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Temporal change in groundwater level following the 1999 (M_w = 7.5) Chi-Chi earthquake, Taiwan

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ABSTRACT

We examine the post-seismic change in the groundwater level following the 1999 (M_w = 7.5) Chi-Chi earthquake in central Taiwan, as recorded by a network of 70 evenly distributed hydrological stations over a large alluvial fan near the epicenter. Four types of post-seismic responses may be distinguished. In type 1, the groundwater level declined exponentially with time following a coseismic rise. This was the most common response in the study area and occurred in unconsolidated sediments on the Choshui River fan. In type 2, the groundwater level rose exponentially with time following a coseismic fall. This occurred in the deformed and fractured sedimentary rocks in the foothills near the Chelungpu fault that ruptured in the Chi-Chi earthquake. In type 3, the groundwater level continued to decline with time following a coseismic fall. This also occurred in the deformed and fractured sedimentary rocks near the ruptured fault. Finally, in type 4, the groundwater level, following a coseismic rise, stayed at the same level or even rose with time before it eventually declined. This occurred mostly in unconsolidated sediments along the coast of central Taiwan and along the Peikang Stream. We analyze these post-seismic responses by using a one-dimensional model. Together with the results from well test, the analysis show that the type 1 response may be explained by an aquifer model with coseismic recharge and post-seismic subhorizontal discharge across a length of 500–5000 m; the type 2 response may be explained by a model of coseismic discharge and post-seismic recharge from surface water; the type 3 response may be explained by a model of coseismic discharge and post-seismic subhorizontal discharge across a length of 500–5000 m; and the type 4 response may be explained by a model of coseismic recharge and sustained post-seismic recharge from surface water. The characteristic time for the post-seismic changes is similar to that for the groundwater-level decline during dry seasons before the earthquake, suggesting that there was no earthquake-induced changes in the aquifer properties (i.e. hydraulic conductivity), confirming the earlier results from recession analyses of the post-seismic streamflow elsewhere after several earthquakes.

Key words: earthequake, groundwater, Taiwan

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INTRODUCTION

Coseismic disturbances of the groundwater level have been widely noted and discussed (see compilations in Muir-Wood & King 1993; Roeloffs 1996; King & Igarashi 2002). Several models have been advanced to explain the effect of an earthquake on groundwater level. (1) Water is expelled from the crust as a result of coseismic elastic strain (Wakita 1975; Muir-Wood & King 1993; Quilty & Roeloffs 1997; Wang *et al.* 2001b, 2003; Lee *et al.* 2002). (2)

Water is released from the upper crust due to an increased permeability from fractures formed in earthquakes (Rojstaczer & Wolf 1992; Rojstaczer *et al.* 1995; Brodsky *et al.* 2003). (3) Water is released from coseismic liquefaction or consolidation of loose sediments (Wang *et al.* 2001b, 2003). Coseismic changes in stream discharge have also been widely reported (for an overview, see Montgomery *et al.* 2003). The same hypotheses as listed above have been invoked to explain the changes in stream discharge, namely, the coseismic elastic strain model (Muir-Wood & King

1993; Roeloffs 1996; Ge and Stover, 2000; Lee *et al.* 2002), the enhanced permeability model (Briggs, 1991; Rojstaczer & Wolf 1992; Rojstaczer *et al.* 1995; Tokunaga, 1999; Sato et al., 2000; Wang *et al.* 2003), and the coseismic consolidation-liquefaction model (Manga 2001; Manga *et al.* 2003; Montgomery *et al.* 2003).

However, the mechanism for the temporal change in groundwater level following an earthquake has received much less attention (Roeloffs 1998; Brodsky *et al.* 2003). A study of the post-seismic changes in groundwater level may reveal the mechanism(s) by which the coseismic hydrological disturbances are dissipated and the hydraulic characteristics of the local groundwater system. One difficulty in the study of the post-seismic change in groundwater level has been the fact that, as shown in this paper, there are different, and sometimes contradicting, types of post-seismic changes in the groundwater level. Thus the results of the analysis of groundwater-level changes in one well may not be applicable to another location, even in the same earthquake. In order to understand the various post-seismic changes in the groundwater level, one needs to examine data for the same earthquake from a variety of hydrological regimes. Such data, unfortunately, is often not available.

The 1999 Chi-Chi ($M_w = 7.5$) earthquake, the largest to hit Taiwan in the last century, ruptured the crust along an approximately 80 km segment of the Chelungpu fault close to the eastern border of the Choshui River fan (Fig. 1). A dense network of hydrological stations on the alluvial fan near the epicenter of the earthquake captured the changes of the groundwater level before, during, and after the earthquake. The close proximity to a large earthquake and the dense network of hydrological stations provide a rare opportunity for examining the effect of an earthquake on groundwater. Several papers have discussed the coseismic changes of the groundwater level in this earthquake (Hsu *et al.* 1999; Chia *et al.* 2001; Wang *et al.* 2001b, 2003; Lee *et al.* 2002), but few touched upon the post-seismic changes. In this paper we focus on the post-seismic change of the groundwater level of the Chi-Chi earthquake, with the objective of understanding the mechanism(s) by which the coseismic hydrological disturbances were dissipated and the hydraulic characteristics of the local groundwater system.

SETTING

Taiwan is a mountainous island that rises in places to approximately 4 km. It was formed in the late Cenozoic, with the oblique collision between the Luzon volcanic arc on the Philippine Sea plate and the continental margin of China (Teng 1990). The prevailing structural trend in Taiwan is that of an elongated arc convex to the west.
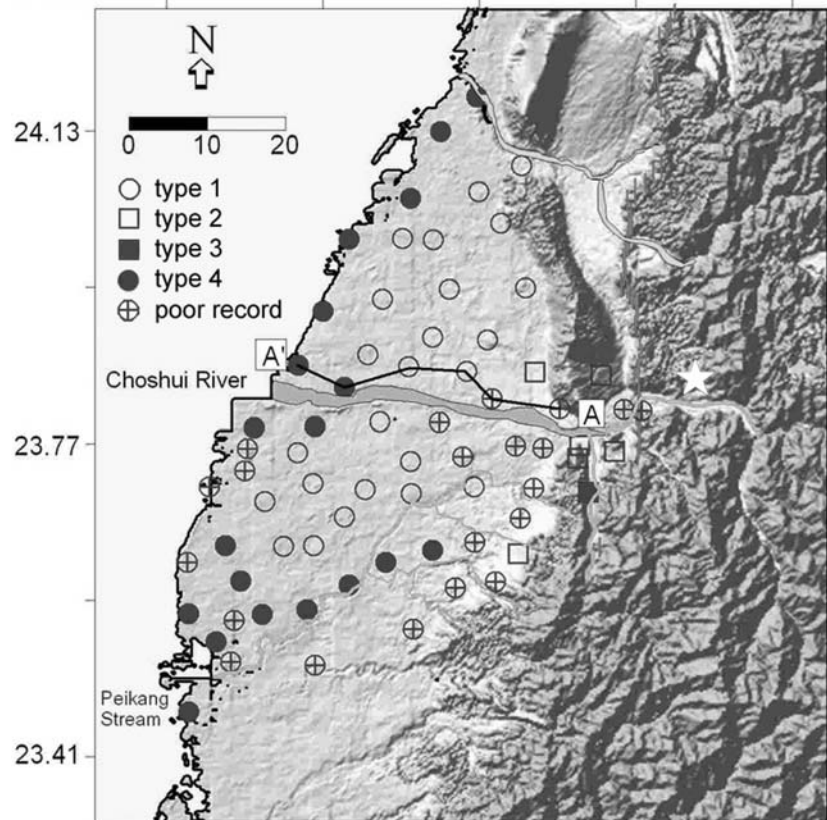
Fig. 1. Location map of the Choshui River fan and the hydrological stations. The epicenter of the Chi-Chi earthquake is marked by a star, the surface rupture of the Chelungpu fault by broken traces. Stations with type 1 (up-down) post-seismic response are marked by open circles; stations with type 2 (down-up) post-seismic response by open squares; Liyu station with type 3 (down-down) post-seismic response by a solid square; stations with type 4 (up-up) post-seismic response by solid circles; stations with poor records by open circles with crosses.

Several NS-trending structural belts may be differentiated, from west to east: the Coastal Plain that is floored by a pre-Tertiary block-faulted basement and covered by Neogene and Quaternary sediments; the Western Foothills that is a fold-and-thrust belt of sedimentary rocks; the Central Ranges that is the core of the mountain belt and consists of various metamorphic rocks, and the Coastal Range that runs along the eastern margin of the island and represents a deformed and uplifted portion of the Luzon arc (Ho 1988).

The Choshui River fan (Fig. 1) of central Taiwan is a part of the Coastal Plain; it is the largest alluvial fan (1800 km^2) on the island. Two Pleistocene ridges, the Pakuashan anticline and the Touliu anticline, form the eastern boundary of the fan. Since 1992, a network of 70 evenly distributed hydrological stations (Fig. 1), with a total of 188 wells, has been installed on the Choshui River fan in central Taiwan for monitoring the groundwater resources (Fig. 1). At each station, one to five monitoring wells were drilled to different depths from 24 to 306 m. Each well was instrumented with a piezometer that records the temporal changes of groundwater level of a particular aquifer. The groundwater levels in the wells are converted from automatic, digital piezometric recordings, to a precision of 1 mm at an hourly rate (Hsu *et al.* 1999). In addition, 15 rain stations across the Choshui River fan and the adjacent foothills have provided continuous records of precipitation in the area.

Hydrological well logs show that the alluvial fan consists of unconsolidated Holocene and Pleistocene sediments of various kinds. Massive gravel beds accumulated in the proximal section of the fan near the exit of the Choshui River from the foothills to the coastal plain. Away from the proximal section towards the west, southwest and northwest, sediments in the fan become finer with distance and grade into layers of sand and mud (Fig. 2). Reconstruction of the subsurface structures (Water Resource Bureau 1999), based on well logs to depths from 24 to 306 m, showed three distinct aquifers (Fig. 2): Aquifers II and III are confined; aquifer I, the topmost aquifer, is partly confined and partly unconfined. For this reason, it may not be correct to refer to the topmost aquifer as an unconfined aquifer.

The subsurface geology of the Taichung Basin east of the Pakuashan and Touliu Terraces is less well understood. From surface geology and limited exploratory well logs, Suppe (1976) and others showed that, beneath a thin veneer of Holocene sediments, the subsurface geology east of the terraces is dominated by consolidated and folded Pleistocene sedimentary rocks. Due to their proximity to active faults, these rocks are often fractured by repeatedly earthquakes in the recent past.

OBSERVATION

From examining the well logs from all the hydrological wells in the earthquake affected area, we recognize four
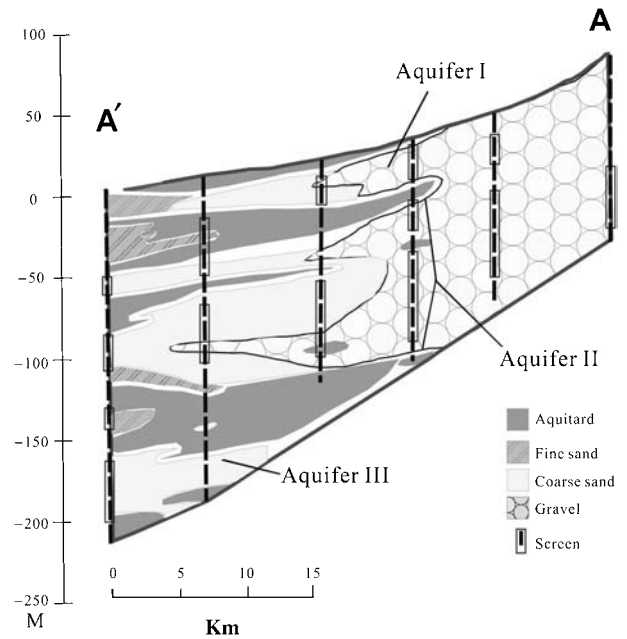

Fig. 2. Structural cross-section of the Choshui River fan along the A-A′ transect marked in Fig. 1. Massive gravel beds occur in proximal area; away from proximal area, gravel beds decrease in thickness with distance, while coarse sands and fine sands increase in proportion and interfinger with gravel beds; further away, silty sands and silty clays increase in proportion and eventually dominate distal margin of fan.

types of post-seismic responses. In type 1 (Fig. 3A), the groundwater level declined gradually with time following a coseismic rise. This type of changes occurred in unconsolidated and undeformed sediments on the Choshui River fan and was the most common type of changes after the Chi-Chi earthquake. The decline may be a simple exponential function of time following a coseismic rise in the groundwater level (Fig. 3A) or it may be a more complex function of time (Chen 2001). Chen (2001) interpreted the latter as indicating the onset of vertical transferring of water between adjacent aquifers. For sake of easy recall, this type of response will be referred later as the 'up-down' response.

In type 2, the groundwater level rose gradually with time following a coseismic fall (Fig. 3B). These changes occurred east of the Pakuashan and Touliu Terraces in fractured sedimentary rocks near the Chelungpu fault that ruptured in the Chi-Chi earthquake. This type of response will be referred later as the 'down-up' response.

In type 3, the groundwater level continued to decline with time following a coseismic fall (Fig. 3C). These changes also occurred east of the Pakuashan and Touliu Terraces in fractured sedimentary rocks near the ruptured Chelungpu fault. This type of response will be referred later as the 'down-down' response.

Finally, in type 4, the groundwater level, following a coseismic rise, stayed at the same level or even rose for a period of time before it eventually declined (Fig. 3D).
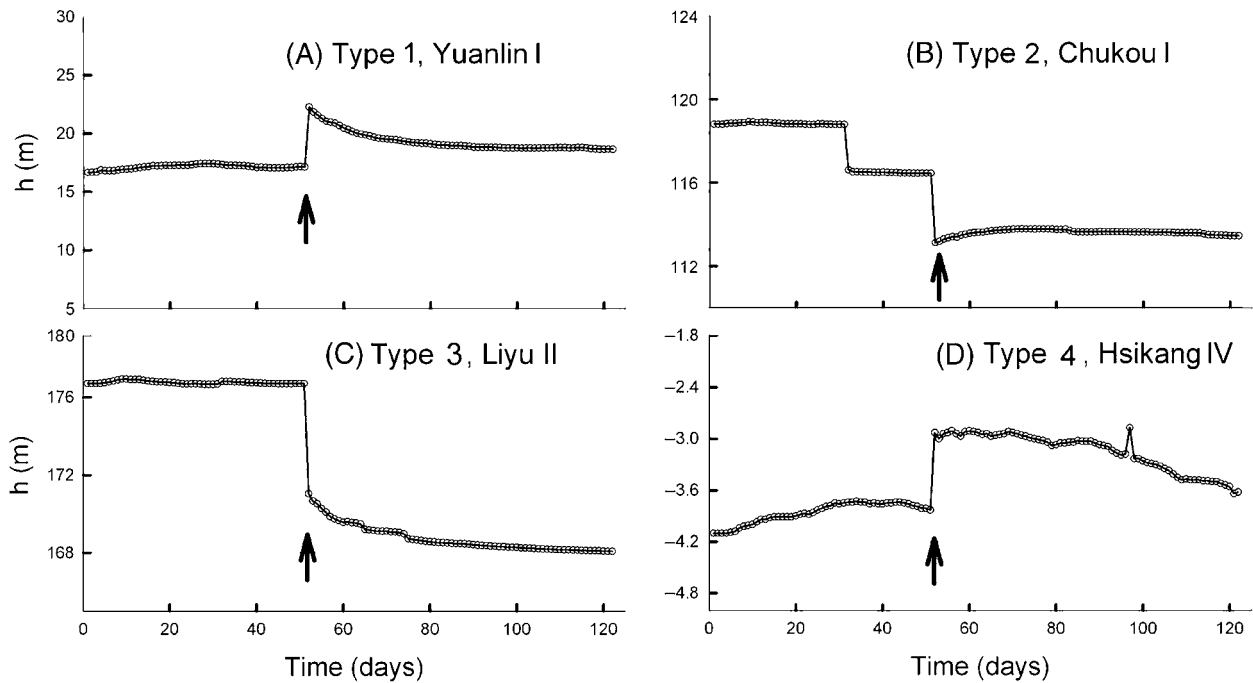
Fig. 3. Diagrams showing four types of post-seismic responses of groundwater level. (A) Type 1 (up-down), exponential decline of groundwater level following a coseismic rise; (B) type 2 (down-up), exponential rise of groundwater level following a coseismic drop; (C) type 3 (down-down), continued decline of groundwater level following a coseismic drop; and (D) type 4 (up-up), maintenance of groundwater level following a coseismic rise.

These changes occurred mostly in unconsolidated sediments along the coast and along the Peikang Stream. This type of response will be referred later as the 'up-up' response.

DATA ANALYSIS

Various environmental factors such as precipitation and tides, and human activities such as the withdrawal or injection of groundwater, may affect the records of the temporal changes. Here we select to study those water-level records that are free from the environmental disturbances. We first select a segment of the groundwater-level record and determine a post-seismic equilibrium level from the record. This is subtracted from the raw record; the difference is the post-seismic time-history of the earthquake-induced groundwater-level change (i.e. the residuals). For the type 2 (down-up) changes, where the groundwater level rose after the earthquake, the reference level lies above the rest of the post-seismic groundwater level and the residuals are negative. In such case, the absolute values of the residuals are taken.

By plotting the logarithm of the post-seismic residuals of the groundwater level, h, against time, t, a linear relation appears for most stations showing the up-down, down-up and down-down responses, after a sufficient lapse of time (Fig. 4), i.e.

$$\log h = a - bt \tag{1}$$

where a and b are the constants for the linear fit. A minus sign is chosen in front of the coefficient b so that b itself is positive. We may define a characteristic time as $\tau \equiv 1/b$, i.e. the inverse of the slope of the above linear relation. Although the above relation is entirely empirical, some physical interpretation may be useful. Assuming that the post-seismic changes in the groundwater level may be represented by discharge or recharge in a simplified one-dimensional aquifer (Fig. 5), we may solve the differential equation, with appropriate boundary conditions, that govern the flow in this model. As given in the next section, the solution leads to a constant $\partial \log h/\partial t \sim$ constant after a sufficient lapse of time. This constant is related to the hydraulic diffusivity and the length of the aquifer (equation 7), but is independent of the spatial distribution of the discharge or recharge, and of the location of measurement. Thus the slope of the above linear relation (1) may be used to estimate the hydraulic characteristics of the aquifer. At small t, however, the relation between $\log h$ and t is nonlinear and the above relation no longer holds.

Table 1 lists the values for b, τ and the square of the correlation coefficient, R^2, determined from the least square fit of the data for a number of stations for the different types of post-seismic changes in the groundwater level. Some aspects of the tabulated characteristic times are worth noticing: (1) The characteristic time for the type 1 (up-down) and type 3 (down-down) response is of the
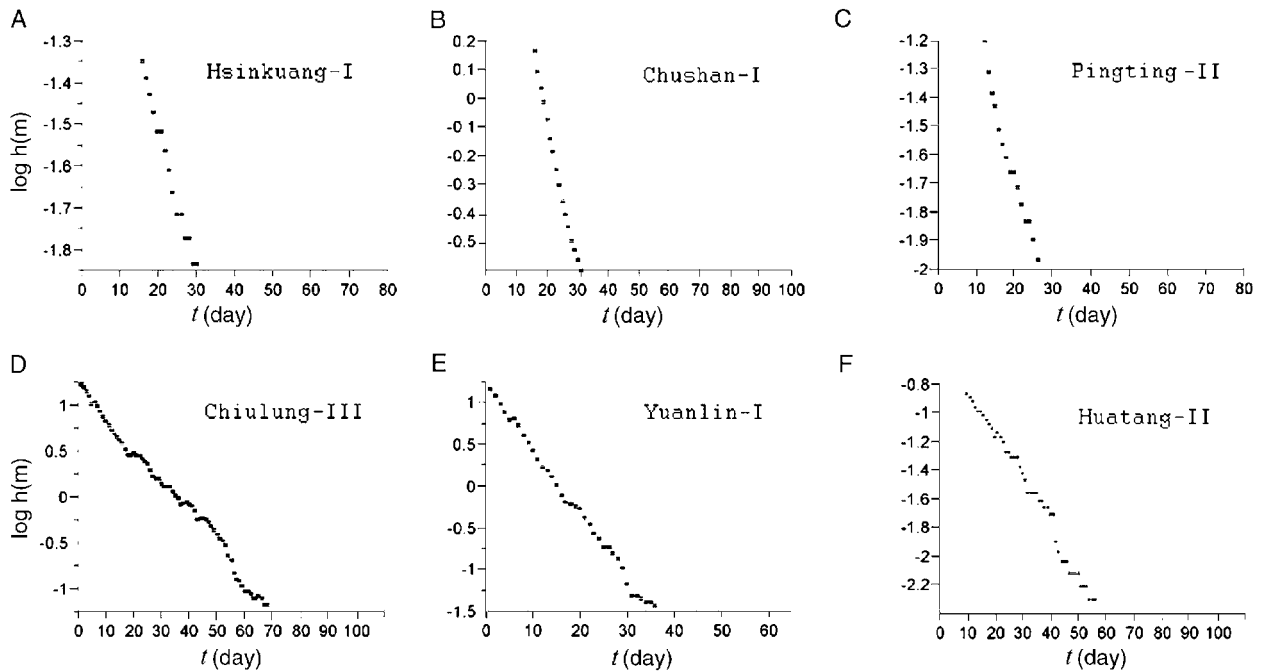
Fig. 4. Diagrams showing logarithmic of post-seismic residual hydraulic head plotted against time for six wells. Dots are data; straight lines are least-square linear fits to data. *R*-squares of linear fits are listed in Table 1.
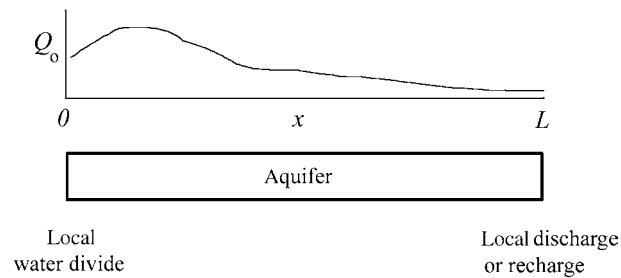

Fig. 5. Schematic drawing to show model geometry and distribution of coseismic water source (or sink).

order of 10^6 sec. (2) The characteristic time for the type 2 (down-up) response is of the order of 10^5 sec. (3) The characteristic times for different aquifers at the same hydrological stations are of similar magnitude. These aspects of the characteristic times may have important implications on the mechanisms of the dissipation processes, as discussed in the next section.

Most stations with the type 4 (up-up) post-seismic changes are located close to the coast and along the banks of the Peikang Stream (Fig. 1). Because this type of post-seismic response, as a rule, does not show a clear time-dependence, a characteristic time cannot be defined. However, their distinct association with the coast and the Peikang Stream suggests a model that is distinctly different from those for the other types of response, as discussed in the last section.

MODEL

Aquifers in the Choshui River fan are subhorizontal, with length scales much greater than their thicknesses. Here we make no attempt to simulate the details of the groundwater flow following an earthquake, but we consider a simple one-dimensional model of confined aquifer extending from $x = 0$ (at a local groundwater divide) to $x = L$ (at a local discharge or recharge area) (Fig. 5). The magnitude of L will be estimated from the field data. During the earthquake, there may be a coseismic source of water from the coseismic consolidation of the unconsolidated sediments (Wang *et al.* 2001b; Manga *et al.* 2003; Montgomery *et al.* 2003) or a coseismic sink of water due to earthquake-induced porosities and fractures (Rojstaczer & Wolf 1992; Wang *et al.* 2001a).

Analytical solutions for the above problem may be obtained through two different approaches. In one, the source (or sink) is represented by an increase (or decrease) in the hydraulic head; in this case, the governing differential equation is:

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial x^2} \qquad (2)$$

where h is hydraulic head, K is the hydraulic conductivity along x, and S_s is the specific storage. In the other approach, the source (or sink) is explicitly included in the equation, and the governing differential equation is:

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial x^2} + A \qquad (3)$$

Table 1 Parameters b and τ for aquifers, as determined from least-square fit with equation 1 to data for post-seismic change of groundwater level.

	Aquifer I	Aquifer II	Aquifer III	R^2
Type 1 (up-down)				
Chiulung				
b			4.0×10^{-7} sec^{-1}	0.99
τ			2.5×10^6 sec	
Hsihu				
b			3.6×10^{-7} sec^{-1}	0.99
τ			2.8×10^6 sec	
Huatang				
b		3.8×10^{-7} sec^{-1}		0.99
τ		2.6×10^6 sec		
Kuoshen				
b		9.7×10^{-7} sec^{-1}		0.98
τ		1.0×10^6 sec		
Yuanlin				
b	8.8×10^{-7} sec^{-1}	9.3×10^{-7} sec^{-1}		1.0, 0.95
τ	1.1×10^6 sec	1.1×10^6 sec		
Type 2 (down-up)				
Chukou				
b	1.7×10^{-6} sec^{-1}	2.0×10^{-6} sec^{-1}		0.98, 0.98
τ	5.9×10^5 sec	5.0×10^5 sec		
Chushan				
b	1.4×10^{-5} sec^{-1}			0.99
τ	0.7×10^5 sec			
Hsichou				
b		1.0×10^{-5} sec^{-1}		0.92
τ		1.0×10^5 sec		
Hsinkuang				
b	1.0×10^{-5} sec^{-1}			0.99
τ	1.0×10^5 sec			
Pingting				
b	1.4×10^{-5} sec^{-1}			0.98
τ	0.7×10^5 sec			
Type 3 (down-down)				
Liyu				
b	4.4×10^{-7} sec^{-1}	6.0×10^{-7} sec^{-1}		0.98, 0.99
τ	2.2×10^6 sec	1.7×10^6 sec		

where A is the rate of water released per unit volume of the aquifer in the earthquake. In the case where new porosities or fractures were created in the earthquake (Rojstaczer & Wolf 1992; Wang *et al*. 2001a), 'A' corresponds to a sink and is negative. The first approach was adopted by Manga *et al*. (2003) in their study of the earthquake-induced increase in streamflow. Here we adopt the second approach because the explicit inclusion of the source (or sink) in the equation is a more direct expression of the physical problem; it also provides explicit information on the change of porosity in the earthquake.

Although this is a highly simplified model, previous analyses (e.g. Roeloffs 1998; Brodsky *et al*. 2003; Manga *et al*. 2003) have used essentially the same model to obtain useful information on the response of aquifer systems to earthquakes. For convenience of discussion we rewrite (3) in a slightly different form

$$\frac{\partial h}{\partial t} = D\frac{\partial^2 h}{\partial x^2} + A/S_s \tag{4}$$

where D is the hydraulic diffusivity along x and is defined, for confined aquifers, as

$$D = K/S_s. \tag{5}$$

Equations 2 to 4 are also the linearized forms of the differential equations that govern the groundwater level in unconfined aquifers, but with S_s replaced by S_y/d where S_y is the specific yield and d the thickness of the unconfined aquifer. Because these equations are linear, the head change due to the earthquake may be superimposed on the background hydraulic head. Taking this background head as the reference head, i.e. $h = 0$, we may take the coordinate x along any direction, including the horizontal and the vertical.

For boundary conditions, we adopt a no-flow boundary condition at $x = 0$ (i.e. a local water divide) and $h = 0$ at $x = L$ (i.e. a local discharge or recharge). Under these conditions, the solution of equation 2 for A as a function of x only, is given in Carslaw & Jaeger (1959; p. 132, equation 10):

$$h(x, t) = \frac{4L}{\pi^2 K} \sum_{n=1}^{\infty} \frac{1}{n^2} \left[1 - \exp\left[-\frac{Dn^2\pi^2 t}{4L^2} \right] \right]$$
$$\cos\frac{n\pi x}{2L} \int_{-L}^{L} A(x) \cos\frac{n\pi x'}{2L} dx' \qquad (6)$$

As the source (or sink) for the present study is a function of both x and t, we apply the Duhamel's principle (Carslaw & Jaeger 1959; p. 32, equation 20) to (6), obtaining

$$h(x, t) = \frac{1}{LS_s} \sum_{n=1}^{\infty} \cos\frac{n\pi x}{2L} \int_{-L}^{L} \int_{0}^{t} \exp\left[\frac{-Dn^2\pi^2(t-\lambda)}{4L^2} \right]$$
$$A(x, \lambda) \cos\frac{n\pi x'}{2L} d\lambda dx' \qquad (7)$$

As the time duration for the coseismic release of water is very much shorter than the time duration for the post-seismic evolution of groundwater level, we may consider the coseismic release of water to be instantaneous; i.e.

$$A(x, t) = A_o(x)\delta(t = 0) \qquad (8)$$

where $A_o(x)$ is the spatial distribution of the earthquake-induced fluid source (Fig. 5) and $\delta(t = 0)$ is the delta function that equals 1 when $t = 0$ and equals zero when $t > 0$. Equation 7 is then reduced to

$$h(x, t) = \frac{1}{LS_s} \sum_{n=1}^{\infty} \cos\frac{n\pi x}{2L} \exp\left[-\frac{Dn^2\pi^2 t}{4L^2} \right] \int_{-L}^{L} Q_o(x') \cos\frac{n\pi x'}{2L} dx'$$
$$(9)$$

where

$$Q_o(x) = \int_{0}^{t} A_o(x)\delta(t)dt \qquad (10)$$

The function $A_o(x)$ has a unit of volume per volume per time, while the function $Q_o(x)$ has a unit of volume per volume.

For sufficiently long time after the earthquake such that $t \geq \frac{4L^2}{\pi^2 D}$, we obtain from (9)

$$\frac{\partial \log h}{\partial t} \approx -\frac{\pi^2 D}{4L^2}. \qquad (11)$$

Note that the above expression is independent of the spatial distribution of the coseismic source or sink of water, and of the location of measurement. As noted earlier, the left-hand side of the above expression is given by the slope of the field-based empirical relation (equation 1) between the hydraulic head and time for the post-seismic change. Thus we have

$$\tau \approx \frac{4L^2}{\pi^2 D}. \qquad (12)$$

The above equation relates field measurements to the hydraulic and geometrical properties of the aquifers. It shows that, for sufficiently long time after the earthquake,

the characteristic time determined from the field record is directly proportional to the square of its characteristic length (L) and inversely proportional to the diffusivity of the aquifer (D), but is independent of the spatial distribution of the source or sink or of the location of the measurement.

A complete calculation of the post-seismic change of the hydraulic head, using equation 6, requires a prescription the spatial distribution of the coseismic source or sink (Q_o). Assuming a model of $Q_o(x) = Q_o$ for $x < L'$ and $Q_o(x) = 0$ for $x > L'$, and using equation 8, we obtain the hydraulic head at location x and time t as

$$h(x, t) = \frac{4Q_o}{\pi S_s} \sum_{n=1}^{\infty} \frac{1}{n} \sin\frac{n\pi L'}{2L} \cos\frac{n\pi x}{2L} \exp\left[-n^2 \frac{t}{\tau} \right] \qquad (13)$$

The corresponding specific discharge is

$$q(x, t) = \frac{2KQ_o}{LS_s} \sum_{n=1}^{\infty} \sin\frac{n\pi L'}{2L} \sin\frac{n\pi x}{2L} \exp\left[-n^2 \frac{t}{\tau} \right]. \qquad (14)$$

If we assume furthermore that $L' = L$, equation 9 becomes

$$h(x, t) = \frac{4Q_o}{\pi S_s} \sum_{r=1}^{\infty} \frac{(-1)^{r+1}}{(2r-1)} \cos\frac{(2r-1)\pi x}{2L} \exp\left[-(2r-1)^2 \frac{t}{\tau} \right].$$
$$(15)$$

Given the values of τ determined from the field data (Table 1) and a specific storage of 10^{-4} m^{-1} from well tests (Tyan *et al.* 1996), we may compare the model prediction with the data for the post-seismic groundwater level. As an example, we compare in Fig. 6 the post-seismic residual hydraulic head h for Yuanlin (1) against the model predictions for different values of x/L. A value of $Q_o = 3.4 \times 10^{-4}$ m^3 m^{-3} was used to match the amplitude of h at $t = 0$. The curve for $x/L = 0.5$ shows an excellent fit to the field data, suggesting that the Yuanlin station may be situated at the mid-point of an aquifer between a local groundwater divide and a local discharge. As the ratio x/L is not known *a priori* at any given station, a good fit to the field data by one of these curves does not prove the validity of the model; it merely demonstrates the consistency of the model with the field data. For this reason, it may not be instructive to show more examples of the similar fits at other stations. In the following we discuss the implications of the observations on the mechanisms for the four types of post-seismic responses.

DISCUSSION

Type 1 (up-down) post-seismic responses

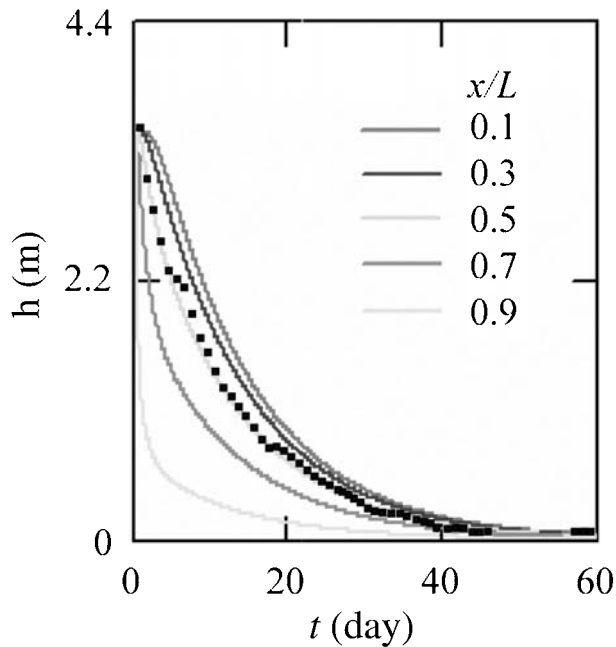It may be curious why the characteristic time for the topmost aquifer and that of the confined aquifers are similar in

Fig. 6. Diagram showing example from Yuanlin (1) for comparing model prediction of post-seismic residuals *h* (curves) for several values of *x/L* against field data (dots). Note excellent fit between data and curve for *x/L* = 0.5.

this type of post-seismic response. A probable reason is that the topmost aquifer is partly confined. In the following we try to examine this problem more closely with the following analysis. Using the relation $D = T/S$, where T is the transmissivity and S the storativity of the aquifers, we may estimate the characteristic lengths of the aquifers from equation 8. The values of T were determined from well tests for the aquifers on the Choshui River fans (Kester & Ouyang 1996; Lee & Wu 1996; Tyan *et al.* 1996) and do not differ greatly between the confined and the topmost aquifers. However, the values of S are determined only at two stations (Hsihu, Hsichou) among those listed in Table 1. For the confined aquifers, there is consistency between the storativities determined at the two stations: $1–3 \times 10^{-3}$ at the Hsihu station and approximately 1×10^{-3} at the Hsichou station. Thus, using an average $T \sim 10^{-2}$ m^2 sec^{-1} for the confining aquifers (Kester & Ouyang 1996; Lee & Wu 1996; Tyan *et al.* 1996), we obtain $D \sim 10$ m^2 sec^{-1}; further, using equation 8 and $\tau \sim 10^6$ sec, we obtain $L \sim 5000$ m for the confined aquifers.

For the topmost aquifer, the storativity is approximately 5×10^{-4} at the Hsihu station and approximately 2×10^{-1} at the Hsichou station. The great variability in storativity implies a great variability in the characteristic length of the aquifers from place to place. If $S \sim 5 \times 10^{-4}$, $L \sim 300$ m; if $S \sim 2 \times 10^{-1}$, $L \sim 7000$ m. The great variability in the characteristic length may reflect the fact that the topmost aquifer is partly confined and partly unconfined, as noted earlier.

It may be interesting to note that the characteristic lengths for the confined aquifers estimated above (i.e. 5000 m) is considerably smaller than that shown on the geologic cross-sections reconstructed from the hydrological well logs (Water Resource Bureau 1999). This difference might be expected because the actual geologic structure of the aquifers in the alluvial fan must be greatly more complex than that shown on a simplified geologic cross-section.

The stations with the type 1 (up-down) responses are located on the unconsolidated sediments of the Choshui River fan where the groundwater table generally lies above the local streams (except in the coastal area and along the Peikang Stream where the type 4 (up-up) responses dominated). The coseismic rise in the groundwater table at these stations suggests a coseismic 'source' due to coseismic consolidation of the sediments (Wang *et al.* 2001b; Manga *et al.* 2003; Montgomery *et al.* 2003). Thus a model of coseismic source and local discharge (model 1) may explain the type 1 (up-down) changes.

Type 2 (down-up) post-seismic responses

All the stations with the type 2 (down-up) responses are located near the Chelungpu fault that ruptured in the Chi-Chi earthquake (Chia *et al.* 2001; Wang *et al.* 2001a). The coseismic drop in the groundwater table at these stations suggests a coseismic 'sink' due perhaps to increased vertical permeability formed in the earthquake (Rojstaczer & Wolf 1992; Wang *et al.* 2001a). The water level in the local streams is tens of meters above the local groundwater level. It is unclear whether the streams are connected to the groundwater system by a saturated bump in the water table or they are perched. If they are perched, the rapid post-seismic response suggests the occurrence of a earthquake-induced high vertical hydraulic conductivity between the streams and the groundwater system. The coseismic drop in the water level implies an increase in the hydraulic gradient between the surface water and the groundwater table and therefore an increase in the recharge from the surface water to the groundwater. A model of coseismic sink and vertical recharge (model 2) may explain the type 2 (down-up) responses. Using equation 8 and $\tau \sim 10^5$ sec (Table 1) and $D \sim 0.1$ m^2 sec^{-1} (Tyan *et al.* 1996), we obtain $L \sim 100$ m.

Type 3 (down-down) post-seismic responses

The Liyu station with the type 3 (down-down) response is also located near the Chelungpu fault. Unlike the post-seismic rises that occurred at the stations with the type 2 (down-up) responses, however, the groundwater level continued to decline following a coseismic drop of approximately 6 m. The water level in a nearby stream (the

Chinshui Stream) is tens of meters above the local groundwater level. It also experienced a sudden drop of approximately 1 m in the stream level immediately following the earthquake (Water Resource Bureau 2000), caused by the damming of the upper reach of the stream by an earthquake-induced landslide. Given the coseismic approximately 6 m drop in the groundwater level, however, there was a net increase of approximately 5 m in the difference between the stream level and the groundwater level immediately following the earthquake. Thus one might have expected, as for the other stations near the Chelungpu fault, a post-seismic increase in the recharge from the local stream and a corresponding increase in the groundwater level. The unexpected post-seismic decline of the groundwater level at the Liyu station suggests that an enhanced permeability to a lower reference level was established in the earthquake, which facilitated the groundwater discharge. Thus a model of coseismic sink and local discharge (model 3) may explain the type 3 (down-down) changes. Using equation 8 and $\tau \sim 10^6$ sec (Table 1) and $D \sim 10$ m^2 sec^{-1} for confined aquifers (Tyan *et al.* 1996), we obtain $L \sim 5000$ m.

Type 4 (up-up) post-seismic response

As noted earlier, the stations that showed a sustained post-seismic response in the groundwater level occur mostly along the coast and along the Peikang Stream. A common characteristics shared by the coastal stations and those along the Peikang Stream is that the groundwater levels beneath these stations are all several meters or more below the local surface water level. The coastal groundwater level has fallen over the past 25 years to 5–10 m below the sea level due to continued and increased over-withdrawal of the groundwater along the coast. The Peikang Stream, However, is a natural losing stream that recharges the local groundwater. During the Chi-Chi earthquake, the stations along the coast and along the Peikang Stream recorded a small (<1 m) coseismic increase in the groundwater level (Chia *et al.* 2001; Wang *et al.* 2001b). But the coseismic groundwater level remained below the surface water level. Again, it is unclear whether the streams are connected to the groundwater system by a saturated bump in the water table or they are perched. If they are perched, the post-seismic response suggests the occurrence of a earthquake-induced high vertical hydraulic conductivity between the streams and the groundwater system. We envision a model of vertical recharge from the surface water to the local groundwater (model 4), due to increased vertical permeability from fractures and cracks formed in the earthquake. Although this mechanism is the same as that in model 2, it produces the opposite effect on the groundwater recovery; i.e. while in model 2, the mechanism helps the post-seismic recovery of the groundwater level, here it retards the post-seismic recovery of the groundwater level.

SUGGESTED TESTS

Four types of models have been presented in this paper; it may be interesting to discuss possible tests for these models. At first thought, the characteristic lengths of the aquifers estimated earlier might seem to be a testable quantity. However, as the actual characteristic lengths of the aquifers are not directly observable, other means are needed to test the models presented in this paper.

In model 1, a coseismic rise in groundwater level is followed by a local discharge leading to a post-seismic decline of groundwater level. The magnitude of the volume strain to produce the post-seismic changes in groundwater level in Yuanlin I, as estimated earlier, is of the order of 10^{-4} which may be too small to be measured in the field with confidence. However, a geochemical test may be useful in this regards. As the post-seismic response was a discharge from the aquifer, there is no water input from outside to the aquifer; thus the model implies that there is no change in the geochemical composition of the groundwater. In model 2, a coseismic drop in groundwater level is followed by a vertical recharge, leading to a post-seismic rise of groundwater level. The model implies a post-seismic input of water from the local surface water. This would induce a change in the geochemical composition of the groundwater towards that of the surface water if the streams are perched. However, if the streams are connected to the groundwater system prior to the earthquake, the aquifer there was already dominated by surface water recharge. Thus a negative result (no change in chemistry) would not rule out the mechanism proposed. In model 3, a coseismic drop in groundwater level is followed by a local discharge, leading to a continuous, post-seismic drop of groundwater level. Like model 1, the model implies that there is no input of water from outside of the groundwater system and thus no change in the geochemical composition of the groundwater. In model 4, a coseismic rise in groundwater level is followed by a vertical recharge, leading to a post-seismic maintenance or rise of groundwater level, before it eventually drop. Like model 2, the model implies a post-seismic input of water from the local surface water. If the streams are perched, the post-seismic recharge of the aquifer would have induced a change in the chemical composition of the groundwater towards that of the surface water. However, if the streams were connected to the groundwater system prior to the earthquake, there would be no change in chemistry.

Two sets of 180 groundwater samples have been collected from the wells on the Choshui River fan before and after the Chi-Chi earthquake, and analyzed for the groundwater composition, including the hydrogen and oxygen

isotopes (Wang *et al.* 2001a). Wang *et al.* (2004) also suggested that vertical mixing of waters among different aquifers with different isotopic compositions, due perhaps to enhanced vertical permeability in the earthquake, may be required to explain some of the geochemical changes in the groundwater after the earthquake. A careful account of the effects of both the horizontal and vertical mixing on the groundwater composition would be needed before the available geochemical data becomes useful for testing the present models, which is beyond the scope of the present paper.

CONCLUDING REMARKS

The dense hydrological network in central Taiwan made it possible to capture a variety of post-seismic responses of the groundwater level following the Chi-Chi earthquake. In this work we show that a combination of coseismic sources (or sinks) and subhorizontal discharge across a length of 500–5000 m may explain the type 1(up-down) and type 3 (down-down) types of post-seismic changes. However, a combination of coseismic sources (or sinks) and recharge from surface water may explain the type 2 (down-up) and type 4 (up-up) post-seismic changes.

It would be interesting to compare the characteristic times determined for the post-seismic responses of the groundwater level with that determined before the earthquake in the dry seasons. This comparison would reveal whether significant changes in the aquifer properties (i.e. hydraulic conductivity) have occurred in the earthquake; it is, however, outside the scope of this work. In the long run, earthquake-induced consolidation, a primary mechanism for creating the coseismic water-source, may significantly change the aquifer porosity, that in turn may significantly alter the other hydraulic properties (e.g. permeability) of the aquifers. Given a recurrence time of 10^2 years for large earthquakes and assuming an average volume reduction of 10^{-4} m^3 m^{-3} per large earthquake (this study), porosity would be reduced by an amount of approximately 10% in 10^5 years – a brief geological time.

Geochemical compositions of the groundwater before and after the earthquake may provide useful information for testing the models. However, this would require an understanding whether the streams are connected to the groundwater system or they are perched, and a careful account of the effect of vertical mixing on the composition of the groundwater between different aquifers would be required before the geochemical data could be effectively used in model testing.

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