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ISOTOPE CHARACTERISTICS OF TAIWAN GROUNDWATERS

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

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 (Fig. 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 valuable and useful database for further integrating studies.

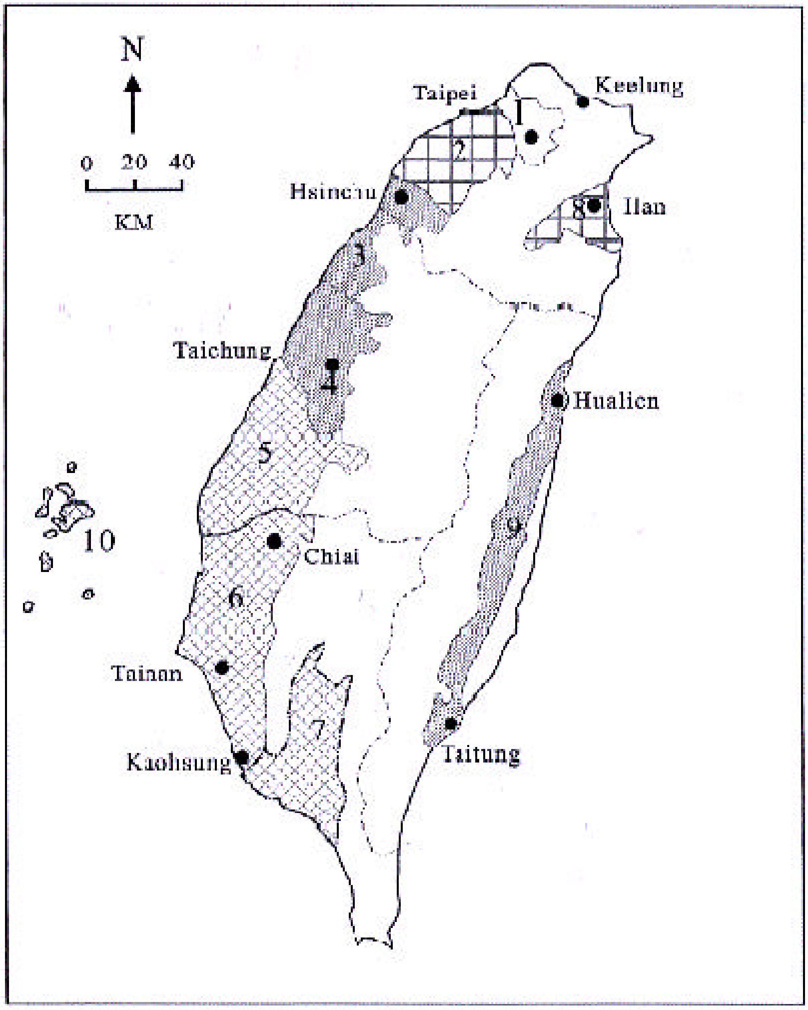

Figure 1. The groundwater regions in Taiwan (1: Taipei; 2: Taoyuan; 3: Hsinmiao; 4: Taichung; 5: Choshuichi; 6: Chianan; 7: Pingtung; 8:I-lan; 9: Huatung; 10: Penghu). Except the Taipei area, all other nine groundwater regions are qualitatively grouped and marked into three categories based on isotope 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 la., 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 precision expressed as 1σ for the laboratory standards are ±1.3‰ for δD and ±0.08‰ for $\delta^{18}O$, respectively. The average differences of duplicate analyses of water samples are ±1.5‰ for δD and ±0.11‰ for $\delta^{18}O$, 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 1σ uncertainties are ±0.1 TU for tritium and ±1% PMC for ^{14}C, respectively.

RESULTS AND DISCUSSION

Naturally occurring stable (H, O) and radiogenic (T, ^{14}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‰ to -4.3‰ per 100m for δD and -0.11‰ to -0.58‰ pre 100m for $\delta^{18}O$, 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}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}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	δD/100m	$\delta^{18}O$/100m	Local MWL
Taoyuan	-0.7	-0.11	$\delta D = 8.1\delta^{18}O + 14.2$
Hsinmiao	-1.6	-0.21	$\delta D = 7.6\delta^{18}O + 8.6$
Taichung	-1.4	-0.20	$\delta D = 7.9\delta^{18}O + 12.8$
Choshuichi	-1.3	-0.19	$\delta D = 8.1\delta^{18}O + 13.8$
Chianan	-4.3	-0.58	$\delta D = 7.9\delta^{18}O + 11.8$
Pingtung	-4.3	-0.55	$\delta D = 7.5\delta^{18}O + 7.4$
Penghu	-	-	$\delta D = 8.0\delta^{18}O + 10.1$
I-Lan	-2.8	-0.38	$\delta D = 8.9\delta^{18}O + 20.3$
Huatung	-3.0	-0.39	$\delta D = 8.3\delta^{18}O + 14.4$

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

Region	Dry Season				Wet Season			
	Number of samples	δD_{max}	δD_{min}	δD_{mean}	Number of samples	δD_{max}	δD_{min}	δD_{mean}
Taoyuan	45	-22	-45	-33	-	-	-	-
Hsinmiao	17	-29	-55	-41	20	-30	-53	-43
Taichung	18	-41	-61	-55	17	-44	-55	-51
Choshuichi	403	-40	-73	[illegible]	72	-37	-75	-43
Chianan	152	2	-61	-41	133	1	-37	-42
Pingtung	481	3	-77	-58	53	-9	-33	-37
Penghu	256	6	-50	-35	193	1	-50	-33
Ilan	91	7	-46	-25	45	-13	-40	-21
Hualung	29	-41	-65	-65	41	19	79	-37

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	-4.2	-7.5	-5.4		-	-	-
Hsinmiao	17	-4.8	-8.3	-6.9	20	-5.5	-8.2	-6.6
Taichung	13	-6.0	-9.0	-7.8	11	-6.7	-8.6	-7.8
Choshuichi	403	-2.5	-10.1	-7.8	72	-4.4	-10.5	-6.5
Chianan	152	1.3	-8.7	-6.4	133	0.4	-5.1	-6.3
Pingtung	481	-5.1	-10.6	-8.3	52	-5.5	-10.1	-8.5
Penghu	256	0.9	-7.6	-5.6	193	-0.2	-7.2	-6.5
Ilan	91	-0.1	-8.4	-5.7	45	-5.1	-6.5	-5.8
Hualung	29	-7.0	-12.1	-9.2	45	-6.7	-10.8	-8.9

In Figure 2, the seasonal features of stable isotope compositions expressed as δD 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 (δD < 40‰, $\delta^{18}O$ < 5‰) 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 (δD > 60‰, $\delta^{18}O$ > 6‰) and extreme enriched values (δD > 0‰, $\delta^{18}O$ > -0.9‰). 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).

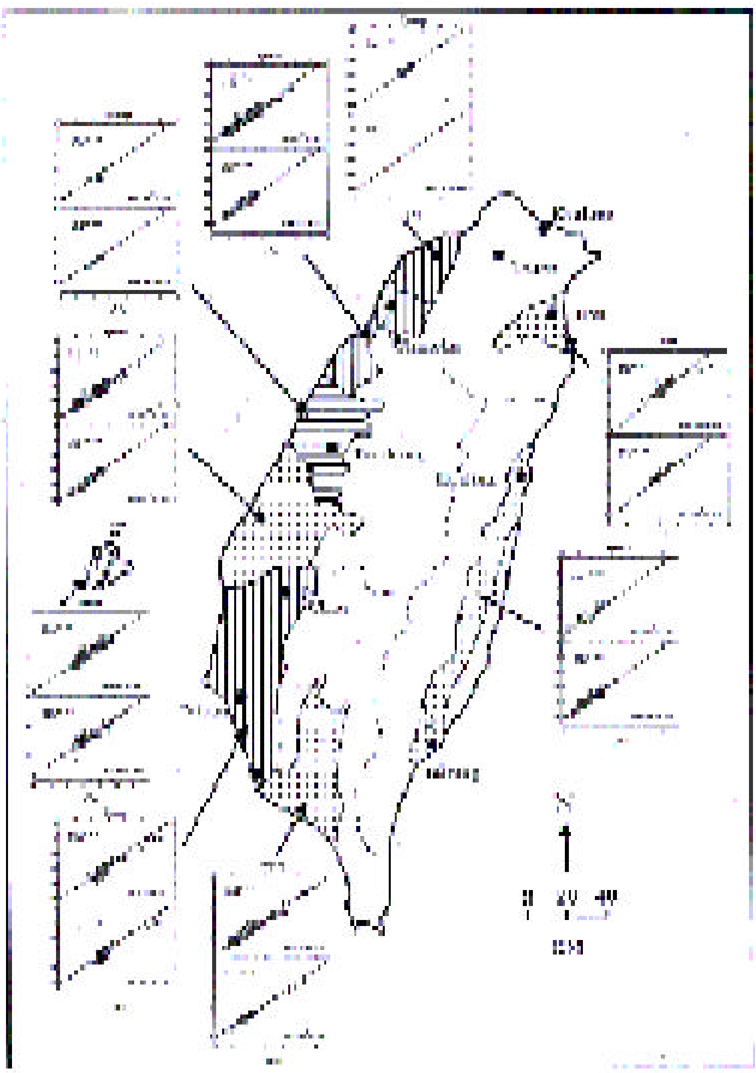

Figure 2. Hydrogen versus oxygen isotope plots for nine Taiwan groundwater regions. The base patterns for Taiwan groundwater regions are adopted from WRPC (1992) referring to their hydraulic conductivities (dotted points: high; horizontal lines: intermediate; vertical lines: low).

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 (Tab. 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 ($\delta D < -56‰$, $\delta^{18}O < -8.3‰$), indicating their high-elevation locations for groundwater recharging. On the other hand, Taoyuan, Penghu and I-Lan regions show relatively enriched values ($\delta D > -35‰$, $\delta^{18}O > -5.9‰$), 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 (Tab. 1). Nonetheless, their mean groundwater values are distinctly different by about 10‰ for δD and 2‰ for $\delta^{18}O$, 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}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	0.9	1.9	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	[illegible]
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

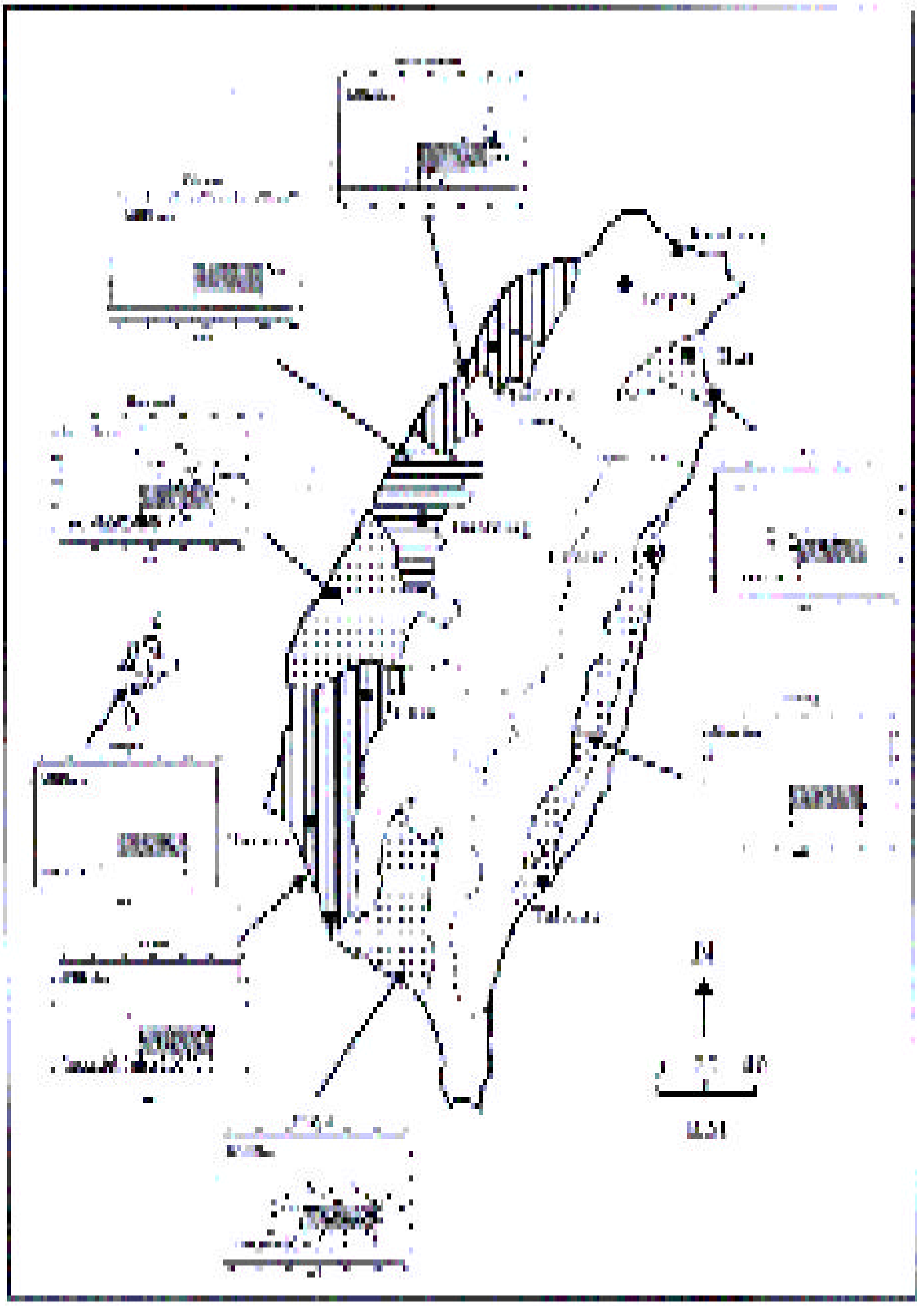

Figure 3. Tritium (TU) versus carbon-14 (as PMC) composition plots for eight Taiwan groundwater regions. The base patterns for Taiwan groundwater regions are adopted from WRPC (1992) referring to their hydraulic conductivities (dotted points: high; horizontal lines: intermediate; vertical lines: low).

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 ground- waters. 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}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 (Fig. 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}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.

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