

# ISOTOPE CHARACTERISTICS OF TAIWAN GROUNDWATERS

Chung-Ho Wang<sup>1</sup>, Ching-Huei Kuo<sup>1</sup>, Tsung-Ren Peng<sup>2</sup>, Wen-Fu Chen<sup>3</sup>, Tsung-Kwei Liu<sup>4</sup>,  
Chung-Jung Chiang<sup>5</sup>, Wen-Cheh Liu<sup>6</sup> and Jia-Jang Hung<sup>7</sup>

1. Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
2. Department of Soil and Environmental Sciences, National Chung Hsing University, Taichung, Taiwan
3. Center of Groundwater Development and Conservation, Taiwan Sugar Corporation, Tainan, Taiwan
4. Department of Geological Sciences, National Taiwan University, Taipei, Taiwan
5. Central Geology Survey, Ministry of Economic Affairs, Taipei, Taiwan
6. Taiwan Sugar Corporation, Ministry of Economic Affairs, Taipei, Taiwan
7. Institute of Marine Geology and Chemistry, National Sun Yat-Sen University, Kaohsiung, Taiwan

## ABSTRACT

Isotope characteristics have been summarized in this report for nine groundwater regions of Taiwan. The isotope signals for these nine regions are quite distinct with each other and closely related with their meteorological variations, recharge sources, and water utilization. In view of future exploitation for groundwater resources, three categories, good, fair, and poor, are adopted to classify these groundwater regions based on isotope measurements. Among the nine regions, central and southern areas are the most damaging and alarming regions in terms of groundwater resources management. Appropriate remediable measures are immediately needed to effectively alleviate the existing groundwater crisis.

Key words: groundwater, isotopes, water resources

## INTRODUCTION

Groundwater is one of the most important and indispensable water resources in Taiwan (WRPC, 1992). The establishment of the "Groundwater Monitoring Network Plan" (GMNP) by the Water Resources Bureau since 1992 is aiming to accumulate basic and essential hydrological, geological, chemical and geophysical data of Taiwan groundwaters for an efficient water resource management (Hsu, 1998). In complement with the ongoing GMNP program, we have independently measured the naturally occurring isotope compositions of groundwaters collected during the past decade for nine groundwater regions with an objective to build the fundamental isotope database (Figure 1). In this report, we have

summarized and synthesized published data to illustrate their isotope characteristics and discuss the associated implications. These isotope signals collected thus far would serve as a valuable and useful database for further integrating studies.

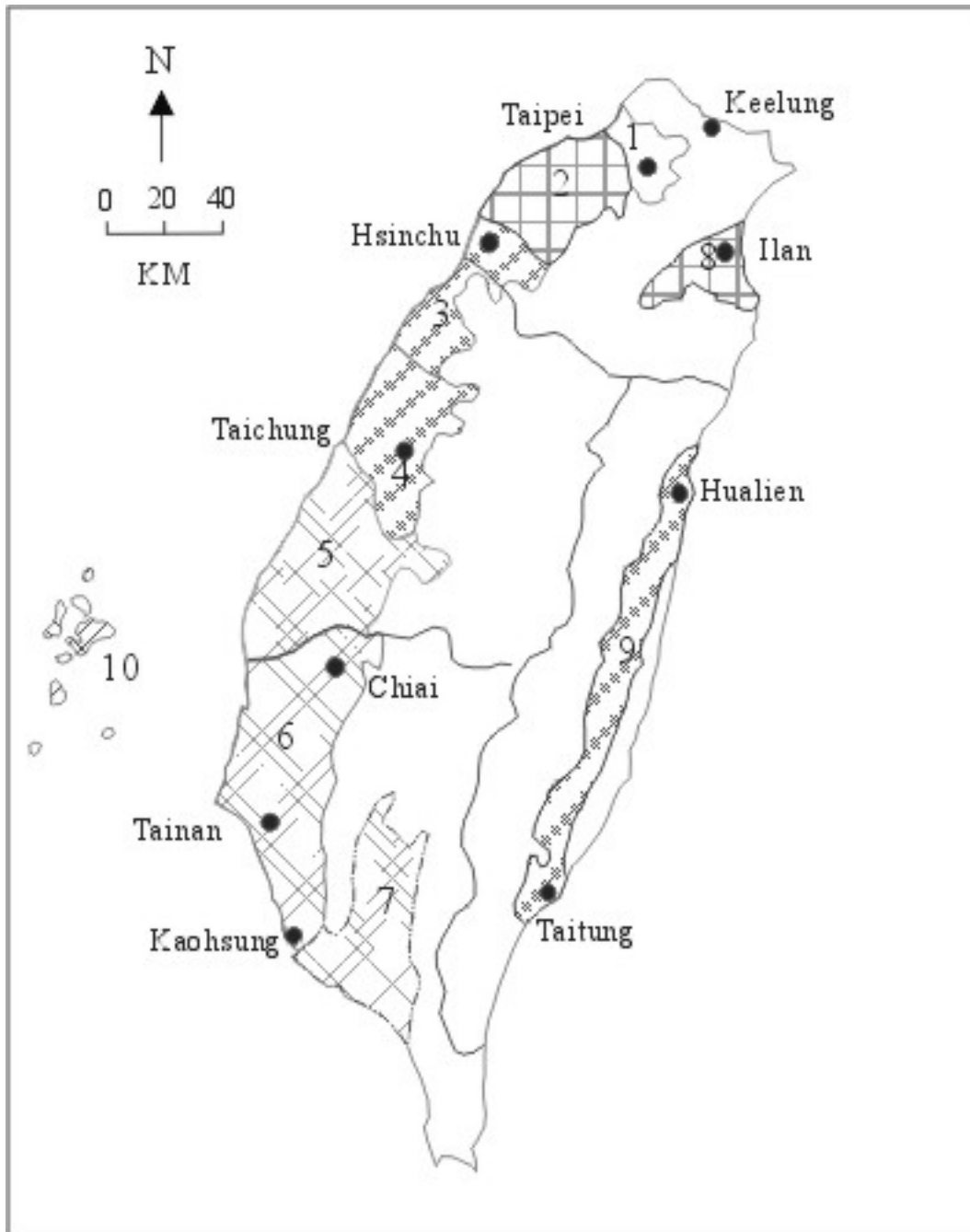


Figure 1. The groundwater regions in Taiwan (1: Taipei; 2: Taoyuan; 3: Hsinmiao; 4: Taichung; 5: Choshuichi; 6: Chianan; 7: Pingtung; 8: I-lan; 9: Huatung; 10: Penghu). Except the Taipei area, all other nine groundwater regions are qualitatively grouped and marked into three categories based on isotope evidences (shaded area: good and abundant; open squares: fair and normal; open crosses: poor and alarming). See texts for details.

## DATA AND METHODS

All isotope data in this work are retrieved from previous studies (Chang, 1994; Ho, 1989; Hung, 1998; Lin, 1992; Liu et al., 1982, 1984, 1990; Liu, 1992, 1994, 1995a, 1995b, 1996, 1997a, 1997b; Liu et al, 1996; Peng and Liu, 1992; Peng et al., 1993, 1994, 1997; Peng, 1995, 2000; Shieh et al., 1983; Wang et al., 1990, 1993, 1994a, 1994b, 1994c, 1995, 1996, 1996b, 1996c, 1996d, 1997a, 1997b, 1997c, 1998a, 1998b, 1999a; Wang and Liu, 1997).

The stable isotope compositions are expressed relative to VSMOW (Vienna Standard Mean Ocean Water) as per mill (‰) notation according to recommendations issued by the International Atomic Energy Agency (IAEA) and International Organization for Standardization (ISO) (Gonfiantini, 1978; IAEA, 1983; ISO, 1992). Detailed analytical description can be found in reports of Institute of Earth Sciences, Academia Sinica (Wang et al., 1990; 1993). The analytical precisions expressed as  $1\sigma$  for the laboratory standards are  $\pm 1.3\text{‰}$  for  $\delta\text{D}$  and  $\pm 0.08\text{‰}$  for  $\delta^{18}\text{O}$ , respectively. The average differences of duplicate analyses of water samples are  $\pm 1.5\text{‰}$  for  $\delta\text{D}$  and  $\pm 0.11\text{‰}$  for  $\delta^{18}\text{O}$ , respectively.

Tritium concentrations are expressed in TU, where 1 TU indicates a T/H ratio of  $10^{-18}$  (Taylor and Roether, 1982). Carbon-14 concentrations are expressed as per cent modern carbon (PMC) according to the definition of Stuiver and Polach (1977). Repeated analyses of samples and laboratory standards show that the  $1\sigma$  uncertainties are  $\pm 0.1$  TU for tritium and  $\pm 1\%$  PMC for  $^{14}\text{C}$ , respectively.

## RESULTS AND DISCUSSION

Naturally occurring stable (H, O) and radiogenic (T,  $^{14}\text{C}$ ) isotopes of water have been widely and extensively used in groundwater studies over the last forty years. The major applications are to address problems related to groundwater recharge, delineation of flow systems and quantification of mass-balance relationships (Clark and Fritz, 1997; Gat, 1980, 1981, 1996; Gonfiantini, 1986; Fontes, 1980; IAEA, 1981; Rozanski et al., 1997). In Taiwan, we have conducted naturally occurring isotopic measurements for the last decade and it is an appropriate occasion to synthesize and present the preliminary results. Since the groundwater is primarily derived from precipitation and surface waters, it is a common practice to concurrently examine the isotope signals of these different water bodies and make comparisons among them. Accordingly, stable isotope altitude gradients derived from major rivers of watersheds of nine groundwater regions and corresponding local meteoric water lines (MWL) are listed in Table 1 to facilitate the comparison. In Table 1, stable isotope gradients that depend upon local topography and climate spread from  $-0.7\text{‰}$  to  $-4.3\text{‰}$  per 100m for  $\delta\text{D}$  and  $-0.11\text{‰}$  to  $-0.58\text{‰}$  per 100m for  $\delta^{18}\text{O}$ , respectively, in Taiwan. These values are in good accordance with those published elsewhere (Clark and Fritz, 1997; Fontes, 1980).

The corresponding local meteoric water lines (MWL) in Table 1 are the least-square regression lines from stable isotopes of precipitations as recommended by IAEA (IAEA, 1992) and composed of long-term isotopic signatures of precipitation at each groundwater regions. Their slopes are functions of humidity, temperature, and other factors (Gat, 1981; Rozanski et al., 1997) of each groundwater territories. Although all slopes in nine groundwater regions are relatively close to the global mean value of 8 (IAEA, 1981, 1992), the northeastern I-Lan region carries the highest slope value (=8.9), whereas the southwestern Pingtung reveals a relatively low slope figure (=7.5). This distinguishing feature clearly illustrates the major difference in prevailing climate factors controlling those different groundwater regions in Taiwan. Thus these MWLs are the ultimate and essential reference basis for each groundwater regions.

The seasonal features of hydrogen and oxygen isotope compositions of nine groundwater regions are listed in Tables 2 and 3 with observed maximum, minimum and mean values, respectively. The dry (October - April) and wet (May - September) seasons are determined by meteorological observations for the precipitation (Wang et al., 1994d). The mean values of dry season groundwaters are generally enriched in D and  $^{18}\text{O}$  relative to those of wet seasons, except for the Huatung area. This season-variation attribute is mainly due to monsoon-controlled precipitation, as the greater the rainfall the lower the D and  $^{18}\text{O}$  content (IAEA, 1992), and is also in good agreement with many observations for low latitude marine sites of the IAEA monitoring stations (IAEA, 1992).

Table 1. Stable isotope altitude gradients and local MWLs for nine groundwater watersheds in Taiwan.

Region	$\delta\text{D}/100\text{m}$	$\delta^{18}\text{O}/100\text{m}$	Local MWL
Taoyuan	-0.7	-0.11	$\delta\text{D} = 8.1\delta^{18}\text{O} + 14.2$
Hsinmiao	-1.6	-0.21	$\delta\text{D} = 7.6\delta^{18}\text{O} + 8.6$
Taichung	-1.4	-0.20	$\delta\text{D} = 7.9\delta^{18}\text{O} + 12.8$
Choshuichi	-1.3	-0.19	$\delta\text{D} = 8.1\delta^{18}\text{O} + 13.8$
Chianan	-4.3	-0.58	$\delta\text{D} = 7.9\delta^{18}\text{O} + 11.8$
Pingtung	-4.3	-0.55	$\delta\text{D} = 7.5\delta^{18}\text{O} + 7.4$
Penghu	-	-	$\delta\text{D} = 8.0\delta^{18}\text{O} + 10.1$
I-Lan	-2.8	-0.38	$\delta\text{D} = 8.9\delta^{18}\text{O} + 20.3$
Huatung	-3.0	-0.39	$\delta\text{D} = 8.3\delta^{18}\text{O} + 14.4$

Table 2. Seasonal hydrogen isotope compositions for nine groundwater regions in Taiwan.

Region	Dry Season				Wet Season			
	Number of samples	$\delta D_{max}$	$\delta D_{min}$	$\delta D_{mean}$	Number of samples	$\delta D_{max}$	$\delta D_{min}$	$\delta D_{mean}$
Taoyuan	45	-22	-45	-33	-	-	-	-
Hsinmiao	17	-29	-55	-44	20	-30	-53	-43
Taichung	13	-40	-61	-50	13	-44	-58	-51
Choshuichi	462	-10	-75	-51	75	-37	-75	-53
Chianan	183	2	-61	-41	133	3	-57	-42
Pingtung	481	3	-77	-56	92	-9	-72	-57
Penghu	286	0	-50	-35	198	2	-50	-33
I-Lan	90	3	-44	-29	45	-13	-40	-31
Huatung	39	-40	-85	-60	45	-39	-79	-57

Table 3. Seasonal oxygen isotope compositions for nine groundwater regions in Taiwan.

Region	Dry Season				Wet Season			
	Number of samples	$\delta^{18}O_{max}$	$\delta^{18}O_{min}$	$\delta^{18}O_{mean}$	Number of samples	$\delta^{18}O_{max}$	$\delta^{18}O_{min}$	$\delta^{18}O_{mean}$
Taoyuan	45	-4.4	-7.5	-5.9	-	-	-	-
Hsinmiao	17	-4.8	-8.3	-6.9	20	-5.0	-8.2	-6.9
Taichung	13	-6.9	-9.0	-7.8	13	-6.7	-8.9	-7.8
Choshuichi	462	-2.2	-10.5	-7.8	75	-6.4	-10.5	-8.3
Chianan	183	0.5	-8.3	-6.4	133	0.4	-8.1	-6.5
Pingtung	481	0.1	-10.6	-8.3	92	-1.5	-10.1	-8.3
Penghu	286	-0.9	-7.6	-5.6	198	-0.9	-7.2	-5.5
I-Lan	90	-0.1	-8.0	-5.7	45	-3.1	-6.9	-5.8
Huatung	39	-7.0	-12.3	-9.2	45	-6.7	-10.8	-8.9

In Figure 2, the seasonal features of stable isotope compositions expressed as  $\delta D$  versus  $\delta^{18}O$  plots in Taiwan groundwaters are shown with corresponding local MWLs. In general, most of groundwater isotopes distribute along their corresponding MWLs as commonly observed in groundwater studies (Gat, 1980). Isotope signals in groundwaters normally represent long-term average values (Fontes, 1980) and exhibit relatively narrow ranges ( $\delta D < 40\text{‰}$ ,  $\delta^{18}O < 5\text{‰}$ ) comparing to those of surface waters and precipitation, as illustrated by regions of Taoyuan, Hsinmiao, Taichung, and Huatung. However, regions such as I-Lan, Choushuichi, Chianan, Penghu and Pingtung display both abnormally greater isotopic ranges ( $\delta D > 60\text{‰}$ ,  $\delta^{18}O > 6\text{‰}$ ) and extreme enriched values ( $\delta D > 0\text{‰}$ ,  $\delta^{18}O > -0.9\text{‰}$ ). The anomalous phenomena are mainly due to intense mixing with surface waters resulting from agriculture activities and seawater contamination along coastal aquifers (Chiang and Wang, 1998; Ho et al., 1990; Wang et al., 1996a, 1996b, 1996c; 1999b; Peng, 2000; Yu et al., 1998). The encroachment of seawater toward inland along coastal aquifers in Taiwan is also observed by other studies (CGS, 1999; WRB, 1999).

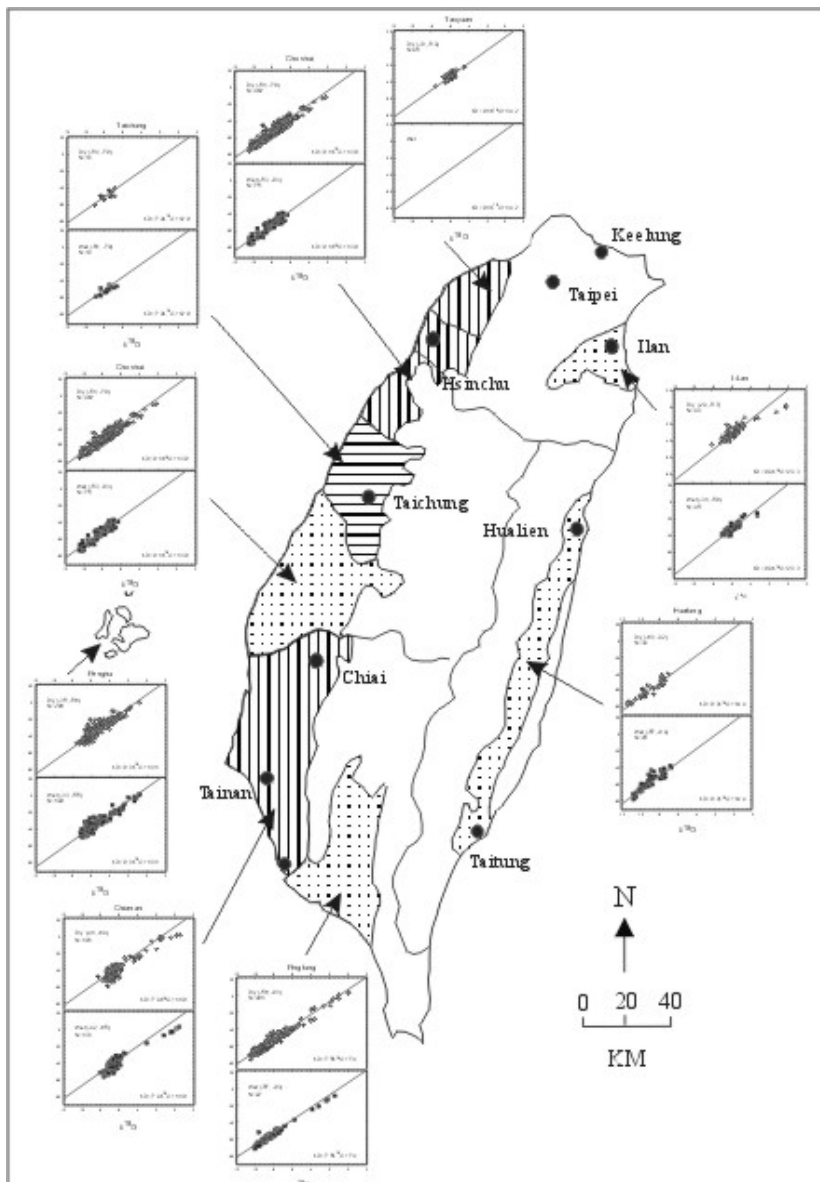


Figure 2. Hydrogen versus oxygen isotope plots for nine Taiwan groundwater regions. The base patterns for Taiwan groundwater regions are adopted from WRPC (1992) referring to their hydraulic conductivities (dotted points: high; horizontal lines: intermediate; vertical lines: low).

The isotope mean values in Tables 2 and 3 primarily reflect the elevations of groundwater recharge sources of each groundwater regions when compared with the altitude gradients of local rivers (Table 1). In short, the recharging elevations for groundwaters in Taiwan range from 100 to 500 m, that is, essential foothill areas of the Taiwan Central Range. Among nine groundwater regions, Huatung and Pingtung exhibit the most depleted values ( $\delta D < -56\text{‰}$ ;  $\delta^{18}\text{O} < -8.3\text{‰}$ ), indicating their high-elevation locations for groundwater recharging. On the other hand, Taoyuan, Penghu and I-Lan regions show relatively enriched values ( $\delta D > -35\text{‰}$ ;  $\delta^{18}\text{O} > -5.9\text{‰}$ ), suggesting their relative low-altitude natures of recharging zones. It is also interesting to note that both Chianan and Pingtung have the highest altitude gradients among the eight watersheds (Table 1). Nonetheless, their mean groundwater values are distinctly different by about 10‰ for  $\delta D$  and 2‰ for  $\delta^{18}\text{O}$ , respectively. This sharp contrast of stable isotope mean values clearly implies that there is an altitude difference of about 300 m for groundwater recharging between the Chianan and Pingtung regions.

The residence time of a groundwater carries very important and practical implications for water resource management. The tritium (TU) and carbon-14 (expressed as PMC) contents of eight groundwater regions with their maximum, minimum and mean values, respectively, are presented in Table 4. Generally, TU ranges from 0 to 8.9 and PMC spans from 0% to 120%, respectively, in Taiwan groundwaters. In Figure 3, the TU (half life = 12.43 years) versus PMC (half life = 5730 years) plots provide unique and valuable clues for groundwater utilization of eight groundwater regions. The shadow belts shown in TU versus PMC plots of Figure 3 represent the observed distribution ranges (TU: 3.7 - 1.5; PMC: 52% - 98%) of modern Taiwan river waters and precipitation. Data points of groundwaters fell in the shadow belt are thus recently percolated and recharged waters for the last decades.

Table 4. Tritium and  $^{14}\text{C}$  (as PMC) compositions for eight groundwater regions in Taiwan.

Region	Tritium (TU)				PMC (%)			
	Number of samples	Max	Min	Mean	Number of samples	Max	Min	Mean
Hsinmiao	53	6.6	0.0	4.4	53	120	44	88
Taichung	6	8.5	2.9	4.1	6	116	75	104
Choshuichi	182	8.9	0.0	1.6	182	120	1	56
Chianan	129	7.1	0.0	1.0	129	106	0	43
Pingtung	180	6.2	0.0	2.2	180	117	2	65
Penghu	18	2.9	0.0	1.1	18	99	1	44
I-Lan	22	4.6	0.0	2.4	22	83	16	49
Huatung	10	3.1	1.9	2.4	10	101	59	74

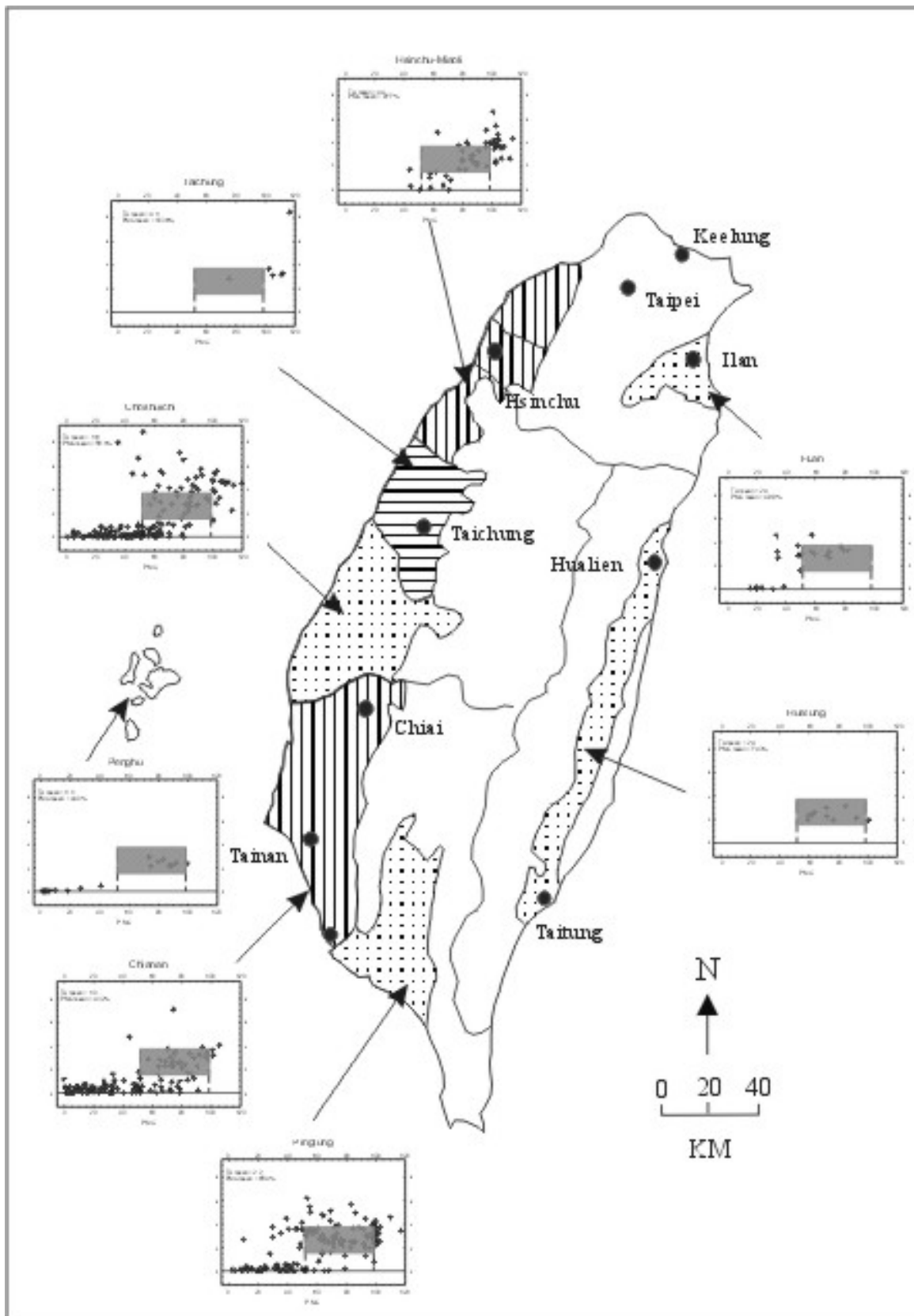


Figure 3. Tritium (TU) versus carbon-14 (as PMC) composition plots for eight Taiwan groundwater regions. The base patterns for Taiwan groundwater regions are adopted from WRPC (1992) referring to their hydraulic conductivities (dotted points: high; horizontal lines: intermediate; vertical lines: low).

Among eight groundwater regions, Penghu area shows the most typical decay pattern of TU and PMC contents in groundwaters. Two-group data points can be distinctly visualized and exemplify for shallow unconfined modern groundwaters and old deep confined groundwaters, respectively, in the Penghu groundwaters. Regions such as Hsinmiao, Taichung, and Huatung, reveal the sole modern nature of their groundwaters (mean TU > 2.4, mean PMC > 74%). Obviously, groundwaters of these regions are continuously renewed and can be qualitatively ranked as having a relatively high recharge/draft ratio. Therefore, their groundwater exploitations are potentially sustainable and adequate in terms of water resources. On the other hand, the wide spread and relative large variance of data points in excessive irrigation areas, such as Choshuichi, Chianan and Pingtung, demonstrate the intense and reiterating mixing between surface and groundwaters. Stable isotopes, chemical and water level data also support the same observation (Wang et al., 1997a; Wang and Liu, 1997; WRB, 1999). The very low  $^{14}\text{C}$  contents (PMC < 2%) found in these regions of deep confined aquifers are significantly heralding severe and alarming signals in groundwater utilization, and represent very low recharge/draft ratios in these regions. This warning notion means that we are actually mining the groundwater resources in a dangerous and inappropriate manner in these three groundwater regions. Appropriate remediable actions and measures are urgently needed to effectively alleviate the on-going groundwater crisis.

## CONCLUSIONS

Based on isotopic data collected thus far, Taiwan groundwaters can be qualitatively grouped into three categories in terms of water resource and utilization (Figure 1):

1. Good and abundant: Hsinmiao, Taichung, and Huatung belong to this category. These regions have relative high recharge/drafting ratio based on their high TU and PMC values. No seawater contaminations were observed for groundwaters.
2. Fair and normal: I-Lan and Taoyuan fit into this category. They have intermediate recharge/drafting ratios with minor seawater contaminations found in coastal groundwater samples.
3. Poor and alarming: Choshuichi, Chianan, Pingtung, and Penghu are in this category. These areas have relatively low recharge/drafting ratios with very low  $^{14}\text{C}$  compositions measured for groundwaters in deep aquifers. Severe seawater encroachments are also commonly observed along coastal aquifers. Appropriate remediable actions are urgently needed for a sustainable usage of groundwater resources in these regions.

These isotope signals presented above not only reflect the local meteorological and hydrological characteristics of groundwater basins, but also provide the essential and valuable isotopic database for a further study in Taiwan. With numerous GMNP data and stable isotope compositions on hand, we are now in a better position to conduct an integrated

research along with water-level, chemical, geophysical and any other relevant data for Taiwan groundwaters in the years to come.

## ACKNOWLEDGMENTS

This work was financially supported by Academia Sinica and National Science Council (NSC88-2116-M-001-017; NSC89-2116-M-001-019; NSC89-2116-M-001-023; NSC89-2116-M-001-036).

## REFERENCES

- CGS (Central Geological Survey). (1999) The seawater intrusion in aquifers of the Pingtung Plain. Central Geological Survey Report 88008, Ministry of Economic Affairs, Taipei, Taiwan, 77pp. (in Chinese)
- Chang, P.Y. (1994) Carbon-14 Dating and Hydrogeology of Groundwaters in Choshui Alluvial Fan, Changhua, Taiwan, M. S. Thesis, Department of Geology, National Taiwan University, Taipei, Taiwan, 66pp. (in Chinese)
- Chiang, C.J. and Wang, C.H. (1998). Seawater intrusion in the Pingtung Plain groundwaters. Proceedings of Symposium of Groundwater and Hydrogeology in the Pingtung Plain, March 1998, Taipei, Taiwan, 297-315. (in Chinese)
- Clark, I.D. and Fritz, P. (1997) Environmental Isotopes in Hydrogeology. Lewis Publishers, New York, USA, 328pp.
- Fontes, J.Ch.(1980) Environmental isotopes in groundwater hydrology. In; P. Fritz and J.Ch. Fontes, eds., Handbook of Environmental Isotope Geochemistry, p.75-140.
- Gat, J.R. (1980) The isotopes of hydrogen and oxygen in precipitation. In; P. Fritz and J.Ch. Fontes, eds., Handbook of Environmental Isotope Geochemistry, Elsevier Scientific Pub. Co., Amsterdam, p.21-47.
- Gat, J.R. (1981) Isotopic fractionation. In: Stable isotope Hydrology, Deuterium and oxygen-18 in the Water Cycle. IAEA Technical Reports Series 210, pp.21-34.
- Gat, J.R. (1996) Oxygen and hydrogen isotopes in the hydrologic cycle. *Annu. Rev. Earth Planet. Sci.*, **24**, 225-262.
- Gonfiantini, R. (1978) Standards for stable isotope measurements in natural compounds. *Nature*, 271:534-536.
- Gonfiantini, R. (1986) Environmental isotopes in lake studies. In; P. Fritz and J.-Ch. Fontes (Eds.), Handbook of Environmental Isotope Geochemistry, Vol.2, The Terrestrial Environment, B. Elsevier, Amsterdam, The Netherland, p.113-168.
- Ho, L.J. (1989) Preliminary study of groundwater geochemistry in the Peikang Area. MS thesis. National Sun Yat-Sun Memorial University, 76p. (in Chinese)
- Ho, L.Z., Wang, C.H. and Chen, C.T.A. (1990) Preliminary study of groundwater geochemistry in the Peikang area. *Jour. Environmental Protection, ROC*, **13**, 38-59. (in Chinese).

- Hsu, S.K. (1998) Plan for a groundwater monitoring network in Taiwan. *Hydrogeology Journal.*, **6**, 405-415.
- Hung, J.J. (1998) The effect of acid rain on the leaching and distribution of heavy metals in the soils. Institute of Marine Geology and Chemistry, National Sun Yat-Sea University, 123pp. (in Chinese)
- IAEA (International Atomic Energy Agency). (1981) Stable isotope hydrology: deuterium and oxygen-18 in the water cycle. IAEA. Gat, J.R. and Gonfiantini, R. (Editors), Vienna, Tech. Rep. Ser. No.210.
- IAEA (International Atomic Energy Agency). (1983) Guidebook on Nuclear Techniques in Hydrology. Technical Reports Series, No.91, 439pp.
- IAEA (International Atomic Energy Agency). (1992) Statistical Treatment of Data on Environmental Isotopes in Precipitation. Technical Reports Series, No.331, 781pp.
- ISO (International Organization for Standardization), (1992) ISO 31-0, Quantities and Units, part O, General Principles, subclause 2.3.3. International Organization for Standardization, Geneva.
- Lin, M.C. (1992) Carbon-14 Dating of Groundwaters in Choshui Alluvial Fan, Yulin, Taiwan, M. S. Thesis, Department of Geology, National Taiwan University, Taipei, Taiwan, 88pp. (in Chinese)
- Liu, K.K., Yui, T.F., Shieh, Y.N., Chen, L.H., Hu, C.Y. and Chiang, S.C. (1982) Carbon, hydrogen, and oxygen stable isotope geochemistry of the Chingshui geothermal area in Ilan. Institute of Earth Sciences, Academia Sinica, 73pp. (in Chinese).
- Liu, K.K., Chen, C.H., Shieh, Y.N. and Chiang, S.C. (1984) Carbon, hydrogen and oxygen stable isotope geochemistry of the Tatun geothermal area. Institute of Earth Sciences, Academia Sinica, ASIES-CR 8401, 39pp. (in Chinese).
- Liu, K.K., Yui, T.F., Shieh, Y.N., Chiang, S.C., Chen, L.H. and Hu, J.Y. (1990) Hydrogen and oxygen isotopic compositions of meteoric and thermal waters from the Chingshui geothermal area, northeastern Taiwan. *Proc. Geol. Soc. China*, **33**, 143-165.
- Liu, T.K. (1992) The  $^{14}\text{C}$  study of groundwaters from the Ping-Tung Plain. National Taiwan University, 40pp. (in Chinese)
- Liu, T.K. (1994) "Flow rate and recharge of groundwater in Choushuichi Fan-delta based on radiocarbon dating and tritium as a tracer", Proceedings of Symposium on Groundwater Resources and Water Quality Protection, Taipei, Taiwan, p.1-23. (in Chinese)
- Liu, T.K. (1995a) Carbon-14 dating study for groundwaters of the Pingtung Plain. Groundwater Monitoring Network Plan, Phase I, 1995 report, Water Conservancy Bureau, Taiwan Provincial Government, Taichung, Taiwan, 46pp. (in Chinese)
- Liu, T.K. (1995b) Tritium study for the Pingtung Plain groundwaters. Water Resources Planning Commission, Ministry of Economic Affairs, Taipei, Taiwan, 46pp. (in Chinese)
- Liu, T.K. (1996) Carbon-14 dating study for groundwaters. Groundwater Monitoring Network Plan, Phase I, 1996 report, Water Conservancy Bureau, Taiwan Provincial Government, Taichung, Taiwan, 43pp. (in Chinese)
- Liu, T.K. (1997a) Carbon-14 dating study for groundwaters. Groundwater Monitoring Network Plan, Phase I, 1997 report, Water Conservancy Agency, Taiwan Provincial Government, Taichung, Taiwan, 111pp. (in Chinese)

- Liu, T.K. (1997b) Carbon-14 dating and tritium study for groundwaters of the Chia-Nan Plain. Groundwater Monitoring Network Plan, Phase I, 1997 report, Water Resource Bureau, Ministry of Economic Affairs, Taipei, Taiwan, 112pp. (in Chinese)
- Liu, T.K., Tyan, C.L, Chiu, T.H. and Chang, Y.M. (1996) "Groundwater resource in Choushuichi Fan-Delta revealed by radiocarbon and tritium dating/tracer studies", Proceedings of Symposium on Groundwater and Hydrogeology of the Choushuichi Alluvial Fan, Taipei, Taiwan, p.145-164. (in Chinese)
- Peng, T.R. and Liu, T.K. (1992) Carbon-14 dating and its applications. *Ti-Chih*, **12**, 213-217. (in Chinese)
- Peng, T.R., Liu, T.K. and Wang, C.H. (1993) The preliminary results of hydrogen and oxygen isotopic compositions in Pingtung groundwaters. *Ti-Chih*, **13**, 117-130. (in Chinese)
- Peng, T.R., Liu, T.K. and Wang, C.H. (1994) The preliminary results of hydrogen and oxygen isotopic compositions in I-Lan groundwaters. Proceedings of Symposium on Groundwater Resources and Water Quality Protection, Taipei, Taiwan, p.165-184. (in Chinese)
- Peng, T.R. (1995) Environmental Isotopic Study ( $\delta^{13}\text{C}$ ,  $\delta\text{D}$ ,  $\delta^{18}\text{O}$ ,  $^{14}\text{C}$ , T) on Meteoric Water and Groundwaters in I-Lan Area. Ph.D. Dissertation, National Taiwan University, Taipei, Taiwan, 248pp. (in Chinese)
- Peng, T.R., Liu, T.K. and Wang, C.H. (1997) The  $^{14}\text{C}$  age correction of the groundwater in I-Lan Plain. *Ti-Chih*, **17**, 17-45. (in Chinese)
- Peng, T.R. (2000) Stable hydrogen and oxygen isotope study for Chia-Nan and I-Lan groundwaters. Groundwater Monitoring Network Plan, Phase II, 1999-2000 report, Central Geology Survey, Ministry of Economic Affairs, Taipei, Taiwan, 51pp. (in Chinese)
- Shieh, Y.N., Cherng, F.P. and Hoering, T.C. (1983) Oxygen and hydrogen isotope studies of meteoric and thermal waters in Taiwan. *Geol. Soc. China Mem.*, **5**, 127-140.
- Stuiver, M. and Polach, H. (1977) Reporting of  $^{14}\text{C}$  data. *Radiocarbon*, **19**, 355-363.
- Taylor, C.B. and Roether, W. (1982) A uniform scale for reporting low-level tritium measurements in water. *Int. J. Appl. Radiat. Isot.*, **33**, 377-382.
- Rozanski, K., Johnsen, S.J., Schotterer, U. and Thompson, L.G., (1997) "Reconstruction of past climates from stable isotope records of palaeo-precipitation preserved in continental archives". *Hydrological Sciences Journal*, **42**, 725-745.
- Wang, C.H., Chen, P.F., Peng, T.R. and Yeh, C.C. (1990) A preliminary report on stable isotope geochemistry in groundwaters of the Penghu Islands. Institute of Earth Sciences, IES-ER-705, Taipei, Taiwan, 36pp.
- Wang, C.H., Yeh, H.W., Tsai, P.S. and Wu, S.F. (1993) Hydrogen stable isotope determination of water samples by zinc shot reduction. Institute of Earth Sciences, IESER93-005, Taipei, Taiwan, 25pp.
- Wang, C.H., Peng, T.R., Tsai, P.S., Wu, S.F. Shieh, Y.T. and Cherng, F.P. (1994a) Stable isotope compositions of groundwaters from Penghu Islands and its implications. Proceedings of the First Symposium on Groundwater Resources and Water Protection, April 29, 1994, Taipei, Taiwan, ROC, p.147-163.
- Wang, C.H., Tsai, P.S., Wu, S.F., Peng, T.R. and Shieh, Y.T. (1994b) The preliminary study for the Chia-Nan hydrological cycle: Precipitation and groundwaters. Proceeding of

- Tseng-Wen-Chi Environmental Research Project (I), Academia Sinica, p.55-64. (in Chinese)
- Wang, C.H., Liu, W.C., Tsai, P.S., Wu, S.F., Peng, T.R. and Shieh, Y.T. (1994c) Preliminary results of stable isotope determinations for groundwaters of the alluvial plain in south Chia-Nan area, Taiwan. Institute of Earth Sciences, IESER94-003, Taipei, Taiwan, 56pp.
- Wang, C.H., Li, L.A. and Liu, W.C. (1994d) Some characteristics of the precipitation in Taiwan. In: C.I. Peng and C.H. Chou, Editors, Biodiversity and Terrestrial Ecosystem, Institute of Botany, Academia Sinica Monograph Series, No.14, pp.343-354.
- Wang, C.H., Liu, W.C., Tsai, P.S., Wu, S.F., Peng, T.R. and Shieh, Y.T. (1995) Preliminary results of isotope geochemistry on groundwaters from the alluvial plain in north Chia-Nan area, Taiwan. Institute of Earth Sciences, IESER95-005, Taipei, Taiwan, 45pp.
- Wang, C.H., Peng, T.R. and Liu, T.K. (1996a) The salinization of groundwater in the northern Lan-Yang Plain, Taiwan: stable isotope evidence. *Jour. Geol. Soc. China*, **39**, 627-636.
- Wang, C.H., Chang, T.C., Wang, L.W., Li, L.A. and Chen, J.T. (1996b) The limitation of water supply for the Chih-Kan Subsurface Reservoir, Penghu. Proceedings of the 1996 Annual Symposium of Agriculture Engineering Society, Changhua, Taiwan, ROC, p.633-639. (in Chinese)
- Wang, C.H., Lin, Y.L., Chang, T.C., Li, L.A., Lee, H.H., Chuang, T.M., Lin, K. and Lu, C.S. (1996c) The salinization of the Chih-Kan Subsurface Reservoir, Penghu. Institute of Earth Sciences, Academia Sinica, IESCR96-004, 83pp. (in Chinese)
- Wang, C.H., Chang, T.C., Lin, Y.L., Liu, W.C., Li, L.A., King, S.S., Chang, P.C. and Lan, F.S. (1996d) Natural recharge to the groundwaters in the Pingtung Plain, Taiwan: Isotope evidences. Institute of Earth Sciences, Academia Sinica, IESCR96-021, 72pp. (in Chinese)
- Wang, C.H. and Liu, W.C. (1997) Natural recharge to the groundwaters in the Chia-nan Plain, Taiwan: stable isotope evidences. Proceedings of the Second Symposium on Groundwater Resources and Water Protection, January 9-10, 1997, Tainan, Taiwan, ROC, p.827-838. (in Chinese)
- Wang, C.H., Chang, T.C., Liu, W.C. and Liu, T.K. (1997a) Isotope hydrological variations in the Pingtung area. Proceedings of the Workshop on the Long-term Water Resources Forecast, May 7, Taipei, Taiwan, p.119-131. (in Chinese)
- Wang, C.H., T.C. Chang, L.W. Wang, W.C. Liu, P. Yu, and H.C. Huang, (1997b) The Isotope Hydrologic Variations of the Yun-Lin Area, Taiwan. Institute of Earth Sciences, IESCR97-009, Taipei, Taiwan, 69pp. (in Chinese)
- Wang, C.H., Liu, W.C. and Yu, P. (1997c) Isotopic characteristics of groundwaters from the Meinung area, Taiwan. Proceedings of the 1997 Annual Symposium of Agriculture Engineering Society, Tainan, Taiwan, ROC, p.381-387. (in Chinese)
- Wang, C.H. and Liu, W.C. (1998a) Isotopic characteristics of groundwaters in the Pingtung Plain, southern Taiwan. Proceedings of Groundwater Quality 1998: Remediation and Protection, Tubingen, Germany, Sept. 21-25, p.60-62.
- Wang, C.H., Wang, L.W., Chen, S.F., Liu, W.C., Yu, P. and Huang, H.C. (1998b) Isotope hydrological variations in the Taichung-Changhua area, Taiwan. Institute of Earth Sciences, IESCR98-007, Taipei, Taiwan, 66pp. (in Chinese)

- Wang, C.H., Peng, T.R., Liu, W.C., Chiang, C.J., Yu, P. and Chen, W.F. (1999a) Groundwater recharge in the Yun-Lin area: isotopic evidences. Proceedings of the Third Symposium on Groundwater Resources and Water Protection, January 13-14, 1999, Chung-Li, National Central University, Taoyuan, Taiwan, ROC, p.319-329.
- Wang, C.H., Chiang, C.J., Peng, T.R. and Liu, W.C. (1999b) Deterioration of groundwater quality in the coastal Pingtung Plain, southern Taiwan. In: Impacts of Urban Growth on Surface Water and Groundwater Quality. J.B. Ellis, editor, (Proceedings of IUGG 99 Symposium HS5, July 19-30, 1999, Birmingham, UK), IAHS Publ., no.259, p.39-45.
- WRB (Water Resources Bureau). (1999) Groundwater Monitoring Network Plan in Taiwan, Phase I, 1992-1998 Projects Report, Water Resources Bureau, Ministry of Economic Affairs, Taipei, Taiwan, 385pp. (in Chinese)
- WRPC (Water Resources Planning Commission). (1992) The Groundwater Resources in Taiwan. Ministry of Economic Affairs, Taipei, Taiwan, 45pp. (in Chinese)
- WRPC (Water Resources Planning Commission), (1994) Carbon-14 Dating of Groundwaters in Hsinchu-Miaoli Area. Water Resources Planning Commission, Ministry of Economic Affairs, 54pp. (in Chinese)
- Yu, P., Wang, C.H. and Yang, T.F. (1998) The use of tritium to determine the mean residence time of the groundwater in the Pingtung Plain. The XIII Symposium of Southeast Asian Geotechnics Conference, Nov. 16-20, Taipei, Taiwan, p.727-732.