

## Thematic Article

# Some isotopic and hydrological changes associated with the 1999 Chi-Chi earthquake, Taiwan

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**Abstract** The changes in the isotopic composition of, and the groundwater level in, the Choshui River alluvial fan near the ruptured Chelungpu Fault during and following the 1999 ( $M_w = 7.5$ ) Chi-Chi earthquake in Taiwan are reported. Three aspects of the hydrological changes are noticed. First, following the Chi-Chi earthquake, the lower aquifers beneath the Choshui River fan showed a significant shift in isotopic composition towards that of the surface water in the Choshui River, suggesting enhanced exchanges of water between the river and the groundwater. Second, in some wells, water levels and isotopic compositions in different aquifers converged to the same respective values during the Chi-Chi earthquake, suggesting coseismic exchanges of water between the different aquifers, which implies enhanced permeability due perhaps to the fracturing and breaching of aquitards between the aquifers. Third, the pattern of the coseismic water-level response is distinctly different from that of the shift in the isotopic composition, suggesting that they were produced by different mechanisms.

**Key words:** Chi-Chi earthquake, groundwater flow, groundwater level, oxygen isotope.

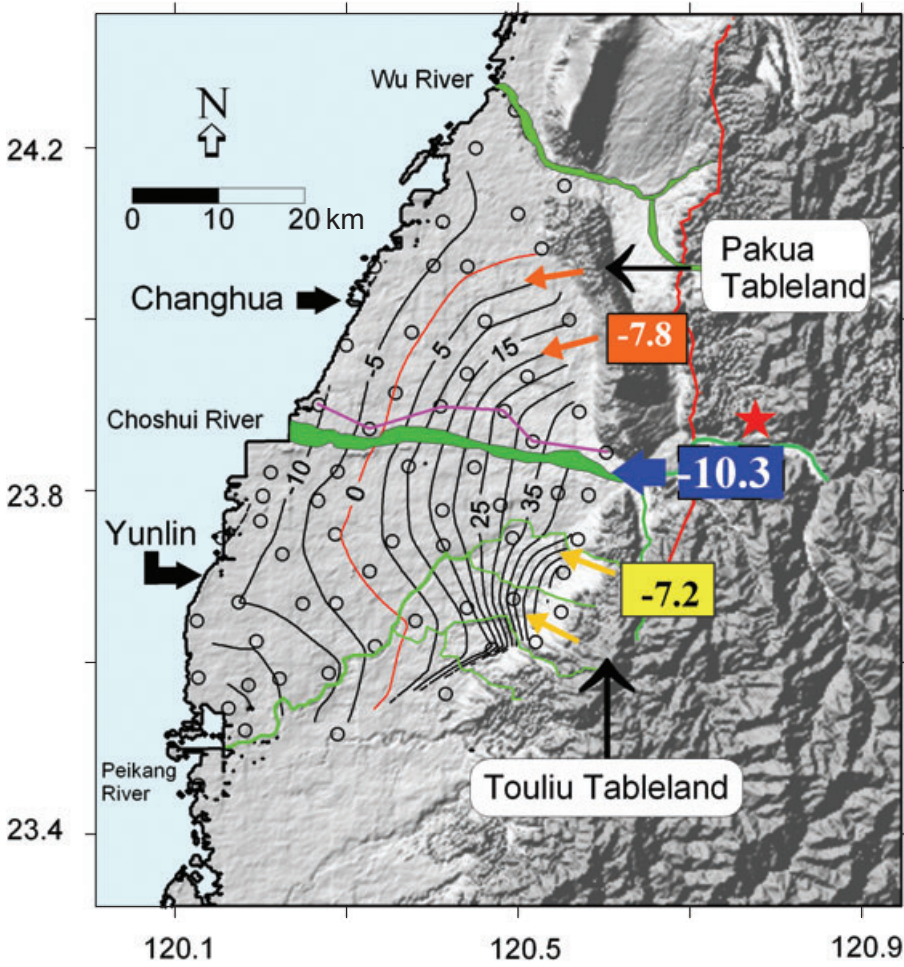
## INTRODUCTION

The 1999 Chi-Chi earthquake ( $M_w = 7.5$ ) on 20 September in central Taiwan (Ma *et al.* 1999) stands as one of the most important geological events in the past century in Taiwan. It ruptured a ~80-km north–south trending segment along the westward Chelungpu thrust (Fig. 1) and has produced profound impacts on the local groundwater hydrology (WCA 1999; Chia *et al.* 2001; 2002; Wang *et al.* 2001a; Lee *et al.* 2002). The Choshui River fan, the largest alluvial fan (1800 km<sup>2</sup>) in Taiwan, is on the west of the Chelungpu thrust fault. The Choshui River (green in color) flows through the middle of the fan and separates it into two sections: northern Changhua and southern Yunlin. Drilling logs in the fan show that it consists of several unconfined and

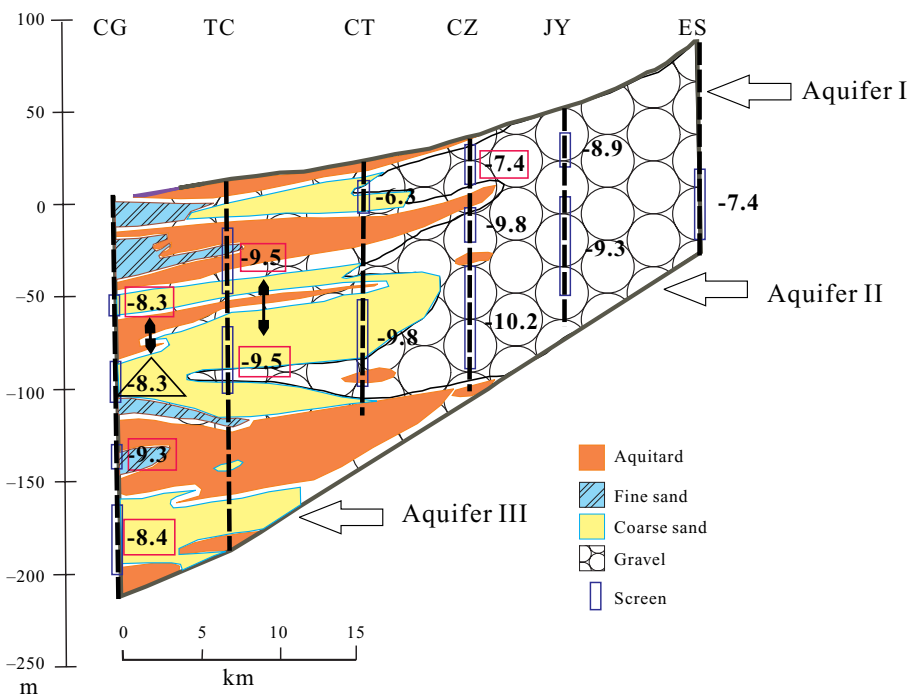
confined aquifers of Holocene to Pleistocene sand and gravel, separated by impermeable marine mud (WCA 1997; Chen & Yuan 1999). From 1992 to 1997, 188 wells were installed at 70 evenly distributed hydrological stations on the Choshui River fan, ranging in depths from 24 to 306 m and at distances of 1 to 50 km from the Chelungpu Fault (Hsu 1998; WRB 1999a). Each station has one to five screens. Generally, the Choshui River fan can be divided into three aquifers to a depth of 250 m according to subsurface hydrogeology (Fig. 2; WRB 1999a). Aquifer I, the top aquifer, is mostly unconfined, with partial confinement at the coastal region, and Aquifers II and III are confined. The groundwater levels of these aquifers indicate two major flow directions: northwest and southwest.

The groundwater levels in the aquifers, measured by piezometers, are recorded digitally every hour (WRB 1999a). During the Chi-Chi earthquake, these wells recorded, for the first time, the widespread response of the groundwater levels of

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**Fig. 1** The Choshui River alluvial fan and the 1999 Chi-Chi earthquake (red star). Traces of the Chelungpu Fault are shown by the solid red line. The Choshui River (in green) flows through the middle of the fan and separates it into two sections: northern Changhua and southern Yunlin. Two other main streams are the Wu River at the upper part and the Peikang River at the lower part of the Choshui River alluvial fan. The groundwater stations of the monitoring network are shown by open circles. The groundwater levels of Aquifer II on 20 September 1999 (one hour before the earthquake) are shown as contour lines with a 5-m interval. The 0-m level is expressed as a thin red line. Negative groundwater levels are found on the west side of the 0-m line. The oxygen isotope compositions of modern recharges from three sources (top: Pakua Tableland [-7.8‰]; middle: Choshui River [-10.3‰]; bottom: Touliu Tableland [-7.2‰]) are shown. The pink line that parallels the Choshui River represents the location of the cross-section shown in Figure 2.



**Fig. 2** Cross-section from Ershui (ES) to Shikong (CG) (the pink line shown in Figure 1) showing the general features of three aquifers in the Choshui River alluvial fan. Three aquifers can be identified from top (Aquifer I) to bottom (Aquifer III). The vertical dashed lines represent boreholes. The numbers represent the oxygen isotope values for each sampling site after the Chi-Chi earthquake. The squares represent sites that had depleted oxygen isotope values after the earthquake, while the triangles represent sites that had increased oxygen isotope values.

various aquifers for the entire fan (WCA 1999). These data provide a basis for understanding groundwater hydrology, aquifer hydraulic properties and seismic wave propagation in alluvial sediments, earthquake-related liquefaction and landslides.

As part of the isotope hydrology study in Taiwan, oxygen isotope compositions for the same set of monitoring wells in the Choshui River fan were measured from 1999 to 2001, before and after the Chi-Chi earthquake. Stable isotopes of hydrogen and oxygen are very useful for hydrogeological investigations because: (i) they are constituents of water molecules and follow their behavior through hydrological cycles; and (ii) they are conservative in low-temperature and low-circulation systems, as long as the relative amount of water involved in chemical reactions remains limited (IAEA 1983). Stable isotopic data can be used to: (i) identify rapid pathways for surface water entry into shallow aquifers; (ii) study the influence of structures such as faults and geological contacts on local subsurface permeability and fluid flow; (iii) determine local groundwater flow directions and rates; (iv) understand vadose zone processes, such as evaporation; (v) estimate the migration of saturation fronts; (vi) assess the groundwater discharge into streams under base flow conditions; and (vii) evaluate freshwater and seawater mixing in coastal aquifers (Fritz & Fontes 1980; Gat & Gonfiantini 1981; Clark & Fritz 1997).

In this study, the preseismic and postseismic changes in the oxygen isotope and coseismic groundwater level in the aquifers of the Choshui River fan are first presented. Some implications regarding the groundwater flow patterns before and after the earthquake are then discussed.

## OXYGEN ISOTOPE VARIATIONS

Water samples were collected from 153 wells in the 64 stations of the Groundwater Monitoring Program in the Choshui River fan for stable isotope analysis in 1999 (January–March), 2000 (June–August) and 2001 (May–July) during the routine annual maintenance. An extra set of groundwater samples was extracted immediately following the Chi-Chi earthquake (October–December 1999) to evaluate the impact of the earthquake on groundwater hydrology. There are 41 wells in Aquifer I, 61 wells in Aquifer II and 51 wells in Aquifer III. Details regarding the date, location and description of each sample and sampling site can be found

in the reports of the Water Resource Bureau, Taiwan (WRB 1999b; 2000; 2001).

The water samples were prepared and their oxygen isotope compositions were analyzed at the Institute of Earth Sciences, Academia Sinica according to well-established methods (IAEA 1983) and expressed in  $\delta^{18}\text{O}$  (per mill, ‰) notation relative to standard mean ocean water (SMOW) standards (Gonfiantini 1978; ISO 1992). The analytical precision is  $\pm 0.1\text{‰}$ . According to previous studies, the seasonal variations in groundwater samples of confined aquifers are found to be less than  $0.4\text{‰}$  for  $\delta^{18}\text{O}$  in our study area (Wang *et al.* 1998; 1999). In other words, the natural background variation would be smaller than two standard deviations of the analytical precision.

All oxygen isotope data from the monitoring wells are listed in Tables 1–3. Figures 3–5 present the contours of oxygen isotope values and the difference compared with the preseismic values for Aquifers I, II and III, respectively, from 1999 to 2001. The modern recharge values that have been identified from three distinctive sources of the Choshui River fan ( $-7.8\text{‰}$  for the Pakua Tableland,  $-10.3\text{‰}$  for the Choshui River and  $-7.2\text{‰}$  for the Touliu Tableland) are shown in Figure 1 for comparison (Wang *et al.* 1998; 1999; 2001b). The groundwater in the aquifers of the Choshui River fan is primarily a mix of these three end-members (Pakua Tableland, Choshui River and Touliu Tableland). The waters from the Pakua Tableland and the Choshui River infiltrate toward the Changhua section north of the Choshui River, while those from the Touliu Tableland and the Choshui River infiltrate toward the Yunlin section south of the Choshui River (WCA 1997; WRB 1999a). Assuming a linear mixing model between two different sources, the contributing percentage of the Choshui River in each sampling site can be estimated:

$$\delta^{18}\text{O}_M = P \times \delta^{18}\text{O}_{CR} + (1 - P) \times \delta^{18}\text{O}_T \quad (1)$$

In Equation (1),  $\delta^{18}\text{O}_M$ ,  $\delta^{18}\text{O}_{CR}$ , and  $\delta^{18}\text{O}_T$  represent the oxygen isotope values of the monitoring well, the Choshui River and the Pakua (or Touliu) Tableland, respectively, and  $P$  is the contribution percentage of the Choshui River. The estimated percentages in each sampling well are also listed in Tables 1–3.

## AQUIFER I

Among the three aquifers in the Choshui River fan, the unconfined top Aquifer I is, on the whole,



Wentso	WR(1)	1/20/1999	-6.0	0	10/27/1999	-6.1	0	6/28/2000	-6.0	0	7/3/2001	-6.6	0
Kanchiao	KC(1)	3/25/1999	-7.0	0	11/15/1999	-7.5	11	7/12/2000	-7.1	0	6/17/2001	-7.1	0
Tzetung	TN(1)	2/2/1999	-7.9	21	11/10/1999	-8.2	33	6/21/2000	-7.8	21	6/19/2001	-8.3	36
Chiulung	JL(1)	1/21/1999	-6.7	0	10/28/1999	-7.7	16	6/27/2000	-6.5	0	7/4/2001	-6.7	0
Huhsi	HH(1)	2/1/1999	-6.8	0	11/15/1999	-6.6	0	6/21/2000	-6.4	0	6/19/2001	-6.7	0
Tienyang	TY(1)	1/21/1999	-7.6	14	11/2/1999	-6.8	0	7/3/2000	-8.3	34	6/11/2001	-8.2	33
Honglung	HR(1)	1/25/1999	-7.2	1	10/28/1999	-7.4	7	6/27/2000	-6.9	0	7/4/2001	-7.3	2
Tungkuang	TK(1)	1/18/1999	-6.6	0	11/1/1999	-6.2	0	6/26/2000	-5.4	0	6/26/2001	-5.4	0
Chiuchuang	GC(1)	1/19/1999	-3.9	0	10/26/1999	-4.0	0	7/6/2000	-3.4	0	7/2/2001	-3.6	0
Haiyuan	HY(1)	1/26/1999	-6.3	0	11/8/1999	-6.4	0	7/4/2000	-6.2	0	6/13/2001	-6.2	0
Minte	MT(1)	1/12/1999	-7.0	0	10/20/1999	-6.9	0	6/20/2000	-6.3	0	5/30/2001	-6.7	0
Paotze	BT(1)	1/13/1999	-7.1	0	10/18/1999	-7.1	0	6/15/2000	-6.3	0	7/5/2001	-7.3	2
Kinghu	KH(1)	1/13/1999	-2.2	0	10/18/1999	-2.6	0	6/15/2000	-2.2	0	5/28/2001	-2.2	0
I-wu	IW(1)	1/14/1999	-6.5	0	10/21/1999	-6.5	0	7/10/2000	-6.2	0	6/27/2001	-6.8	0
Sanho	SH(1)	1/19/1999	-5.9	0	11/2/1999	-5.3	0	7/3/2000	-5.2	0	6/11/2001	-5.4	0
Tungjung	TR(1)	11/16/1998	-7.2	0	10/13/1999	-6.9	0	6/13/2000	-6.4	0	5/23/2001	-6.7	0
Anho	AH(1)	1/7/1999	-6.8	0	10/14/1999	-6.9	0	6/14/2000	-6.4	0	5/24/2001	-6.7	0
Tungshi	TS(1)	1/6/1999	-7.1	0	10/12/1999	-6.9	0	6/12/2000	-6.7	0	5/22/2001	-7.0	0
Entire Choshui River fan		Maximum	-2.2	24		-2.6	33		-2.2	34		-2.2	41
		Minimum	-8.4	0		-8.5	0		-8.4	0		-8.5	0
		Average	-6.6	3		-6.8	6		-6.6	5		-6.8	6
Changhua section		Maximum	-3.5	22		-4.3	26		-4.6	26		-4.4	22
		Minimum	-8.4	0		-8.5	0		-8.4	0		-8.4	0
		Average	-6.5	2		-7.0	6		-6.8	6		-6.8	4
Yunlin section		Maximum	-2.2	24		-2.6	33		-2.2	34		-2.2	41
		Minimum	-7.9	0		-8.2	0		-8.3	0		-8.5	0
		Average	-6.7	4		-6.7	6		-6.4	4		-6.7	7

$\delta^{18}\text{O}$ , oxygen isotope value; CS, contribution percentage.



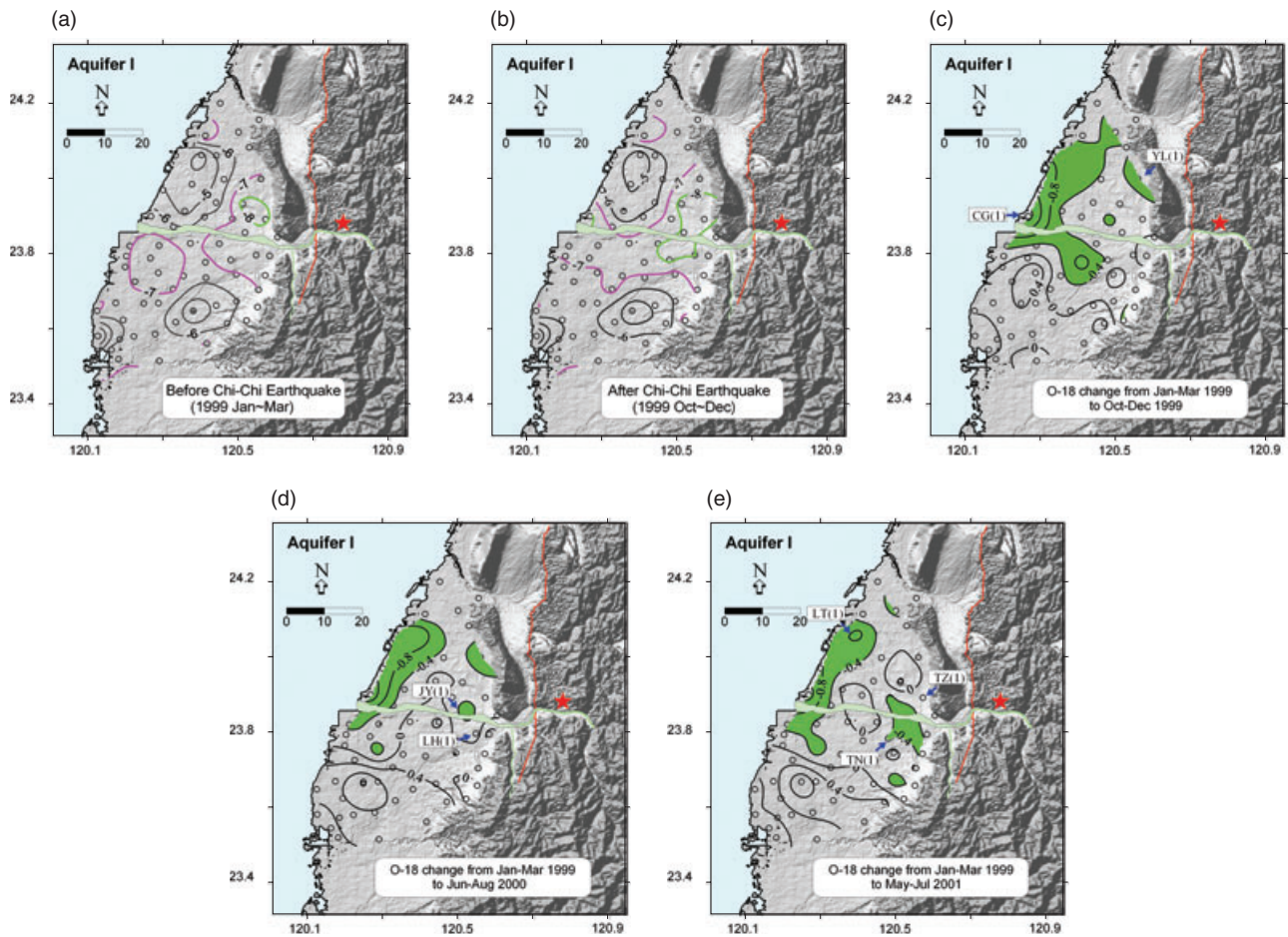
Kanchiao	KC(2)	3/25/1999	-6.8	0	11/15/1999	-7.4	8	7/12/2000	-7.0	0	6/17/2001	-7.1	0
Chiahsin	GH(2)	1/20/1999	-7.0	0	10/27/1999	-7.2	0	6/28/2000	-6.7	0	7/3/2001	-7.1	0
Lungtze	LZ(2)	2/2/1999	-7.1	0	10/26/1999	-7.3	4	7/6/2000	-7.1	0	7/5/2001	-7.2	1
Tzetung	TN(2)	2/2/1999	-8.1	28	11/10/1999	-8.2	31	6/21/2000	-7.3	3	6/19/2001	-8.0	26
Chiulung	JL(2)	1/21/1999	-8.6	46	10/28/1999	-8.7	47	6/27/2000	-8.1	28	7/4/2001	-8.5	42
Hushi	HH(2)	2/1/1999	-8.2	31	11/15/1999	-8.2	31	6/21/2000	-7.3	4	6/19/2001	-8.0	26
Huwei	HE(1)	1/20/1999	-8.1	28	11/2/1999	-8.6	44	7/3/2000	-8.2	33	6/11/2001	-8.5	42
Fangtsao	FT(2)	1/25/1999	-8.0	24	10/28/1999	-8.0	24	6/27/2000	-7.3	4	7/2/2001	-7.7	15
Tienyang	TY(2)	1/21/1999	-8.2	32	11/2/1999	-8.2	33	7/3/2000	-8.4	39	6/11/2001	-8.1	29
Hsinhua	HU(1)	1/27/1999	-9.4	70	11/4/1999	-9.3	67	7/5/2000	-8.8	53	6/15/2001	-9.5	74
Hofeng	HG(1)	1/26/1999	-8.5	42	11/8/1999	-8.3	37	7/4/2000	-8.3	36	6/13/2001	-8.5	41
Haifeng	HF(1)	1/27/1999	-7.8	18	11/4/1999	-8.5	40	7/5/2000	-7.8	19	6/15/2001	-7.9	21
Yuanchang	YC(1)	1/14/1999	-7.0	0	10/21/1999	-7.0	0	7/10/2000	-6.8	0	6/27/2001	-7.1	0
Tungkuang	TK(3)	1/18/1999	-7.2	0	11/1/1999	-7.2	0	6/26/2000	-6.8	0	6/26/2001	-7.0	0
Chiuchuang	GC(3)	1/19/1999	-7.1	0	10/26/1999	-7.0	0	7/6/2000	-6.1	0	7/2/2001	-6.9	0
An-nan	AN(1)	1/18/1999	-8.1	29	11/1/1999	-8.0	27	6/26/2000	-7.3	2	7/5/2001	-7.8	19
Haiyuan	HY(2)	1/26/1999	-6.9	0	11/8/1999	-7.0	0	7/4/2000	-6.3	0	6/13/2001	-6.7	0
Minte	MT(3)	1/12/1999	-7.3	3	10/20/1999	-7.3	2	6/20/2000	-6.6	0	5/30/2001	-7.1	0
Paotze	BT(2)	1/13/1999	-7.4	7	10/18/1999	-7.6	13	6/15/2000	-7.1	0	7/5/2001	-7.6	14
Peikang	PK(1)	1/11/1999	-7.3	4	10/19/1999	-7.4	7	6/19/2000	-7.4	6	5/29/2001	-7.5	10
Tsaitso	TT(1)	1/12/1999	-7.2	1	10/20/1999	-7.1	0	6/20/2000	-6.8	0	6/26/2001	-7.2	0
Shulin	SN(1)	1/11/1999	-7.6	14	10/19/1999	-7.6	13	6/19/2000	-7.1	0	5/29/2001	-7.8	18
Takuo	TG(1)	1/11/1999	-7.5	11	10/19/1999	-7.7	15	6/20/2000	-6.9	0	5/29/2001	-7.5	9
Kinghu	KH(2)	1/13/1999	-7.1	0	10/18/1999	-7.2	1	6/15/2000	-6.7	0	5/28/2001	-6.9	0
I-wu	IW(2)	1/14/1999	-6.2	0	10/21/1999	-7.2	1	7/10/2000	-6.7	0	6/27/2001	-6.8	0
Chiungpu	CP(2)	1/7/1999	-7.1	0	10/14/1999	-7.2	0	6/14/2000	-6.6	0	5/24/2001	-7.1	0
Sanho	SH(2)	3/16/1999	-7.4	7	11/2/1999	-7.5	9	7/3/2000	-7.2	0	6/11/2001	-7.6	13
Tungjung	TR(2)	11/16/1998	-8.0	25	10/13/1999	-7.9	24	6/13/2000	-7.1	0	5/23/2001	-7.8	21
Anho	AH(2)	1/7/1999	-6.9	0	10/14/1999	-6.9	0	6/14/2000	-5.8	0	5/24/2001	-7.1	0
Tungshi	TS(2)	1/6/1999	-6.7	0	10/12/1999	-6.9	0	6/12/2000	-6.7	0	5/22/2001	-7.0	0
Entire Choshui River fan		Maximum	-6.2	100		-6.3	100		-5.8	96		-6.4	94
		Minimum	-10.3	0		-10.3	0		-10.2	0		-10.2	0
		Average	-8.0	27		-8.2	32		-7.8	23		-8.0	25
Changhua section		Maximum	-6.2	100		-6.3	100		-5.9	96		-6.4	94
		Minimum	-10.3	0		-10.3	0		-10.2	0		-10.2	0
		Average	-8.7	41		-9.0	52		-8.7	44		-8.6	37
Yunlin section		Maximum	-6.2	84		-6.8	86		-5.8	62		-6.5	79
		Minimum	-9.8	0		-9.9	0		-9.1	0		-9.7	0
		Average	-7.6	18		-7.8	20		-7.3	11		-7.7	18

$\delta^{18}\text{O}$ , oxygen isotope value; CS, contribution percentage.



Tienyang	TY(3)	1/21/1999	-7.2	0	11/2/1999	-7.0	0	7/3/2000	-7.0	0	6/11/2001	-7.0	0
Hsinhua	HU(3)	1/27/1999	-7.2	0	11/4/1999	-7.2	1	7/5/2000	-6.8	0	6/15/2001	-7.5	9
Hofeng	HG(2)	1/26/1999	-6.8	0	11/8/1999	-6.8	0	7/4/2000	-6.6	0	6/13/2001	-6.9	0
Haifeng	HF(2)	1/27/1999	-7.2	0	11/4/1999	-7.1	0	7/5/2000	-7.1	0	6/15/2001	-7.1	0
Honglung	HR(2)	1/25/1999	-7.2	0	10/28/1999	-7.0	0	6/27/2000	-6.5	0	7/4/2001	-7.2	0
Tungkuang	TK(4)	1/18/1999	-7.2	0	11/1/1999	-7.3	3	6/26/2000	-6.7	0	6/26/2001	-7.1	0
Tungkuang	TK(5)	1/18/1999	-7.2	0	11/1/1999	-7.4	5	6/26/2000	-7.6	13	6/26/2001	-7.5	8
Chiuchuang	GC(4)	1/19/1999	-7.1	0	10/26/1999	-7.2	0	7/6/2000	-7.1	0	7/2/2001	-6.9	0
Chiuchuang	GC(5)	1/19/1999	-6.9	0	10/26/1999	-7.1	0	7/6/2000	-7.1	0	7/2/2001	-6.9	0
An-nan	AN(2)	1/18/1999	-7.1	0	11/1/1999	-7.1	0	6/26/2000	-6.6	0	7/5/2001	-7.1	0
Haiyuan	HY(3)	1/26/1999	-6.8	0	11/8/1999	-7.0	0	7/4/2000	-6.7	0	6/13/2001	-6.9	0
Haiyuan	HY(4)	1/26/1999	-7.1	0	11/8/1999	-7.7	15	7/4/2000	-6.9	0	6/13/2001	-7.1	0
Minte	MT(4)	1/12/1999	-7.3	5	10/20/1999	-7.3	2	6/20/2000	-7.1	0	5/30/2001	-7.2	0
Paozte	BT(3)	1/13/1999	-7.2	0	10/18/1999	-7.3	2	6/15/2000	-7.4	7	7/5/2001	-6.9	0
Shuilin	SN(2)	1/11/1999	-7.9	23	10/19/1999	-7.8	19	6/19/2000	-6.5	0	5/29/2001	-7.5	8
Takuo	TG(2)	1/11/1999	-7.6	12	10/19/1999	-7.5	11	6/20/2000	-7.1	0	5/29/2001	-7.4	8
I-wu	IW(3)	1/14/1999	-6.7	0	10/21/1999	-7.1	0	7/10/2000	-6.8	0	6/27/2001	-6.9	0
I-wu	IW(4)	1/14/1999	-6.8	0	10/21/1999	-7.0	0	7/10/2000	-6.3	0	6/27/2001	-6.9	0
Tungjung	TR(3)				10/13/1999	-8.0	26	6/13/2000	-7.3	3	5/23/2001	-7.6	14
Tungjung	TR(4)				10/13/1999	-7.8	18	6/13/2000	-7.2	0	5/23/2001	-7.1	0
Anho	AH(4)	1/7/1999	-7.2	1	10/14/1999	-7.4	6	6/14/2000	-6.9	0	5/24/2001	-6.8	0
Tungshi	TS(3)	1/6/1999	-6.8	0	10/12/1999	-6.9	0	6/12/2000	-7.0	0	5/22/2001	-6.9	0
Tungshi	TS(4)	1/6/1999	-7.1	0	10/12/1999	-7.0	0	6/12/2000	-6.8	0	5/22/2001	-6.9	0
Entire Choshui River fan		Maximum	-6.6	98		-6.8	95		-6.3	90		-6.6	79
		Minimum	-10.2	0		-10.2	0		-10.0	0		-9.8	0
		Average	-7.8	18		-8.0	24		-7.7	18		-7.8	16
Changhua section		Maximum	-6.6	98		-7.0	95		-6.4	90		-6.6	79
		Minimum	-10.2	0		-10.2	0		-10.0	0		-9.8	0
		Average	-8.4	32		-8.9	46		-8.6	37		-8.5	30
Yunlin section		Maximum	-6.7	64		-6.8	68		-6.3	58		-6.8	56
		Minimum	-9.2	0		-9.3	0		-9.0	0		-8.9	0
		Average	-7.3	6		-7.4	8		-7.0	4		-7.2	5

$\delta^{18}\text{O}$ , oxygen isotope value; CS, contribution percentage.

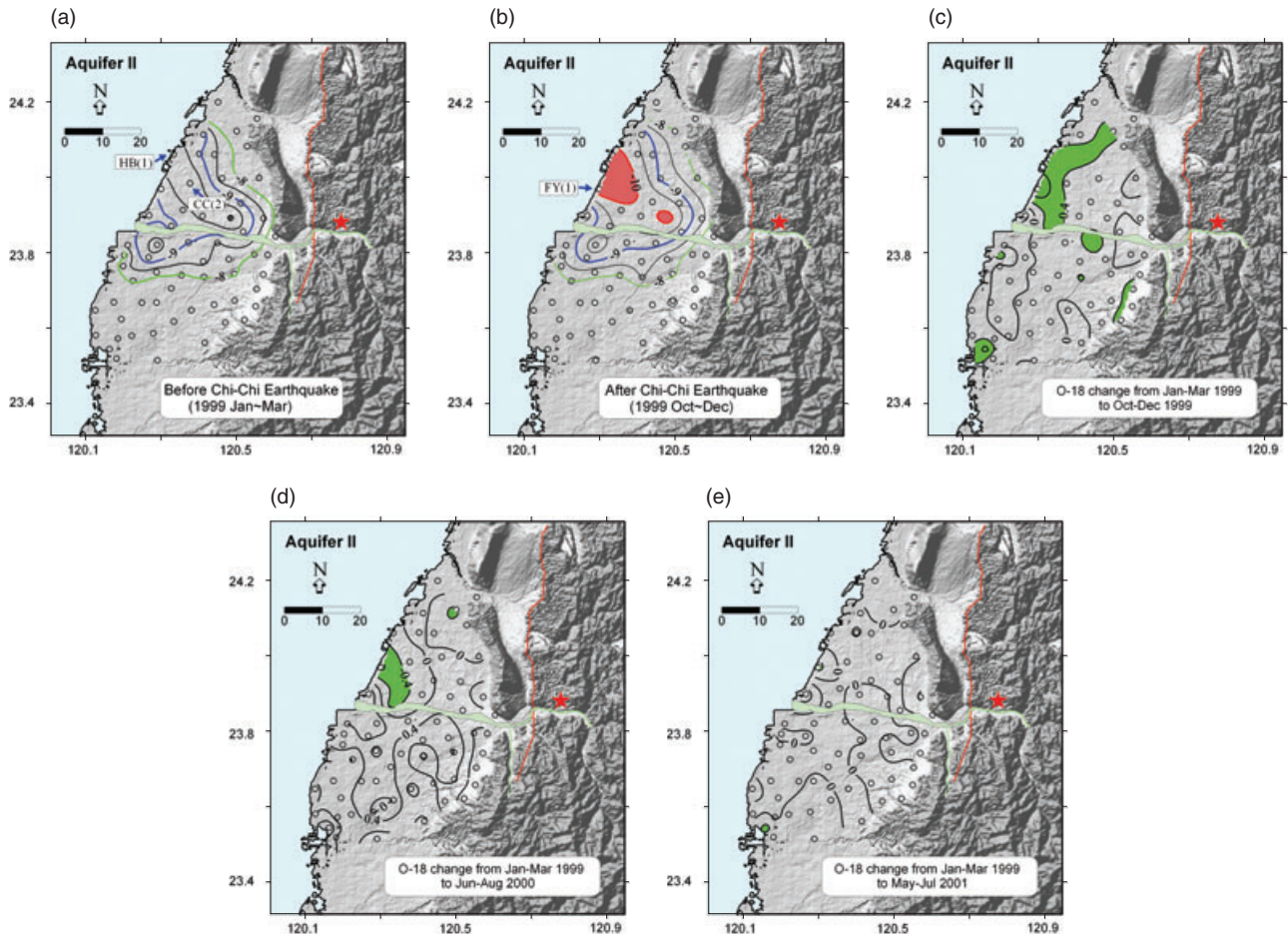


**Fig. 3** Oxygen isotope contours for Aquifer I from 1999 to 2001. The open circles are the sampling wells. The absolute  $\delta^{18}\text{O}$  values in 1‰ intervals are shown for (a) January–March 1999 and (b) October–December 1999. The pink lines and green lines represent  $-7\text{‰}$  contours and  $-8\text{‰}$  contours, respectively. The  $\delta^{18}\text{O}$  difference values in  $0.4\text{‰}$  intervals are shown from January–March 1999 to (c) October–December 1999, (d) June–August 2000 and (e) May–July 2001. The green-colored areas denote areas where the  $\delta^{18}\text{O}$  values are depleted by more than  $-0.4\text{‰}$ . The well sites of CG(1), YL(1), TZ(1), JY(1), LH(1), LT(1) and TN(1) are labeled in (c)–(e). The scale bar unit is km.

relatively enriched in oxygen isotopes (Fig. 3a,b). It is characterized by having a very low percentage of the isotope-depleted water from the Choshui River (only 3% on the average). The oxygen isotope compositions in Aquifer I range widely from  $-2.2\text{‰}$  to  $-8.4\text{‰}$ , with a mean of  $-6.6\text{‰}$  (Table 1; Fig. 3a). Apparently, some sources of enriched oxygen isotope compositions, including local rain-water, seawater over-flooding along the coastal area (Ho *et al.* 1990; Chen & Liu 1997; Chen *et al.* 2001; Liu *et al.* 2003) and surface ponds under heavy evaporation (Wang *et al.* 1998; 1999), were mixed into Aquifer I. Because these local waters are  $\delta^{18}\text{O}$ -enriched, they are easily differentiated from the very  $\delta^{18}\text{O}$ -depleted Choshui River component. Thus, the contribution percentages (CS) in Table 1 are estimated to be 0% if the groundwater isotope values are higher than  $-7.8\text{‰}$  in the Changhua section and  $-7.2\text{‰}$  in the Yunlin section.

Infiltration of isotope-enriched local water into the unconfined aquifer is a common feature everywhere (Gat & Gonfiantini 1981; Clark & Fritz 1997).

Following the Chi-Chi earthquake, the  $\delta^{18}\text{O}$  values of Aquifer I shifted toward relatively depleted values, especially for the proximal area close to the source of the Choshui River (see the expansion of the  $-8\text{‰}$  green contour after the earthquake in Figure 3b), and the mean percentage contribution from the Choshui River increased to 6% (Table 1). Figures 3c–e show the change in the contours of  $\delta^{18}\text{O}$  from the preseismic values. Since the seasonal  $\delta^{18}\text{O}$  variation is less than  $0.4\text{‰}$ , all values that were depleted by more than  $0.4\text{‰}$  mainly because of the earthquake are colored in green to illustrate the affected region. Apparently, the northern Changhua section was affected more than the southern Yunlin section during the earthquake.



**Fig. 4** Oxygen isotope contours for Aquifer II from 1999 to 2001. The open circles are the sampling wells. The absolute  $\delta^{18}\text{O}$  values in  $0.5\text{‰}$  intervals are shown for (a) January–March 1999 and (b) October–December 1999. The blue lines and green lines represent  $-9\text{‰}$  contours and  $-8\text{‰}$  contours, respectively. The red-colored areas denote areas where the  $\delta^{18}\text{O}$  values are depleted by more than  $-10\text{‰}$ . The  $\delta^{18}\text{O}$  difference values in  $0.4\text{‰}$  intervals are shown from January–March 1999 to (c) October–December 1999, (d) June–August 2000 and (e) May–July 2001. The green-colored areas denote areas where the  $\delta^{18}\text{O}$  values are depleted by more than  $-0.4\text{‰}$ . The well sites of FY(1), CC(2) and HB(1) are labeled in (a) and (b). The scale bar unit is km.

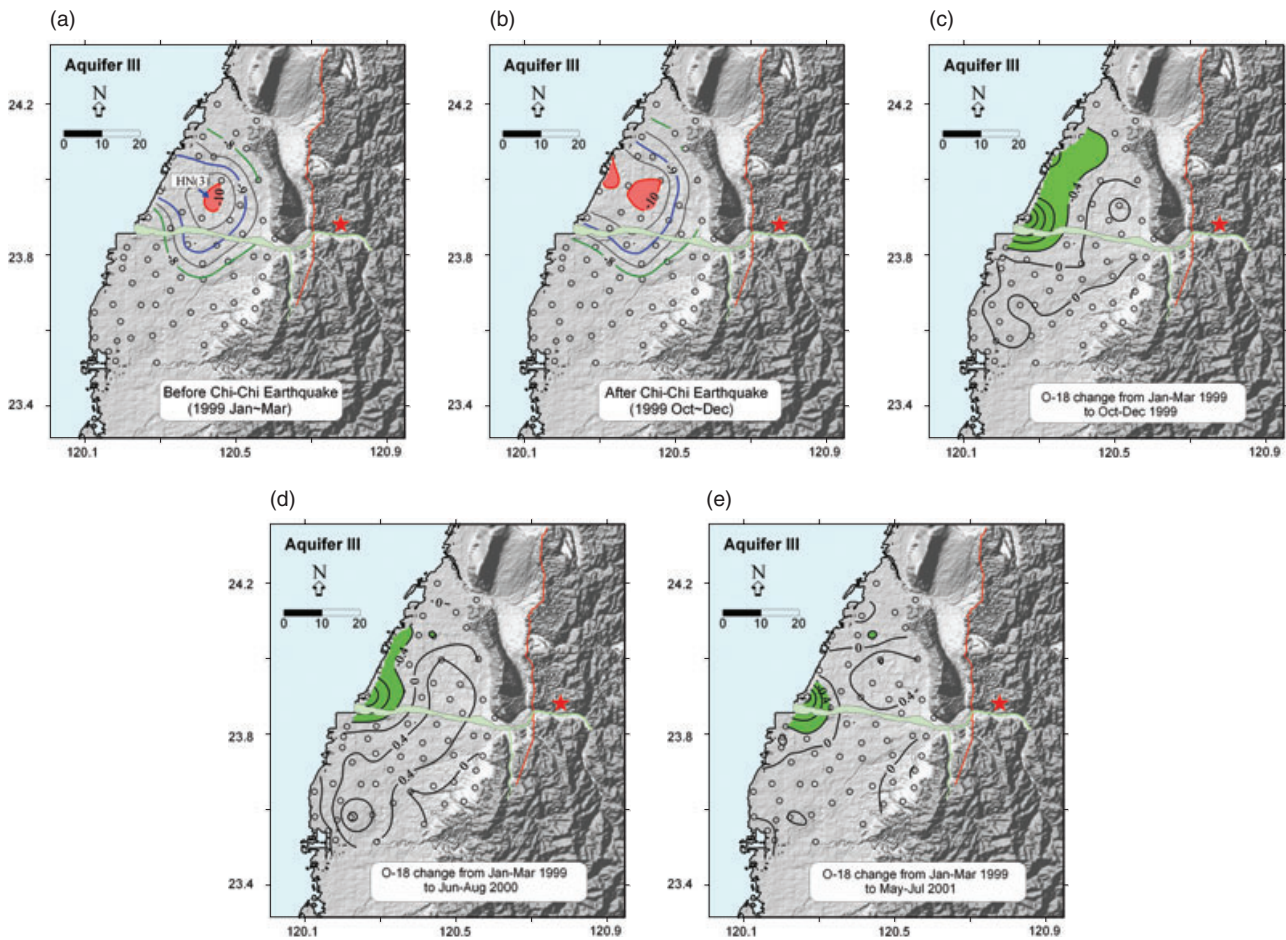
The big shift in  $\delta^{18}\text{O}$  value of Well CG(1) toward a more depleted value as shown in Figure 3c is strong evidence of vertical mixing and will be discussed in a later section. The  $\delta^{18}\text{O}$  value of the YL(1) site that experienced liquefaction in the earthquake also decreased, suggesting vigorous mixing with a different water source.

The increased contribution from the Choshui River remained evident until 2001 (Fig. 3d,e), with the average contribution being higher than 5%. However, the green-colored area was mainly distributed along the coastal region of the Changhua section, indicating that the changes might be primarily derived from Aquifer II below. Before the earthquake, there were only two wells in the proximal area that showed  $\delta^{18}\text{O}$  values lower than  $-8\text{‰}$ , but the number of wells that showed such low  $\delta^{18}\text{O}$  values increased to five after the earthquake. Several wells (e.g. TZ(1), JY(1), LH(1),

LT(1) and TN(1)) showed a steady increasing trend after the earthquake (Table 1). For example, the contributions from the Choshui River in Well LH(1) increased continuously from 24% up to 41% in the summer of 2001 (Table 1). Both advective and dispersive transport may be important in the transport of a solute. But, given the high permeability of Aquifer I, advective transport is probably dominant. Advective transport can be increased either by an increase in the head gradient, or by an increase in the permeability of the aquifer, or both. A detailed analysis is needed in order to determine which factor is more important.

#### AQUIFER II

Aquifer II experienced great changes in the  $\delta^{18}\text{O}$  variations during and after the earthquake (Fig. 4). Before the earthquake, Aquifer II had an



**Fig. 5** Oxygen isotope contours for Aquifer III from 1999 to 2001. The open circles are the sampling wells. The absolute  $\delta^{18}\text{O}$  values in 0.5‰ intervals are shown for (a) January–March 1999 and (b) October–December 1999. The blue lines and green lines represent  $-9\text{‰}$  contours and  $-8\text{‰}$  contours, respectively. The red-colored areas denote areas where the  $\delta^{18}\text{O}$  values are depleted by more than  $-10\text{‰}$ . The well site of HN(3) is labeled in (a). The  $\delta^{18}\text{O}$  difference values in 0.4‰ intervals are shown from January–March 1999 to (c) October–December 1999, (d) June–August 2000 and (e) May–July 2001. The green-colored areas denote areas where the  $\delta^{18}\text{O}$  values are depleted by more than  $-0.4\text{‰}$ . The scale bar unit is km.

average  $\delta^{18}\text{O}$  value of  $-8.0\text{‰}$  (ranging from  $-6.2$  to  $-10.3\text{‰}$ ; Table 2) with a mean contribution of 27% from the Choshui River. The contour lines in Figure 4a show that the Choshui River recharged mainly in the Changhua section and flowed in the northwestern direction. The  $-9\text{‰}$  contour line in Figure 4a,b represents a contribution from the Choshui River to the Changhua and Yunlin sections of 48% and 58%, respectively. In general, the mean contribution from the Choshui River to the Changhua section was 41% before the earthquake. There was very little Choshui River contribution in the Yunlin section (mean value 18%). The subsurface flow route of the Choshui River water in the Changhua section coincides geographically with the old river channels that were identified by Chang (1983). Another reason for the lack of contribution from the Choshui River in the Yunlin area is the relatively high groundwater level in the

Touliu Tableland, which is 20 m higher than the Choshui River in the proximal recharge area (Fig. 1; WCA 1997). This may have suppressed the input from the Choshui River.

After the Chi-Chi earthquake, the contour lines representing relatively depleted  $\delta^{18}\text{O}$  values expanded significantly in the area (Fig. 4b; Wang *et al.* 2001b), and 68% of the wells in Aquifer II showed depleted  $\delta^{18}\text{O}$  values. The mean  $\delta^{18}\text{O}$  value dropped to  $-8.2\text{‰}$  (ranging from  $-6.3$  to  $-10.3\text{‰}$ ; Table 2). The red-colored area that emerged in the northwestern part of Figure 4b represents a contribution of the Choshui River higher than 90%. This phenomenon strongly indicates that after the earthquake, the contribution from the Choshui River to Aquifer II was significantly increased. Because the Choshui River provided the largest supply of groundwater in the Changhua section, the most dramatic change happened along the

main flow channel in the Changhua coastal region. The mean contribution from the Choshui River increased to 52% in the Changhua section. Several wells (FY(1), CC(2) and HB(1)) reached a  $\delta^{18}\text{O}$  value of  $-10.3\text{‰}$ , indicating that they were entirely dominated by the Choshui River (Table 2). However, only minor changes were observed for the Yunlin section, especially in the southern part. The mean contribution of the Choshui River was only 20%, and none of the wells showed  $\delta^{18}\text{O}$  values lowered than  $-10\text{‰}$ , suggesting that local groundwater flow from the Touliu Tableland prevailed in that region.

The pattern of the contoured  $\delta^{18}\text{O}$  values in Figure 4b is unexpected: The relatively depleted  $\delta^{18}\text{O}$  values were not found in the proximal area close to the recharge source of the Choshui River, but in the remote northwestern coastal region. This is the first time that such a pattern of isotope distribution has been observed in Taiwan. Figure 4c–e show the  $\delta^{18}\text{O}$  difference contours (between pre-earthquake and post-earthquake values) for Aquifer II, with  $\delta^{18}\text{O}$  values in the green-colored areas being depleted by more than  $-0.4\text{‰}$ . Figure 4c shows that a great change in  $\delta^{18}\text{O}$  values occurred along the coast of the Changhua section, where the groundwater level is very low, right after the earthquake in late 1999 (Fig. 1). The result showing that only the Changhua section had a large change in isotope values possibly relates to the old river channel. This unexpected reverse pattern of Figure 4b,c strongly implies that there may be  $\delta^{18}\text{O}$ -depleted groundwater beneath Aquifer III. This hypothesis is consistent with the presence of a 'bull's-eye' area in Figure 4c and in Aquifer III with depleted  $\delta^{18}\text{O}$  values before the earthquake (discussed in the following section). Vertical mixing among aquifers during and after the Chi-Chi earthquake, as revealed by isotope and water levels, also supports this argument. This hypothesis may also be tested in the future by drilling beneath Aquifer III.

Another possible source of depleted  $\delta^{18}\text{O}$  values, though less likely, might be deep offshore  $\delta^{18}\text{O}$ -depleted groundwater. There is an impermeable layer of the Choshui River fan that serves as a barrier to impede the groundwater flow. Because it is the end-line of groundwater flow, groundwater with relatively depleted  $\delta^{18}\text{O}$  values is expected to be stored there for a long time. Radiocarbon data also show that deep groundwaters in the coastal Choshui River fan date back to the last glacial age (Liu 1995; Wang *et al.* 2001c). The low groundwater level along the coastal region (and possibly also

the offshore area) of the Choshui River fan (Fig. 1) prevents the  $\delta^{18}\text{O}$ -depleted groundwater from the last glacial age from flowing out. During the Chi-Chi earthquake, the impeded and  $\delta^{18}\text{O}$ -depleted groundwater was pushed backward, thus generating a reverse  $\delta^{18}\text{O}$  pattern in Figure 4b–d. The existence of an offshore barrier is supported by the fact that although the groundwater levels are 20–30 m below sea level along the coastal region of the Choshui River fan, no seawater intrusion has yet been found, contrary to observations elsewhere in Taiwan (Ho *et al.* 1990; Chen & Liu 1997; Chen *et al.* 2001; Liu *et al.* 2003). A further modeling study will be needed to test the feasibility of this possible groundwater source.

In the summer of 2000, the most  $\delta^{18}\text{O}$ -depleted green-colored region diminished in area (Fig. 4d). Only 37% of the wells continued to have relatively depleted  $\delta^{18}\text{O}$  values when compared to the number before the earthquake, and the mean  $\delta^{18}\text{O}$  composition was even slightly enriched ( $-7.8\text{‰}$ ). Apparently, the significant contribution from the Choshui River was severely reduced after the earthquake. In the summer of 2001, the  $\delta^{18}\text{O}$ -depleted green-colored region totally disappeared and the  $\delta^{18}\text{O}$  contour lines returned primarily to their pre-earthquake pattern (Fig. 4e), with a mean  $\delta^{18}\text{O}$  value ( $-8.0\text{‰}$ ) identical to that in early 1999 (Table 2). Thus, the effect of the earthquake on the groundwater flow persisted for at least one year in Aquifer II.

### AQUIFER III

For Aquifer III, the  $\delta^{18}\text{O}$  contour pattern is generally similar to that of Aquifer II before the earthquake (Fig. 5a); that is, there is a much greater contribution from the Choshui River in the Changhua section (32%) than in the Yunlin section (6%). The oxygen isotope compositions range from  $-6.6\text{‰}$  to  $-10.2\text{‰}$ , with a mean of  $-7.8\text{‰}$  (Table 3). However, Figure 5a shows a  $\delta^{18}\text{O}$ -depleted bull's-eye in Well HN(3) in the middle of the Changhua section that was almost exclusively derived from the Choshui River, indicating that the  $\delta^{18}\text{O}$ -depleted source may be located in an aquifer below, because there is no  $\delta^{18}\text{O}$ -depleted source above Aquifer III and the ancient river channel of the old Choshui River lies just beneath (Chang 1983).

After the Chi-Chi earthquake, the bull's-eye area expanded and another  $\delta^{18}\text{O}$ -depleted red-colored region similar to that for Aquifer II emerged in the Changhua coastal region, but with

a smaller extent (Fig. 5b). Again, 64% of the wells showed relatively depleted  $\delta^{18}\text{O}$  values after the earthquake and the mean  $\delta^{18}\text{O}$  value was  $-8.0\text{‰}$  (Table 3). It seems that Aquifer III may have another source down below, in addition to the recharging source from the Choshui River and the Pakua Tableland, thus creating a different  $\delta^{18}\text{O}$  contour pattern from that of Aquifer II.

Figure 5c–e illustrate the contours of  $\delta^{18}\text{O}$  change relative to pre-earthquake values in Aquifer III. Again, the most drastic  $\delta^{18}\text{O}$  change occurred along the coast of the Changhua section, but the area beyond the threshold value of seasonal effect ( $-0.4\text{‰}$ ; green-colored area) is larger than that of Aquifer II, suggesting a net output from Aquifer III toward Aquifer II in terms of vertical mixing. The decrease in the change in isotope values can clearly be seen from Figure 5c–e, implying a recovery to the pre-earthquake state. The effect of the earthquake on Aquifer III seems to be more persistent than that on Aquifer II, because there was still a small  $\delta^{18}\text{O}$ -depleted remnant in the summer of 2001, although the mean  $\delta^{18}\text{O}$  values were essentially identical to that in early 1999.

#### VERTICAL MIXING AMONG AQUIFERS

In general, vertical mixing is hardly observed for confined aquifers in the distal area of the Choshui River fan. This is evidenced by the fact that even within the same aquifer,  $\delta^{18}\text{O}$  values of upper and lower wells are significantly different if there is a local impermeable layer. For instance, Aquifer II at the TC site (Fig. 2) has two wells (TC(1) and TC(2)) that are separated by a thin clay bed, and each well had distinctive  $\delta^{18}\text{O}$  values ( $-8.9\text{‰}$  and  $-8.2\text{‰}$ , respectively; Table 2) before the earthquake, suggesting that there was no connection between them. For wells in different aquifers, such as CG(1) and CG(2) in Figure 2, the  $\delta^{18}\text{O}$  difference was even more significant ( $-6.5\text{‰}$  and  $-8.8\text{‰}$ , respectively) before the earthquake (Tables 1,2).

During and after the Chi-Chi earthquake, different water levels and different isotopic compositions in different aquifers converged to the same respective values in some wells, suggesting coseismic exchanges of water between the different aquifers, which implies enhanced permeability due perhaps to the fracturing and breaching of aquitards between the aquifers. In Figure 2, the homogeneity of  $\delta^{18}\text{O}$  values between the CG(1) and CG(2) wells, and between the TC(1) and TC(2) wells, are good examples of vertical mixing after

the earthquake. The similarity of the  $\delta^{18}\text{O}$  change patterns for aquifers after the earthquake and the cluster of  $\delta^{18}\text{O}$ -depleted regions along the Changhua coast (Figs 3,5) also support interaquifer mixing during the earthquake. Table 4 lists the groundwater level and oxygen isotope differences for some wells before and after the earthquake. It is evident that the groundwater level differences of these wells were reduced and the  $\delta^{18}\text{O}$  values showed little or no difference after the earthquake. The bull's-eye patterns in Figures 4b,c and 5a,b also imply the occurrence of vertical mixing between different aquifers. A further study is needed to thoroughly investigate the transport of solutes and mixing between aquifers in the coastal regions of the Changhua section.

#### COSEISMIC WATER-LEVEL RESPONSE

The coseismic water-level change ( $C_w$ ) on the Choshui River fan associated with the Chi-Chi earthquake was previously reported in several papers (Hsu *et al.* 1999; Chia *et al.* 2001; 2002; Wang *et al.* 2001a; Lee *et al.* 2002). Here, the results will be briefly summarized to examine whether there is any relationship between the changes in the water level and the isotope composition. Hourly water-level records from 124 wells and 64 stations that cover the entire Choshui River fan (WRB 2000) were used in the study. Among these, there are 38 wells in Aquifer I, 51 wells in Aquifer II and 35 wells in Aquifer III.

Figure 6 shows the contours of coseismic water-level changes for Aquifers I, II, and III immediately after the Chi-Chi earthquake. The groundwater levels of three aquifers in the Choshui alluvial fan experienced positive variations during the Chi-Chi earthquake. In the upper unconfined aquifer,  $C_w$  was less than 0.5 m over most parts of the Choshui River fan; but in an area of  $\sim 100\text{ km}^2$  west of the Pakua Tableland,  $C_w$  exceeded 3 m. Most liquefaction on the Choshui River fan occurred in this area of increased  $C_w$  (Fig. 6a).

The  $C_w$  in the lower aquifers showed a completely different pattern: A north–south-trending zone of maximum  $C_w$  occurred at a distance of  $\sim 30\text{ km}$  west of the ruptured Chelungpu Fault (Fig. 6b,c). The magnitude of this  $C_w$  decreased both to the west (towards the coast) and to the east (towards the ruptured fault). This pattern showed no association with the occurrence of liquefaction on the Choshui River fault, suggesting that liquefaction occurred only in the upper aquifer.

**Table 4** Groundwater-level and oxygen isotope changes before and after the Chi-Chi earthquake for some wells that show evidence of vertical mixing

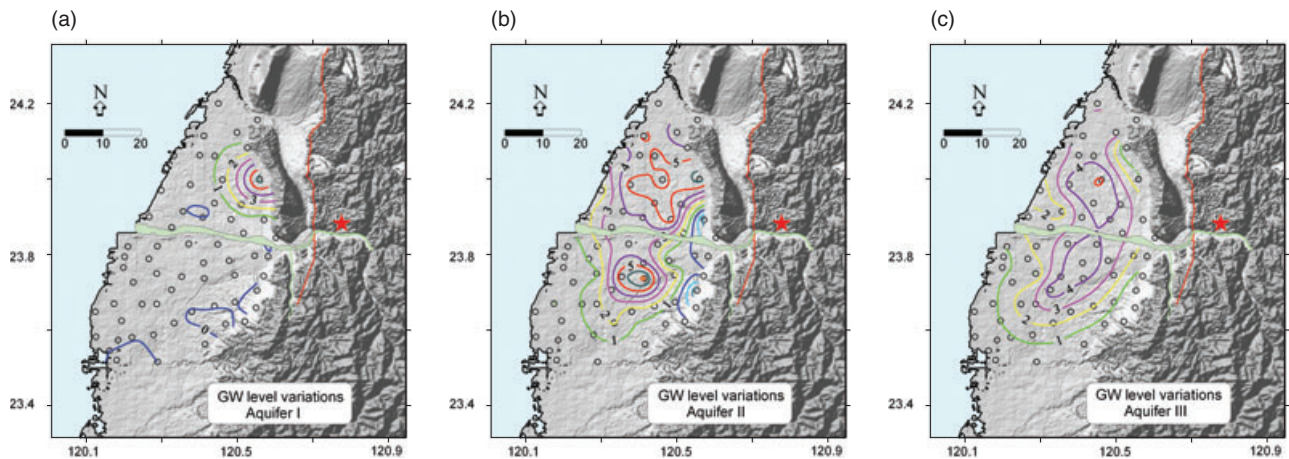
Well	Well ID	Aquifers compared	Groundwater-level difference before earthquake (m) <sup>†</sup>	Groundwater-level difference after earthquake (m) <sup>†</sup>	$\delta^{18}\text{O}$ difference before earthquake (‰) <sup>‡</sup>	$\delta^{18}\text{O}$ difference after earthquake (‰) <sup>‡</sup>
Hsikang	CG(1)-CG(2)	I-II	-1.9	-0.7	2.3	0.0
Tanchien	TC(1)-TC(2)	II (upper)-(lower)	6.8	3.6	-0.7	0.0
Hsihu	CU(1)-CU(2)	II (upper)-(lower)	0.8	0.2	-0.5	0.2
Hanbao	HB(2)-HB(3)	II-III	-5.8	-4.7	-1.3	-0.3
Chaochia	CC(2)-CC(3)	II-III	-0.2	0.8	-0.6	-0.3
Chuanhsin	CH(3)-CH(4)	III (upper)-(lower)	-2.0	-0.8	0.4	0.1

<sup>†</sup>positive values indicate that the groundwater level is higher at the upper aquifer; <sup>‡</sup>positive differences indicate that the upper aquifer is relatively enriched in  $\delta^{18}\text{O}$ .  $\delta^{18}\text{O}$ , oxygen isotope value.

There is little similarity between the spatial patterns of the coseismic water-level change and the oxygen isotope change. Apparently, the processes that caused the coseismic water-level changes did not induce any significant geochemical changes, and the processes that caused the geochemical changes did not induce any significant coseismic water-level changes. Because of the short duration of ground shaking ( $\sim 20$  s), the coseismic response of the water level is widely thought of as an undrained process. The characteristic time for diffusion across a layer of thickness  $L$  is approximately  $L^2/D$ , where  $D$ , which is about  $10^{-11}$  m<sup>2</sup>/s, is the hydrological diffusivity (Ingebritsen & Sanford 1999). Thus, it may be expected that the coseismic change in water level is not associated with a geochemical change. However, geochemical changes must involve some exchanges of water among different sources. It may thus seem paradoxical that such exchanges of water are not associated with the changes in the water level. This apparent paradox may be explained by considering the Peclet number for solute transport; that is,  $P_e = uL/D$ , where  $u$  is the linear velocity of the groundwater flow,  $L$  is the characteristic distance between different aquifers and  $D$  is the coefficient of diffusivity (Ingebritsen & Sanford 1999). When  $P_e > 1$ , advective transport would be an effective means for solute transport; thus, the advective transport of a solute would be effective if  $u \geq D/L$ . Similarly, the change in the hydraulic head is a result of the competition between hydraulic advection and diffusion (Phillips 1991). Advective transport would significantly affect the hydraulic head if  $u \geq (K/S_s)/L$ , where  $K$  is the hydraulic conductivity and  $S_s$  is the specific storage of the aquifer. Now,  $D$  is of the order of  $10^{-11}$  m<sup>2</sup>/s (Ingebritsen & Sanford 1999), while  $K/S_s$  is of the order of 10 m<sup>2</sup>/s for the confined aquifers in the Choshui River fan (Tyan *et al.* 1996). Hence, the amount of exchanged water required to cause appreciable changes in isotopic composition is 12 orders of magnitude smaller than that required to cause appreciable changes in the water level.

## SUMMARY

Oxygen isotope compositions measured before and after the Chi-Chi earthquake at monitoring wells in the Choshui River fan reveal distinct and interesting patterns for various aquifers. The top Aquifer I is relatively enriched in terms of  $\delta^{18}\text{O}$  values, indicating that sources with enriched oxygen



**Fig. 6** Coseismic groundwater (GW)-level contours (in colored 1-m intervals) for (a) Aquifer I, (b) Aquifer II and (c) Aquifer III of the Choshui River alluvial fan during the Chi-Chi earthquake. Red contour lines represent a coseismic groundwater-level change greater than 5 m during the earthquake. The red star represents the epicenter and the red line represents the Chelungpu Fault. Open circles represent the monitoring wells and open squares in (a) are liquefaction sites that are closely associated with the groundwater-level change in the Changhua section in Aquifer I. The scale bar unit is km.

isotope compositions have been mixed into it. After the Chi-Chi earthquake, the monitoring wells in the proximal area showed a slight shift toward relatively depleted  $\delta^{18}\text{O}$  values until the summer of 2001, suggesting that the contribution from the Choshui River had increased and this continued for more than one year.

The isotope changes after the earthquake are even more evident for the confined Aquifers II and III, with many of the depleted  $\delta^{18}\text{O}$  values being mainly attributed to the Choshui River, especially in the Changhua section where the old river channels are located, suggesting that enhanced exchanges of water between the Choshui River and the groundwater had taken place. However, low  $\delta^{18}\text{O}$  contour patterns were unexpectedly found in the remote northwestern coastal region, not in the proximal area close to the Choshui River's origin. Vertical mixing among aquifers with a source under Aquifer III is believed to be the likely cause, but a  $\delta^{18}\text{O}$ -depleted water source off the current shoreline might also play a possible role. The convergence of both  $\delta^{18}\text{O}$  values and  $C_w$  after the earthquake for some wells provides additional evidence for water exchanges between aquifers, which implies enhanced permeability due perhaps to the fracturing and breaching of aquitards. The effect of the earthquake on the groundwater flow persisted for at least one year in Aquifer II, and even longer in Aquifer III.

The coseismic groundwater-level contours exhibit patterns that are quite different for unconfined and confined aquifers, although they all have significant positive variations in the Choshui River

fan. Most liquefaction on the Choshui River fan occurred in an area of  $\sim 100 \text{ km}^2$  west of the Pakua Tableland in Aquifer I, where  $C_w$  exceeded 3 m. There is no association of the  $C_w$  contours of Aquifers II and III with the occurrence of liquefaction, suggesting that the liquefaction happened only in the upper aquifer. Little similarity was found between the spatial patterns of  $C_w$  and the oxygen isotope change. Obviously, the processes that caused the coseismic water-level changes did not induce any significant geochemical changes, and the processes that caused the geochemical changes did not produce any significant coseismic water-level changes.

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