11/4/1999	2617	36.5	2/7/2000	2177	33.7	5/28/2000	2183	33.8
11/5/1999	1851	49.6	2/10/2000	2166	40.6	5/31/2000	2317	37.0
11/6/1999	2623	36.5	2/13/2000	2188	32.5	6/3/2000	2290	34.3
11/7/1999	2558	36.4	2/17/2000	2080	48.1	6/6/2000	2306	21.8

6/9/2000	1886	49.7	10/20/2000	2334	40.7	3/4/2001	2243	30.6
6/12/2000	2299	33.9	10/23/2000	2266	62.4	3/7/2001	2262	57.6
6/15/2000	2306	34.5	10/26/2000	2380	29.3	3/10/2001	2314	41.0
6/18/2000	2313	36.0	10/29/2000	2987	18.0	3/13/2001	2300	24.7
6/20/2000	2311	36.3	11/1/2000	2437	42.9	3/21/2001	2376	36.6
6/21/2000	2312	44.1	11/4/2000	2734	20.7	3/27/2001	2620	35.7
6/24/2000	2321	36.5	11/7/2000	2461	35.7	3/30/2001	2295	54.2
6/30/2000	2329	34.9	11/10/2000	2291	15.9	4/2/2001	2022	36.1
7/6/2000	2345	35.7	11/13/2000	2304	37.4	4/8/2001	2173	42.4
7/9/2000	2339	35.5	11/16/2000	2373	20.7	4/14/2001	2289	39.9
7/12/2000	2361	36.9	11/19/2000	2342	26.2	4/17/2001	2385	30.5
7/18/2000	2366	36.5	11/22/2000	2444	26.2	4/20/2001	2259	38.6
7/21/2000	2386	35.3	11/25/2000	2388	79.3	4/23/2001	2108	16.9
7/24/2000	2418	36.9	11/28/2000	2259	53.9	4/26/2001	2171	34.8
8/2/2000	2365	36.2	12/1/2000	2449	39.2	4/29/2001	2189	43.8
8/5/2000	2305	37.5	12/4/2000	2361	73.0	5/2/2001	2363	39.6
8/8/2000	2382	39.1	12/7/2000	2365	28.2	5/9/2001	1997	24.4
8/11/2000	2299	38.7	12/10/2000	2249	59.6	5/18/2001	2216	6.5
8/14/2000	2188	40.3	12/13/2000	2269	33.3	6/2/2001	1786	5.4
8/17/2000	2307	38.3	12/16/2000	2310	14.0	6/11/2001	2001	24.2
8/20/2000	2542	37.9	12/19/2000	2196	54.5	6/17/2001	2006	22.4
8/23/2000	2508	34.9	12/22/2000	2219	32.3	6/23/2001	2140	42.2
8/26/2000	2538	35.6	12/25/2000	2310	59.3	6/29/2001	2034	67.5
8/30/2000	2406	35.2	12/31/2000	2091	74.4	7/2/2001	2256	20.7
9/4/2000	2329	37.2	1/3/2001	2123	54.1	7/11/2001	2367	52.3
9/7/2000	2320	37.7	1/6/2001	2365	58.1	7/17/2001	2372	54.9
9/10/2000	2267	34.4	1/9/2001	2051	51.4	7/23/2001	1974	24.6
9/13/2000	2222	33.3	1/12/2001	2184	50.9	7/29/2001	2491	17.7
9/17/2000	2182	35.5	1/15/2001	2323	59.9	8/1/2001	2522	22.4
9/20/2000	2212	34.4	1/18/2001	2466	73.1			
9/26/2000	2231	33.4	1/21/2001	2421	111.8			
9/29/2000	2225	33.7	1/27/2001	2518	102.9			
10/2/2000	2178	34.9	2/2/2001	2319	55.9			
10/5/2000	1904	32.3	2/4/2001	1900	28.0			
10/8/2000	2486	31.8	2/5/2001	2331	38.4			
10/11/2000	2346	32.4	2/17/2001	2324	63.6			
10/14/2000	2460	30.4	2/20/2001	2451	31.5			
10/17/2000	2023	40.4	2/26/2001	2297	29.9			

Appendix 2: The Cl^- and SO_4^{2-} concentrations (ppm) of the Chingshan hot spring (50 m)

Date	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**
1/11/2002	621.9	191.4	5/21/2002	647.8	200.6	9/18/2002	601.0	188.5
1/15/2002	620.2	188.8	5/24/2002	600.9	169.8	9/20/2002	608.0	191.1
1/18/2002	619.2	190.1	5/29/2002	618.8	191.9	9/25/2002	605.7	188.3
1/22/2002	617.3	187.9	5/31/2002	630.1	195.8	9/27/2002	603.2	189.5
1/25/2002	621.5	195.0	6/5/2002	637.1	198.5	10/1/2002	605.7	189.0
1/29/2002	616.5	189.9	6/8/2002	625.4	195.0	10/3/2002	602.8	183.8
2/1/2002	620.8	197.6	6/12/2002	638.8	198.5	10/6/2002	606.5	190.5
2/5/2002	618.7	189.4	6/14/2002	617.6	192.7	10/8/2002	604.1	188.1
2/8/2002	615.1	187.2	6/16/2002	611.0	185.9	10/12/2002	599.7	186.3
2/13/2002	618.2	194.9	6/18/2002	618.5	192.5	10/15/2002	603.3	189.8
2/19/2002	619.2	192.8	6/21/2002	620.7	194.1	10/18/2002	632.9	189.6
2/22/2002	621.8	198.2	6/25/2002	626.7	196.3	10/25/2002	632.0	189.4
2/27/2002	614.7	192.2	6/28/2002	624.6	195.0	10/28/2002	626.7	178.9
3/1/2002	620.1	194.2	7/2/2002	624.8	195.9	11/1/2002	624.4	179.2
3/4/2002	603.2	176.2	7/5/2002	628.2	196.3	11/4/2002	641.0	192.0
3/9/2002	614.6	189.8	7/9/2002	621.1	195.1	11/8/2002	639.7	190.4
3/15/2002	614.6	190.2	7/13/2002	616.2	193.7	11/12/2002	641.3	193.2
3/19/2002	616.0	195.8	7/17/2002	631.4	199.3	11/16/2002	633.4	190.2
3/22/2002	614.9	191.6	7/21/2002	627.3	196.4	11/19/2002	639.5	192.0
3/26/2002	615.3	189.9	7/23/2002	618.5	194.5	11/21/2002	635.0	189.8
3/29/2002	596.7	174.2	7/26/2002	603.5	190.3	11/25/2002	636.8	190.0
4/2/2002	617.5	192.0	7/30/2002	603.2	188.2	11/28/2002	635.6	189.7
4/5/2002	614.8	191.6	8/2/2002	601.0	187.8	12/2/2002	635.9	190.2
4/9/2002	615.7	194.1	8/6/2002	603.2	189.9	12/6/2002	638.4	191.5
4/12/2002	602.8	186.7	8/9/2002	602.2	188.3	12/9/2002	629.1	177.9
4/16/2002	607.7	188.7	8/13/2002	608.8	191.7	12/13/2002	644.0	192.0
4/19/2002	594.4	184.5	8/16/2002	606.2	192.0	12/17/2002	642.5	200.2
4/23/2002	612.3	191.7	8/22/2002	601.6	188.5	12/21/2002	640.8	191.6
4/27/2002	594.2	172.6	8/24/2002	597.1	185.9	12/24/2002	639.8	192.0
4/30/2002	605.8	186.2	8/27/2002	604.6	190.2	12/27/2002	642.0	192.2
5/3/2002	609.5	192.6	8/30/2002	593.2	176.7	1/1/2003	617.0	194.8
5/7/2002	604.9	189.8	9/4/2002	601.4	188.0	1/4/2003	614.7	195.5
5/10/2002	597.9	184.7	9/6/2002	600.6	188.8	1/7/2003	614.7	189.2
5/16/2002	626.6	192.7	9/9/2002	600.3	186.7	1/10/2003	603.2	190.6
5/19/2002	630.9	198.0	9/13/2002	588.5	181.8	1/14/2003	610.6	192.0

1/17/2003	613.4	192.4	5/23/2003	611.0	187.2	9/30/2003	633.4	170.9
1/24/2003	606.0	191.8	6/2/2003	626.4	164.6	10/4/2003	668.3	163.1
1/27/2003	603.1	193.1	6/6/2003	599.9	164.9	10/7/2003	649.2	171.5
2/1/2003	597.7	180.4	6/10/2003	627.4	165.0	10/11/2003	629.5	156.4
2/3/2003	608.8	194.2	6/13/2003	634.2	177.8	10/14/2003	642.5	173.2
2/7/2003	614.1	194.2	6/16/2003	631.3	182.9	10/21/2003	639.4	171.6
2/11/2003	615.5	193.5	6/20/2003	629.2	175.4	10/23/2003	636.9	171.9
2/14/2003	615.2	194.1	6/23/2003	627.0	174.6			
2/17/2003	614.1	192.2	6/27/2003	633.1	179.5			
2/21/2003	601.1	191.6	6/30/2003	628.7	175.1			
3/6/2003	599.4	192.3	7/4/2003	630.2	168.9			
3/10/2003	603.4	193.1	7/7/2003	631.0	170.2			
3/14/2003	601.0	192.6	7/11/2003	628.7	169.8			
3/19/2003	589.2	177.5	7/23/2003	631.1	170.8			
3/25/2003	600.9	191.8	7/26/2003	629.6	170.5			
3/31/2003	592.4	175.0	7/29/2003	627.2	169.9			
4/4/2003	610.8	195.1	8/1/2003	627.0	168.1			
4/7/2003	611.4	193.2	8/5/2003	622.8	166.0			
4/11/2003	610.6	192.8	8/9/2003	627.4	171.0			
4/14/2003	607.6	193.5	8/11/2003	627.7	168.8			
4/18/2003	614.5	196.8	8/15/2003	627.2	169.4			
4/22/2003	593.7	155.4	8/22/2003	624.2	168.0			
4/25/2003	605.8	186.0	8/27/2003	623.1	166.8			
4/28/2003	619.4	189.4	9/3/2003	625.2	167.3			
5/1/2003	618.1	189.1	9/5/2003	625.6	128.7			
5/5/2003	613.6	189.4	9/9/2003	624.3	165.3			
5/9/2003	618.2	190.1	9/12/2003	626.3	168.8			
5/12/2003	634.5	190.1	9/16/2003	633.0	171.5			
5/16/2003	618.9	190.2	9/20/2003	630.1	169.6			
5/19/2003	621.7	190.4	9/24/2003	631.2	170.5			

Appendix 3: The Cl^- and SO_4^{2-} concentrations (ppm) of the Chingshan hot spring (100 m)

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
1/11/2002	275.7	68.7	5/21/2002	340.0	42.8	9/18/2002	251.9	63.2
1/15/2002	295.5	72.7	5/24/2002	344.5	70.0	9/20/2002	319.0	76.1
1/18/2002	272.8	68.0	5/29/2002	344.0	69.5	9/25/2002	265.1	65.9
1/22/2002	266.8	70.4	5/31/2002	345.8	69.5	9/27/2002	326.7	76.8
1/25/2002	311.3	78.4	6/5/2002	361.9	71.7	10/1/2002	324.1	77.1
1/29/2002	258.7	67.1	6/8/2002	365.6	71.3	10/3/2002	313.3	74.3
2/1/2002	258.3	67.5	6/12/2002	355.6	69.6	10/6/2002	329.8	77.7
2/5/2002	258.3	65.7	6/14/2002	362.7	74.8	10/8/2002	329.0	77.2
2/8/2002	260.0	67.4	6/16/2002	357.5	74.8	10/12/2002	343.9	74.4
2/13/2002	272.0	69.5	6/18/2002	355.9	74.7	10/15/2002	690.9	79.4
2/19/2002	252.3	65.8	6/21/2002	361.5	75.0	10/18/2002	298.2	67.9
2/22/2002	340.2	83.2	6/25/2002	359.0	74.9	10/25/2002	378.2	83.2
2/27/2002	275.5	70.8	6/28/2002	342.3	73.3	10/28/2002	345.3	75.1
3/1/2002	396.3	70.2	7/2/2002	362.5	75.0	11/1/2002	26.8	64.6
3/4/2002	238.6	64.3	7/5/2002	345.4	68.4	11/4/2002	270.4	64.8
3/9/2002	392.1	99.9	7/9/2002	350.1	68.9	11/8/2002	286.0	58.2
3/15/2002	268.9	67.5	7/13/2002	357.4	69.5	11/12/2002	278.5	65.4
3/19/2002	270.4	63.8	7/17/2002	342.5	67.5	11/16/2002	492.5	73.4
3/22/2002	272.5	66.0	7/21/2002	278.9	69.1	11/19/2002	267.4	64.7
3/26/2002	276.4	69.4	7/23/2002	332.0	77.0	11/21/2002	265.7	64.2
3/29/2002	278.0	69.4	7/26/2002	322.2	75.4	11/25/2002	431.7	92.6
4/2/2002	268.1	66.5	7/30/2002	327.4	76.7	11/28/2002	456.4	100.4
4/5/2002	267.0	40.7	8/2/2002	330.4	76.9	12/2/2002	339.7	76.3
4/9/2002	267.2	66.6	8/6/2002	300.4	72.9	12/6/2002	297.8	68.5
4/12/2002	320.1	82.7	8/9/2002	295.0	71.5	12/9/2002	852.8	243.4
4/16/2002	247.0	70.4	8/13/2002	317.4	75.3	12/13/2002	339.2	73.6
4/19/2002	222.2	63.9	8/16/2002	317.9	74.9	12/17/2002	312.5	70.9
4/23/2002	240.0	67.6	8/22/2002	318.2	75.2	12/21/2002	362.7	78.3
4/27/2002	325.6	78.1	8/24/2002	247.0	62.8	12/24/2002	386.3	79.2
4/30/2002	335.1	77.9	8/27/2002	241.9	62.3	12/27/2002	312.8	70.1
5/3/2002	316.9	73.5	8/30/2002	255.0	63.9	1/1/2003	335.2	75.4
5/7/2002	342.0	70.0	9/4/2002	253.8	64.2	1/4/2003	234.0	56.0
5/10/2002	336.3	68.8	9/6/2002	250.3	63.1	1/7/2003	440.6	108.5
5/16/2002	352.2	70.6	9/9/2002	483.9	65.1	1/10/2003	427.9	104.5
5/19/2002	301.8	64.5	9/13/2002	258.3	64.7	1/14/2003	242.4	56.4

1/17/2003	312.8	73.0	5/16/2003	302.1	69.5	9/20/2003	279.8	70.2
1/24/2003	302.9	67.5	5/19/2003	289.3	67.1	9/24/2003	236.8	65.3
1/27/2003	249.8	58.1	5/23/2003	280.5	66.5	9/30/2003	297.8	72.4
2/1/2003	270.5	62.5	6/2/2003	284.6	71.0	10/4/2003	304.0	73.9
2/3/2003	236.0	55.7	6/6/2003	279.6	68.9	10/7/2003	300.3	73.9
2/7/2003	424.3	98.5	6/10/2003	262.2	67.3	10/11/2003	283.7	70.7
2/14/2003	248.4	57.7	6/13/2003	281.0	73.5	10/14/2003	290.4	76.2
2/17/2003	269.0	62.1	6/16/2003	286.5	69.8	10/21/2003	283.3	70.7
2/21/2003	364.0	92.0	6/20/2003	244.6	66.9	10/23/2003	274.0	69.1
2/24/2003	293.1	68.0	6/23/2003	281.9	71.3			
2/28/2003	275.3	62.4	6/27/2003	300.8	78.8			
3/6/2003	240.4	56.6	6/30/2003	308.8	74.3			
3/10/2003	254.2	60.2	7/4/2003	296.4	68.7			
3/14/2003	249.7	57.0	7/7/2003	296.1	73.3			
3/19/2003	339.8	79.6	7/11/2003	302.7	73.9			
3/25/2003	214.2	56.3	7/23/2003	296.6	72.4			
3/28/2003	661.4	172.6	7/26/2003	284.5	70.8			
3/31/2003	396.7	91.9	7/29/2003	298.4	72.4			
4/4/2003	231.2	58.8	8/1/2003	306.9	74.2			
4/7/2003	365.0	89.6	8/5/2003	281.7	79.4			
4/11/2003	287.0	66.6	8/9/2003	293.2	71.8			
4/14/2003	448.2	103.2	8/11/2003	303.8	73.4			
4/18/2003	290.8	67.7	8/15/2003	300.2	72.2			
4/22/2003	327.0	85.0	8/22/2003	206.6	56.5			
4/25/2003	251.4	71.2	8/27/2003	293.4	71.6			
4/28/2003	286.6	78.0	9/3/2003	309.0	74.4			
5/1/2003	263.5	64.4	9/5/2003	295.2	73.4			
5/5/2003	287.6	67.0	9/9/2003	308.2	73.8			
5/9/2003	197.0	55.9	9/12/2003	304.9	74.5			
5/12/2003	278.7	65.8	9/16/2003	298.2	72.4			

Appendix 4: The Cl^- and SO_4^{2-} concentrations (ppm) of the Tapu hot spring

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
1/11/2002	5793	2233	5/10/2002	5904	2265	8/28/2002	5968	2275
1/14/2002	5646	2171	5/12/2002	5553	2490	8/31/2002	5966	2281
1/16/2002	5823	2160	5/15/2002	5556	2469	9/1/2002	5890	2249
1/17/2002	5348	2157	5/17/2002	6833	2647	9/3/2002	6141	2334
1/20/2002	5685	2176	5/20/2002	5487	2442	9/7/2002	6004	2297
1/23/2002	5447	2116	5/30/2002	7155	2746	9/8/2002	5962	2263
1/26/2002	5275	2108	5/31/2002	5439	2424	9/12/2002	6007	2286
1/29/2002	5487	2144	6/2/2002	7062	2760	9/15/2002	6044	2316
2/1/2002	5613	2166	6/6/2002	6959	2693	9/17/2002	5952	2252
2/4/2002	5704	2197	6/12/2002	7018	2704	9/19/2002	5879	2391
2/12/2002	5841	2188	6/15/2002	6983	2726	9/21/2002	6095	2325
2/15/2002	5863	2265	6/18/2002	6973	2700	9/23/2002	6032	2308
2/18/2002	6282	2423	6/21/2002	6978	2707	9/27/2002	5966	2255
2/21/2002	5756	2206	6/24/2002	7174	2769	9/30/2002	6098	2363
2/24/2002	6071	2250	6/27/2002	7107	2747	10/2/2002	5577	2135
2/27/2002	5848	2208	7/2/2002	6815	2658	10/4/2002	5889	2244
3/2/2002	6107	2180	7/8/2002	6231	2571	10/6/2002	5745	2209
3/8/2002	5977	2279	7/11/2002	5562	2484	10/8/2002	6067	2363
3/11/2002	6877	2538	7/12/2002	5397	2412	10/10/2002	6112	2353
3/14/2002	6509	2601	7/14/2002	5541	2478	10/13/2002	6158	2343
3/17/2002	5811	2219	7/18/2002	5622	2502	10/15/2002	5858	2207
3/20/2002	5985	2283	7/20/2002	5370	2415	10/16/2002	5388	2385
3/23/2002	5907	2217	7/22/2002	5955	2643	10/18/2002	7537	2939
3/26/2002	5857	2166	7/23/2002	6944	2702	10/20/2002	7689	3015
3/29/2002	5829	2150	7/25/2002	5499	2466	10/22/2002	5272	2362
4/1/2002	6143	2284	7/28/2002	5866	2429	10/24/2002	7537	2925
4/4/2002	5849	2285	7/30/2002	6035	2275	10/25/2002	7525	2845
4/7/2002	5959	2150	8/2/2002	5964	2246	10/28/2002	5211	2319
4/10/2002	5895	2251	8/5/2002	5945	2238	11/2/2002	5442	2396
4/13/2002	5968	2175	8/8/2002	5651	2206	11/5/2002	5024	2315
4/17/2002	5920	2249	8/10/2002	5906	2227	11/7/2002	7261	2870
4/20/2002	5872	2227	8/12/2002	6304	2474	11/9/2002	7443	2937
4/23/2002	6078	2257	8/15/2002	6030	2284	11/11/2002	7591	2969
4/27/2002	6072	2218	8/17/2002	5889	2234	11/15/2002	7457	2928
5/4/2002	5910	2270	8/20/2002	6116	2372	11/18/2002	7627	2991
5/7/2002	6038	2336	8/24/2002	5982	2270	11/22/2002	5141	2334

11/26/2002	5113	2292	2/17/2003	5335	2429	5/21/2003	5377	2430
12/1/2002	7574	2949	2/19/2003	5380	2458	5/24/2003	5231	2377
12/6/2002	5393	2380	2/20/2003	5272	2382	6/1/2003	7696	3001
12/9/2002	7449	2913	2/21/2003	5057	2198	6/4/2003	7601	2955
12/10/2002	7448	2919	2/23/2003	5489	2468	6/9/2003	7595	2953
12/11/2002	11928	4119	3/1/2003	5487	2437	6/13/2003	7407	2924
12/17/2002	5344	2354	3/2/2003	5279	2343	6/16/2003	7455	2915
12/19/2002	5327	2354	3/6/2003	5601	2494	6/22/2003	7382	2852
12/21/2002	7836	3307	3/7/2003	5398	2402	6/26/2003	7334	2852
12/22/2002	7631	2568	3/8/2003	5494	2433	6/30/2003	7302	2840
12/24/2002	5229	2329	3/9/2003	5429	2407	9/8/2003	7788	3029
12/26/2002	7766	3005	3/12/2003	5336	2361	9/11/2003	7639	2972
12/27/2002	5249	2337	3/13/2003	5618	2474	9/14/2003	7395	2892
12/30/2002	5328	2355	3/15/2003	5698	2361	9/17/2003	7544	2941
1/2/2003	4938	2195	3/16/2003	5663	2469	9/21/2003	7598	2954
1/7/2003	4626	2095	3/17/2003	5518	2433	9/23/2003	7337	2863
1/8/2003	5249	2353	3/20/2003	5519	2431	9/26/2003	7603	2955
1/13/2003	5332	2382	3/23/2003	5519	2529	9/30/2003	7384	2891
1/14/2003	5485	2428	3/27/2003	5166	2370	10/3/2003	7484	2907
1/16/2003	5313	2383	3/29/2003	5701	2572	10/8/2003	7661	2968
1/17/2003	5424	2417	4/3/2003	5251	2399	10/12/2003	7470	2897
1/19/2003	5542	2483	4/6/2003	5291	2404	10/18/2003	7508	2917
1/21/2003	5667	2538	4/9/2003	5508	2505	10/22/2003	7314	2843
1/22/2003	5274	2385	4/11/2003	5282	2401	10/23/2003	7253	2834
1/25/2003	5340	2402	4/13/2003	5536	2487			
1/26/2003	5367	2420	4/15/2003	5520	2487			
1/27/2003	5584	2501	4/18/2003	5117	2349			
1/28/2003	5639	2531	4/23/2003	5642	2534			
1/29/2003	5430	2440	4/27/2003	5327	2417			
2/1/2003	5292	2393	5/1/2003	5336	2427			
2/2/2003	5414	2445	5/2/2003	5450	2464			
2/6/2003	5772	2428	5/6/2003	5521	2488			
2/8/2003	5438	2462	5/7/2003	5233	2381			
2/10/2003	5662	2559	5/11/2003	5505	2469			
2/11/2003	4753	2192	5/14/2003	5283	2415			
2/12/2003	4274	1992	5/17/2003	5177	2366			
2/16/2003	5412	2460	5/20/2003	5280	2399			

Appendix 5: The Cl^- and SO_4^{2-} concentrations (ppm) of the Yuanshan hot spring

Date	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**
3/1/2003	52.5	6.12	6/2/2003	62.3	6.90	9/2/2003	62.8	7.64
3/4/2003	51.0	6.48	6/5/2003	62.7	6.98	9/5/2003	63.1	7.52
3/7/2003	52.0	6.42	6/8/2003	61.8	7.60	9/8/2003	63.2	7.60
3/10/2003	54.2	6.26	6/11/2003	64.9	6.92	9/11/2003	63.1	7.60
3/13/2003	52.8	6.10	6/14/2003	62.0	7.04	9/14/2003	62.9	8.12
3/16/2003	53.0	6.12	6/17/2003	63.4	7.12	9/17/2003	63.1	7.54
3/19/2003	53.7	6.48	6/20/2003	62.8	7.58	9/20/2003	63.7	7.70
3/22/2003	51.6	6.24	6/23/2003	58.7	6.88	9/23/2003	63.2	8.16
3/25/2003	43.2	6.10	6/26/2003	62.4	6.80	9/26/2003	60.9	19.50
3/28/2003	43.4	6.76	7/1/2003	61.9	6.90	9/30/2003	34.5	7.70
3/31/2003	43.0	6.78	7/4/2003	61.8	6.94	10/2/2003	62.6	7.70
4/3/2003	43.2	6.78	7/7/2003	61.2	7.10	10/5/2003	62.8	7.88
4/6/2003	42.5	6.10	7/10/2003	61.9	6.82	10/8/2003	62.9	7.72
4/9/2003	43.2	6.06	7/13/2003	61.0	6.86	10/11/2003	62.4	8.06
4/12/2003	42.4	6.81	7/16/2003	63.1	6.88	10/14/2003	63.4	8.32
4/15/2003	43.1	6.10	7/19/2003	62.5	6.92	10/17/2003	62.6	7.76
4/18/2003	43.0	6.78	7/22/2003	66.3	6.72	10/20/2003	62.7	7.46
4/21/2003	43.3	6.29	7/25/2003	61.9	6.74			
4/24/2003	43.1	6.06	7/28/2003	61.6	6.76			
4/27/2003	42.4	6.12	7/31/2003	62.0	6.80			
4/30/2003	43.7	6.33	8/3/2003	62.4	6.80			
5/3/2003	43.1	6.35	8/6/2003	61.6	6.84			
5/6/2003	42.0	6.21	8/9/2003	61.9	6.82			
5/9/2003	42.5	7.48	8/12/2003	61.8	8.70			
5/12/2003	33.8	6.80	8/15/2003	55.9	6.76			
5/15/2003	42.3	6.80	8/18/2003	61.8	6.82			
5/18/2003	25.9	6.12	8/21/2003	62.0	6.80			
5/21/2003	42.6	6.10	8/24/2003	61.9	6.92			
5/24/2003	42.9	6.78	8/27/2003	62.1	7.72			
5/27/2003	42.2	6.82	8/30/2003	63.5	7.72			

Appendix 6: The Cl^- and SO_4^{2-} concentrations (ppm) of the Kuantzeling artesian spring

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
1/7/2000	3.17	26.6	4/24/2000	2.96	26.6	7/31/2000	2.57	23.4
1/10/2000	2.58	27.4	4/27/2000	2.97	24.2	8/2/2000	2.20	24.3
1/13/2000	2.60	28.4	4/30/2000	2.66	23.7	8/4/2000	2.09	24.6
1/16/2000	2.71	27.8	5/3/2000	3.14	24.1	8/6/2000	2.08	21.1
1/19/2000	2.40	23.8	5/6/2000	3.27	24.4	8/8/2000	2.20	24.1
1/22/2000	2.48	27.8	5/9/2000	2.99	23.9	8/10/2000	2.07	21.4
1/25/2000	2.19	25.0	5/12/2000	3.15	24.1	8/12/2000	2.03	21.5
1/28/2000	2.71	28.4	5/15/2000	2.91	24.9	8/14/2000	2.17	21.3
1/31/2000	2.72	28.4	5/18/2000	3.23	24.5	8/16/2000	2.21	21.6
2/3/2000	3.11	26.9	5/21/2000	3.23	24.6	8/18/2000	2.48	26.0
2/6/2000	2.94	28.4	5/24/2000	3.15	24.9	8/20/2000	2.50	27.6
2/9/2000	2.79	26.5	5/27/2000	2.91	24.4	8/22/2000	1.96	21.2
2/12/2000	2.78	27.9	5/30/2000	3.52	24.2	8/24/2000	2.11	22.4
2/15/2000	2.14	24.2	6/1/2000	4.21	24.8	8/26/2000	2.11	22.2
2/18/2000	2.54	28.3	6/4/2000	3.30	25.0	8/28/2000	1.98	21.6
2/21/2000	2.20	25.6	6/7/2000	2.87	23.7	8/30/2000	2.08	21.3
2/24/2000	2.84	27.8	6/10/2000	5.24	64.8	9/1/2000	2.20	24.6
2/27/2000	2.44	26.6	6/13/2000	5.55	62.4	9/4/2000	2.33	27.3
3/1/2000	2.60	27.7	6/16/2000	4.29	24.1	9/7/2000	2.28	27.1
3/4/2000	2.28	25.2	6/18/2000	2.91	24.7	9/10/2000	2.54	28.3
3/7/2000	2.43	27.0	6/19/2000	4.12	24.1	9/13/2000	2.44	28.8
3/10/2000	2.57	25.8	6/20/2000	4.09	25.2	9/16/2000	2.33	25.8
3/13/2000	2.11	25.2	6/22/2000	3.48	27.0	9/19/2000	2.51	28.6
3/16/2000	2.46	24.2	6/25/2000	3.27	25.5	9/22/2000	2.61	28.9
3/19/2000	2.98	28.1	6/28/2000	3.53	27.6	9/25/2000	2.78	29.5
3/22/2000	2.98	28.8	7/1/2000	3.59	27.2	9/28/2000	2.29	28.1
3/25/2000	3.05	27.7	7/4/2000	3.27	26.6	9/30/2000	2.38	28.9
3/28/2000	2.95	28.3	7/7/2000	3.35	27.7	10/1/2000	2.48	28.2
3/31/2000	2.44	26.2	7/10/2000	3.48	28.8	10/4/2000	2.45	27.8
4/3/2000	2.20	27.6	7/13/2000	3.38	28.8	10/7/2000	2.27	27.5
4/6/2000	2.93	29.2	7/16/2000	4.63	26.9	10/10/2000	2.39	27.0
4/9/2000	2.90	25.1	7/19/2000	2.62	24.6	10/13/2000	2.26	24.3
4/12/2000	6.14	50.8	7/22/2000	2.95	27.7	10/16/2000	2.32	26.7
4/15/2000	6.43	50.1	7/25/2000	2.90	27.5	10/19/2000	2.50	26.7
4/21/2000	2.96	26.6	7/28/2000	3.18	27.8	10/22/2000	2.59	26.9

10/25/2000	2.71	26.0	2/5/2001	2.95	24.7	7/7/2001	1.63	26.6
10/28/2000	2.53	26.0	2/13/2001	2.96	24.2	7/11/2001	1.60	26.2
10/31/2000	2.63	26.3	2/15/2001	2.80	24.5	7/21/2001	1.53	21.9
11/3/2000	2.49	26.0	2/18/2001	2.90	24.1	8/3/2001	1.87	23.4
11/6/2000	2.92	28.2	3/3/2001	3.23	24.2	8/8/2001	1.65	24.9
11/9/2000	2.73	25.9	3/6/2001	3.33	24.1	8/15/2001	1.34	24.4
11/12/2000	2.86	26.2	3/8/2001	3.04	24.1	8/20/2001	1.89	24.9
11/15/2000	2.62	26.9	3/12/2001	3.17	23.0	8/26/2001	1.50	19.2
11/18/2000	2.64	27.4	3/19/2001	2.88	21.8	8/29/2001	1.16	19.6
11/21/2000	2.58	26.5	3/21/2001	3.16	21.4			
11/24/2000	3.08	27.7	3/24/2001	3.26	24.6			
11/27/2000	2.79	28.0	3/29/2001	2.90	21.9			
11/30/2000	2.95	26.3	4/1/2001	2.90	21.6			
12/1/2000	2.78	27.8	4/5/2001	2.76	23.1			
12/4/2000	2.78	27.5	4/9/2001	2.92	21.1			
12/7/2000	3.25	26.9	4/14/2001	3.07	21.0			
12/10/2000	2.99	26.8	4/16/2001	2.70	20.7			
12/16/2000	2.95	26.0	4/21/2001	2.84	20.9			
12/19/2000	2.71	25.0	4/24/2001	2.73	21.3			
12/22/2000	2.80	26.1	4/29/2001	2.59	21.5			
12/25/2000	3.06	25.9	5/5/2001	2.72	20.8			
12/28/2000	2.95	26.3	5/10/2001	1.76	21.1			
12/31/2000	2.88	27.1	5/16/2001	2.15	25.6			
1/3/2001	3.02	26.3	5/29/2001	2.88	24.5			
1/9/2001	3.35	28.0	6/3/2001	1.56	22.0			
1/12/2001	3.03	28.6	6/9/2001	2.06	22.3			
1/23/2001	3.29	26.0	6/15/2001	2.19	24.1			
1/25/2001	2.97	25.8	6/19/2001	2.08	25.1			
1/27/2001	3.05	24.4	6/26/2001	1.41	24.1			
2/2/2001	2.90	25.0	7/1/2001	1.74	26.1			

Appendix 7: The Cl^- and SO_4^{2-} concentrations (ppm) of the Meinong groundwater

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
1/5/2000	10.6	74.2	6/12/2000	12.0	80.7	11/23/2000	12.7	87.7
1/8/2000	10.1	72.3	6/13/2000	12.0	81.6	11/30/2000	11.3	87.4
1/11/2000	10.5	72.0	6/19/2000	11.8	82.2	12/7/2000	12.7	89.0
1/14/2000	10.1	72.6	6/29/2000	11.9	83.7	12/14/2000	10.2	85.7
1/17/2000	10.2	70.5	7/3/2000	12.5	86.3	12/21/2000	12.3	86.5
1/20/2000	10.2	70.1	7/6/2000	13.0	84.7	12/28/2000	12.2	79.4
1/24/2000	11.1	69.8	7/11/2000	11.9	83.3	1/4/2001	11.5	83.6
1/27/2000	10.4	70.1	7/14/2000	12.0	83.1	1/11/2001	13.3	89.2
1/28/2000	10.2	69.9	7/27/2000	12.1	86.5	1/18/2001	12.7	76.8
1/31/2000	10.5	71.9	8/3/2000	12.3	90.0			
2/10/2000	11.2	75.6	8/7/2000	12.2	91.0			
2/19/2000	10.8	72.1	8/11/2000	12.2	90.9			
2/22/2000	11.0	73.2	8/16/2000	12.5	94.0			
3/3/2000	10.6	73.9	8/22/2000	12.4	93.2			
3/7/2000	10.6	72.5	8/28/2000	11.4	91.3			
3/10/2000	10.9	73.8	9/2/2000	11.0	88.5			
3/13/2000	11.7	74.7	9/7/2000	11.4	90.6			
3/21/2000	10.9	74.2	9/11/2000	11.0	91.9			
3/28/2000	11.2	74.6	9/15/2000	11.3	91.3			
4/10/2000	11.0	73.8	9/20/2000	11.4	93.1			
4/17/2000	11.1	73.1	9/23/2000	12.7	96.7			
4/22/2000	11.4	74.4	9/26/2000	12.3	99.5			
4/27/2000	13.0	74.3	9/29/2000	12.3	97.1			
5/3/2000	13.1	74.4	10/12/2000	11.1	88.1			
5/12/2000	11.5	73.7	10/16/2000	9.9	83.6			
5/18/2000	11.0	72.2	10/19/2000	9.8	82.6			
5/25/2000	12.1	73.2	10/26/2000	11.2	86.2			
5/30/2000	12.7	85.2	11/2/2000	11.4	84.4			
6/3/2000	12.7	83.5	11/9/2000	9.9	79.2			
6/7/2000	12.3	84.0	11/16/2000	10.2	75.3			

Appendix 8: The Cl^- and SO_4^{2-} concentrations (ppm) of the Tashu groundwater

Date	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**
11/26/1999	13.80	54.00	4/20/2000	13.32	57.13	12/23/2000	14.63	67.32
11/29/1999	13.51	61.57	4/27/2000	13.20	56.00	12/29/2000	13.59	59.62
11/30/1999	13.64	61.62	5/15/2000	13.33	56.01	1/4/2001	13.89	58.22
12/4/1999	13.51	62.65	5/22/2000	13.11	56.80			
12/7/1999	13.70	60.25	5/29/2000	13.22	56.28			
12/8/1999	12.29	50.50	6/5/2000	13.07	55.73			
12/9/1999	12.77	57.30	6/13/2000	11.95	51.60			
12/10/1999	13.39	63.02	6/21/2000	13.16	54.34			
12/11/1999	13.30	56.05	7/3/2000	15.58	61.46			
12/14/1999	13.47	59.46	7/10/2000	15.29	58.28			
1/3/2000	13.50	56.57	7/27/2000	15.49	61.16			
1/7/2000	13.63	57.50	8/9/2000	14.78	58.56			
1/10/2000	13.23	57.42	8/16/2000	15.60	62.48			
1/20/2000	12.80	60.25	8/24/2000	15.27	61.87			
1/27/2000	12.90	54.61	8/30/2000	15.27	58.70			
1/30/2000	12.84	55.13	9/15/2000	15.08	59.46			
2/7/2000	10.12	55.13	9/23/2000	15.59	62.61			
2/15/2000	12.90	54.80	10/12/2000	15.07	59.29			
2/18/2000	13.09	57.30	10/16/2000	14.72	60.50			
2/21/2000	13.07	60.29	10/17/2000	13.81	53.85			
2/29/2000	12.46	50.80	10/18/2000	14.14	57.32			
3/2/2000	13.20	58.67	10/24/2000	13.86	65.61			
3/6/2000	13.41	55.94	11/5/2000	14.33	61.60			
3/13/2000	13.25	55.30	11/11/2000	14.03	57.90			
3/16/2000	13.74	57.75	11/17/2000	13.76	57.20			
3/20/2000	13.40	57.47	11/23/2000	12.85	65.30			
3/24/2000	13.14	55.35	11/29/2000	14.22	64.32			
3/27/2000	13.18	52.54	12/5/2000	14.96	59.60			
4/11/2000	13.49	56.12	12/11/2000	15.23	60.95			
4/17/2000	13.13	54.06	12/17/2000	15.36	61.32			

Appendix 9: The Cl^- and SO_4^{2-} concentrations (ppm) of the Chaochou groundwater

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
1/8/2000	2.68	47.72	4/25/2000	2.93	46.40	8/20/2000	2.84	50.36
1/11/2000	2.59	47.25	5/1/2000	3.00	45.70	8/23/2000	2.93	52.37
1/14/2000	2.66	47.93	5/4/2000	2.80	45.64	8/25/2000	2.75	49.48
1/17/2000	2.65	48.15	5/7/2000	2.88	45.71	8/28/2000	2.85	50.29
1/20/2000	2.68	48.17	5/10/2000	2.93	45.76	8/31/2000	2.55	50.05
1/23/2000	2.61	47.66	5/13/2000	2.82	45.86	9/4/2000	2.88	52.47
1/26/2000	2.61	47.09	5/19/2000	2.63	45.86	9/6/2000	2.93	50.80
1/29/2000	2.57	47.48	5/20/2000	2.95	46.58	9/9/2000	2.85	51.92
2/1/2000	2.65	47.74	5/25/2000	2.55	48.85	9/12/2000	2.59	50.73
2/4/2000	2.74	48.09	5/28/2000	2.61	46.90	9/15/2000	2.65	47.65
2/7/2000	2.62	48.12	5/31/2000	2.92	49.24	9/18/2000	2.63	52.43
2/10/2000	2.65	47.97	6/3/2000	2.86	48.26	9/21/2000	2.71	47.74
2/13/2000	2.68	48.34	6/6/2000	2.79	49.99	9/24/2000	2.86	52.14
2/16/2000	2.70	48.37	6/9/2000	2.85	51.78	9/27/2000	2.65	50.96
2/19/2000	2.90	47.80	6/12/2000	2.92	52.17	9/30/2000	2.34	51.42
2/22/2000	2.64	47.90	6/15/2000	2.81	50.20	10/3/2000	2.41	49.69
2/25/2000	2.73	47.33	6/18/2000	2.67	50.23	10/6/2000	2.37	50.39
2/28/2000	2.67	47.09	6/21/2000	2.87	51.07	10/9/2000	2.68	50.75
3/2/2000	2.61	48.29	6/24/2000	2.68	51.18	10/12/2000	2.66	49.16
3/5/2000	2.67	47.57	6/27/2000	2.89	50.39	10/15/2000	2.59	49.80
3/8/2000	2.69	47.43	7/3/2000	2.97	52.16	10/18/2000	2.49	48.59
3/11/2000	2.98	46.44	7/6/2000	2.88	49.50	10/25/2000	2.68	47.56
3/14/2000	2.70	48.45	7/9/2000	2.98	51.45	11/1/2000	2.57	50.97
3/17/2000	2.54	48.20	7/12/2000	2.90	50.57	11/8/2000	2.77	46.22
3/20/2000	3.04	47.91	7/15/2000	2.66	50.11	11/15/2000	2.89	49.21
3/23/2000	2.66	48.67	7/18/2000	2.71	49.89	11/22/2000	2.66	47.22
3/26/2000	2.86	47.65	7/21/2000	2.81	49.90	11/29/2000	2.67	48.36
3/29/2000	2.74	48.11	7/24/2000	2.95	51.38	12/6/2000	2.59	51.20
4/1/2000	2.93	47.04	7/27/2000	2.60	49.66	12/13/2000	2.67	47.32
4/4/2000	2.71	47.05	7/30/2000	2.93	50.35	12/20/2000	2.75	49.13
4/7/2000	2.92	47.38	8/2/2000	2.74	50.12	12/27/2000	2.77	48.37
4/10/2000	3.01	46.35	8/8/2000	2.70	50.38	1/3/2001	2.59	48.65
4/13/2000	2.52	45.64	8/11/2000	2.91	50.56	1/10/2001	2.62	47.32
4/16/2000	2.92	46.60	8/14/2000	2.65	50.94	1/17/2001	2.62	47.37
4/22/2000	2.83	45.60	8/17/2000	2.85	49.55			

Appendix 10: The Cl^- and SO_4^{2-} concentrations (ppm) of the Yuanshan groundwater

Date	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**	**Date**	**Cl^-**	**SO_4^{2-}**
2/27/2003	2.25	13.54	5/8/2003	5.09	15.62	8/20/2003	4.56	17.94
2/28/2003	2.25	14.71	5/10/2003	5.08	15.33	8/22/2003	4.70	17.87
3/1/2003	2.27	14.69	5/15/2003	5.27	15.43	8/25/2003	4.28	17.98
3/3/2003	2.27	14.74	5/17/2003	4.99	15.39	8/27/2003	4.64	18.00
3/4/2003	2.34	14.63	5/20/2003	5.04	15.49	8/29/2003	4.58	17.97
3/6/2003	2.30	14.54	5/22/2003	4.98	15.22	9/1/2003	4.51	18.00
3/11/2003	2.34	14.57	6/11/2003	5.09	15.62	9/3/2003	4.52	17.95
3/13/2003	2.30	15.00	6/17/2003	5.08	15.33	9/5/2003	4.58	17.81
3/15/2003	2.33	15.00	6/19/2003	5.27	15.43	9/8/2003	4.59	18.03
3/18/2003	2.29	15.01	6/21/2003	4.99	15.39	9/12/2003	4.57	17.82
3/20/2003	1.93	14.81	6/24/2003	5.04	15.49	9/15/2003	17.94	5.63
3/22/2003	1.52	12.25	6/26/2003	4.98	15.22	9/17/2003	4.54	17.93
3/24/2003	1.90	15.00	7/2/2003	5.01	15.33	9/19/2003	4.58	17.98
3/25/2003	1.93	15.50	7/5/2003	4.97	15.07	9/22/2003	4.63	17.90
3/27/2003	1.99	15.21	7/10/2003	5.02	15.03	9/24/2003	4.55	17.83
3/29/2003	1.95	15.24	7/14/2003	5.09	15.35	9/27/2003	4.49	17.93
4/1/2003	1.92	15.30	7/16/2003	5.04	15.30	10/1/2003	17.33	17.70
4/3/2003	2.02	13.22	7/18/2003	4.94	15.19	10/3/2003	4.16	15.38
4/8/2003	1.92	15.35	7/21/2003	7.02	15.36	10/7/2003	4.11	15.54
4/10/2003	1.94	15.36	7/24/2003	4.91	15.14	10/9/2003	4.22	15.33
4/15/2003	1.95	15.46	7/28/2003	4.27	17.77	10/11/2003	4.17	15.45
4/16/2003	1.95	15.33	7/30/2003	4.32	17.90	10/13/2003	4.10	15.38
4/17/2003	1.94	15.47	8/1/2003	4.29	17.73	10/15/2003	4.17	15.45
4/19/2003	1.94	15.34	8/4/2003	4.58	18.05	10/17/2003	4.17	15.54
4/23/2003	1.95	15.40	8/6/2003	4.30	17.89	10/20/2003	4.19	15.69
4/26/2003	1.95	15.45	8/8/2003	4.29	17.74			
4/29/2003	1.95	15.38	8/11/2003	4.35	17.94			
5/1/2003	1.96	15.38	8/13/2003	4.29	17.77			
5/3/2003	1.95	15.44	8/15/2003	4.57	18.19			
5/6/2003	1.94	15.40	8/18/2003	4.28	17.67			