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Notes

Coseismic release of water from mountains: Evidence from the 1999 ($M_w = 7.5$) Chi-Chi, Taiwan, earthquake

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ABSTRACT

Earthquake-induced increases in streamflow, producing $\sim 0.7 \text{ km}^3$ of total excess water, were documented after the 1999 ($M_w = 7.5$) Chi-Chi earthquake in central Taiwan. Analysis of stream gauge data and well records suggests that the excess water originated in the mountains. We propose that the extensive high-angle fractures formed during the earthquake allow rapid release of water from mountains and that mountains in tectonically active areas may be repeatedly flushed by meteoric water at time intervals comparable to the recurrence time of large earthquakes.

Keywords: streamflow, earthquake, mountains, hydrology, active tectonics.

INTRODUCTION

Increases in streamflow are commonly observed following earthquakes (for an overview, see Montgomery and Manga, 2003). Volumes of streamflow increases include $\sim 0.7 \text{ km}^3$ of excess water released after the $M = 7.5$ Chi-Chi earthquake (this study), 0.5 km^3 after the $M = 7.5$ Hebgen Lake earthquake (Muir-Wood and King, 1993), 0.3 km^3 after the $M = 7.3$ Borah Peak earthquake (Muir-Wood and King, 1993), and 0.01 km^3 after the $M = 6.9$ Loma Prieta earthquake (Rojstaczer et al., 1995). Where did the excess water come from? Three hypotheses have been advanced: (1) Water is expelled from the crust as a result of coseismic elastic strain (Muir-Wood and King, 1993; Roeloffs, 1996; Ge and Stover, 2000; M. Lee et al., 2002). (2) Water is released from the upper crust because of an increased permeability from fractures formed during earthquakes (Briggs, 1991; Rojstaczer and Wolf, 1992; Rojstaczer et al., 1995; Tokunaga, 1999; Sato et al., 2000). (3) Water is released from coseismic liquefaction or consolidation of loose sediments (Manga, 2001; Manga et al., 2003; Montgomery et al., 2003).

The different mechanisms imply different processes for groundwater recharge and discharge in earthquake cycles (e.g., Rojstaczer et al., 1995; Roeloffs, 1998; Manga, 2001; Wang et al., 2001; Brodsky et al., 2003) and thus different impacts on geologic processes. Are all three mechanisms viable, their relative importance varying with different tectonic setting? Or can one explanation account for all the observed increases in streamflow associated with earthquakes? Owing largely to a lack of adequate data, the hydrological models in the previous studies are underconstrained, and these questions cannot be answered definitively.

Taiwan is a mountainous island that was formed by the collision between the Philippine

Sea plate and the continental margin of the Eurasian plate since the late Cenozoic (Fig. 1A; Ho, 1988; Teng, 1990). The 1999 $M_w = 7.5$ Chi-Chi earthquake in central Taiwan created a wealth of data and an opportunity to test these hypotheses in a fold-and-thrust tectonic setting. The 17 stream gauges (Fig. 1) on 3 stream systems registered large postseismic increases in discharge (Water Resource Bureau, 2000). In addition, a network of 70 hydrologic stations (Fig. 1B) captured changes of the groundwater level near the epicenter (Wang et al., 2001; Chia et al., 2001).

SETTING

The Chi-Chi earthquake occurred on a thrust fault beneath the foreland fold-and-thrust foothills of the mountain belt in central Taiwan (Fig. 1A). A large (1800 km^2) alluvial fan is to the west of the thrust front (Fig. 1B); sediments on the fan are unconsolidated, with massive gravels near the steep mountains and sands and muds in distal areas (Fig. 1C). The alluvial fan overlies a sedimentary basin containing alternating Pleistocene to Miocene sandstones and shales (Fig. 1C; Ho, 1988). In the foothills the sandstones and shales are folded and faulted (Fig. 1C; Suppe and Jamson, 1979). The Central Ranges, composed of metamorphic rocks of various grades (Ho, 1988), rise locally to 4 km elevation to the east of the foothills.

The average annual precipitation over the island reaches 2.5 m, equivalent to a volume of water of 90 km^3 . The rainy season normally starts in late April or early May and ends in early September. In the study area, the 1999 rainy season was over well before the Chi-Chi earthquake on 21 September 1999. Three stream systems occur in the study area (Fig. 1B): the Choshui Stream system, the largest of the three, the Wushi Stream system along the north margin, and the Peikang Stream system along the southern margin of the study

area. Both the Choshui and the Wushi systems have extensive tributaries in the mountains, but the Peikang Stream system originates on the sloping side of the Choshui fan, with no tributaries in the mountains.

OBSERVATIONS

Stream gauge data are listed on the Web site of the Water Resources Agency of Taiwan (http://wis.wra.gov.tw/wis/is/is_menu.cfm). We list in Table 1 the five-day average discharge in several streams, before and after the Chi-Chi earthquake. Streams in the mountainous areas all showed large postseismic streamflow increases. On the alluvial fan, both the Choshui Stream and the Wushi Stream, which have tributaries in the mountains, showed large increases in streamflow. The amount of increase in streamflow in the proximal area of the Choshui alluvial fan (gauge H057) was about the same as that in the distal area of the fan (gauge H058), suggesting that most of the excess water originated in the mountains and that the contribution from the sediments in the fan was insignificant. By contrast, the Peikang Stream system (Fig. 1), which does not have tributaries in the mountainous area, did not show any noticeable postseismic increase in streamflow (Table 1, gauges H009, H014, and H029). This result shows that any coseismic consolidation and liquefaction of sediments on the alluvial fan were not substantial enough to cause noticeable postseismic increase in streamflow.

MODELS

M. Lee et al. (2002) suggested that the changes in the groundwater level and streamflow during and immediately after the Chi-Chi earthquake were caused by the coseismic elastic strain (hypothesis 1). Given the small coseismic elastic strain ($<10^{-6}$; M. Lee et al., 2002), however, water would have been expelled from a layer $\sim 400 \text{ km}$ thick beneath the Choshui fan in order to provide the 0.7 km^3 of excess water in the postseismic streamflow—a conclusion inconsistent with the rapid response of the groundwater level and the streamflow after the earthquake.

The observations described in the previous section also appear to contradict hypothesis 3—that water was released from coseismic consolidation or liquefaction of sediments. There was insignificant contribution to the streams from the sediments on the Choshui

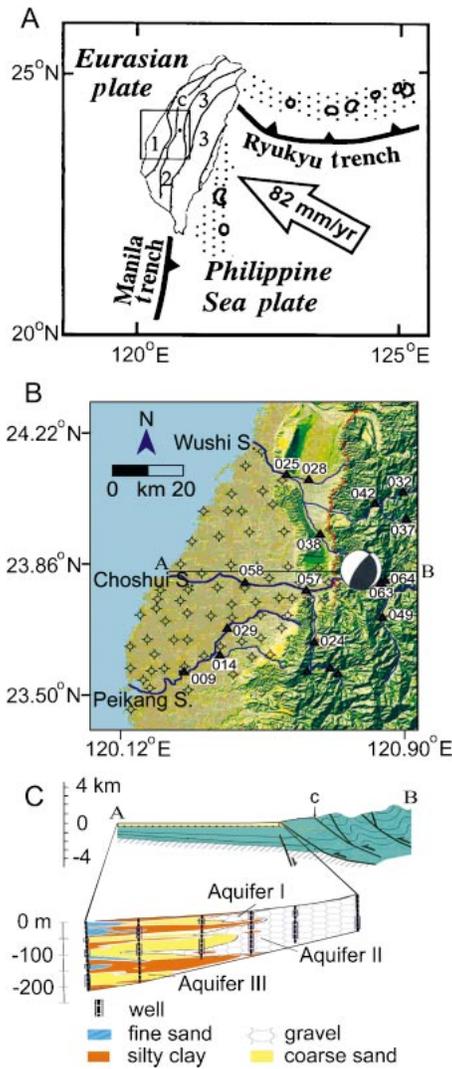


Figure 1. A: Plate tectonic setting of Taiwan. Major structural belts: 1—coastal plain; 2—foothills, 3—Central Ranges. Dot in box—Chi-Chi earthquake epicenter; c—Chelungpu fault. B: Topographic map of study area. Choshui alluvial fan is on west side and foothills are on east side. Triangles—stream gauges; circles with cross—well locations. Major stream systems are labeled S. Tributaries are listed together with stream gauges in Table 1. C: Simplified geologic cross section along line A–B marked in B; c—Chelungpu fault. Pleistocene–Miocene sandstone and shale beds (in green) underlie Choshui fan and are folded and thrust faulted in foothills. Sediment structures in fan are enlarged in inset.

fan despite the occurrence of liquefaction (Wang et al., 2003). Is the new observation consistent with hypothesis 2—that the increase in streamflow was due to increased permeability in the shallow crust? In the absence of recent precipitation or snowmelt, the discharge in a stream is dominated by base flow, i.e., groundwater flow from the saturated zone to streams (Freeze and Cherry, 1979, p. 4), irrespective of whether the groundwater occurs in soil, regolith, or rocks. The discharge

TABLE 1. FIVE-DAY AVERAGE DISCHARGES BEFORE AND AFTER CHI-CHI EARTHQUAKE

Stream system	Tributary	Gauge	Location	Discharge (m ³ /s)		
				Before	After	Excess
Choshui Stream system		H058	Tzechiang Bridge	~150	255	~105
		H057	Changyuen Bridge	124	237	113
	Choshui Stream	H063	Yufeng Bridge	94	207	113
	Shuili Stream	H064	Shuili Bridge	~45	15	~30
	Chinshui Stream	H024	Tongtuo Bridge	~10	5	~5
Wushi Stream system		H025	Tatu Bridge	<100*	~170	>70
	Wushi Stream	H042	Chienfeng Bridge	~46	111	~65
	Beikang Stream	H032	Nanpeitong Bridge	18	81	63
	Nankang Stream	H037	Kangying Bridge	28	66	38
Peikang Stream system		H009	Peikang Bridge	~30	~25	~5
	Peikang Stream	H014	Shikou Bridge	~2	~2	~0
	Peikang Stream	H029	Tuku Bridge	~10	~8	~2

*Due to precipitation.

of the stream decreases with time along an exponential curve (e.g., de Marsily, 1986). The slope of the logarithm of discharge vs. time is proportional to the ratio D/L^2 , where D is hydraulic diffusivity and L is the length of the aquifer. Manga (2001; also Montgomery et al., 2003; Manga et al., 2003) found no

detectable changes in hydraulic diffusivity, and hence permeability, of different groundwater systems providing base flow following several earthquakes, in apparent contradiction to hypothesis 2. The logarithm of the discharge for several streams in the study area is plotted against time in Figure 2. The slope of

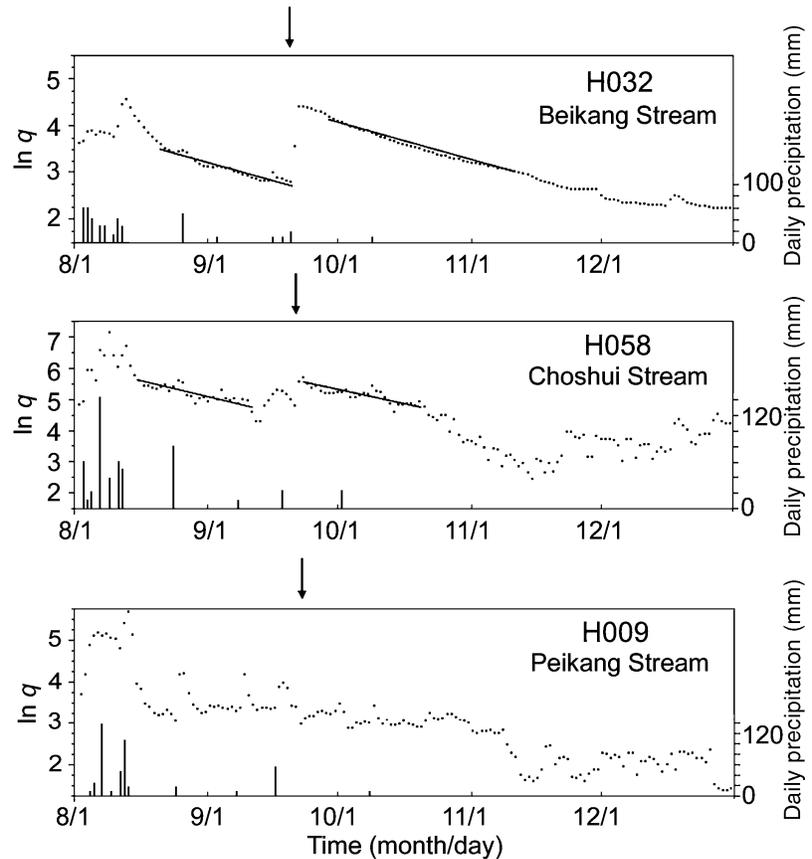


Figure 2. Diagrams showing representative discharges (q , in m³/s) of streams (daily averages, in logarithmic scale) in study area as functions of time. Earthquake occurrence is marked by vertical arrows. Top: Stream gauge H032, located on stream in mountains. Note surge in discharge after Chi-Chi earthquake. Linear segments of data before and after earthquake are fitted by straight lines with similar slopes. Center: Stream gauge H058, located on Choshui Stream on Choshui alluvial fan. Note surge in discharge after Chi-Chi earthquake but greater scatter in data. Slopes of linear fits to data are similar before and after Chi-Chi earthquake. Bottom: Stream gauge H009, located on Peikang Stream on Choshui fan. No noticeable surge in discharge occurred after earthquake.

TABLE 2. D/L^2 FROM RECESSION ANALYSIS AND VQ_0 FROM MODEL FITTING FOR SEVERAL STREAMS

Streams	Stream gauges	D/L^2 (s^{-1})	VQ_0 (km^3)
Wushi system			
Wushi	H025	2.1×10^{-7}	0.21
Beikang	H032	2.0×10^{-7}	0.14
Nankang	H037	2.0×10^{-7}	0.10
Wushi	H042	1.9×10^{-7}	0.23
Choshui system			
Choshui	H057	1.4×10^{-7}	0.56
Choshui	H058	2.7×10^{-7}	0.55
Choshui	H063	2.0×10^{-7}	0.44

the curves, and the corresponding values for D/L^2 (Table 2), remained the same before and after the Chi-Chi earthquake, confirming that the horizontal hydraulic diffusivity of the groundwater system providing base flow did not change after the earthquake. Thus, it may appear that the new data are also inconsistent with hypothesis 2.

Here, however, we propose a model of earthquake-induced anisotropy in the hydraulic diffusivity that reconciles these data with hypothesis 2. After the earthquake, many wells in the foothills above the thrust fault showed a significant drop in the water level (Lin, 2000; Yan, 2001; Chia et al., 2001; Wang et al., 2001). At the same time, numerous subvertical tensile cracks appeared in the foothills (Angelier et al., 2000; C. Lee et al., 2000; J. Lee et al., 2002). These cracks may have been formed by tensile stresses generated in the hanging wall when it collapsed under gravity (J. Lee et al., 2002), or they may have been due to strong ground shaking as far as tens of kilometers away from the epicenter (Shin and Teng, 2001).

The foothills are underlain by alternating beds of sandstone and shale, and the vertical permeability before the earthquake would have been controlled by the impervious shales. Hence the vertical flow was impeded, and groundwater flow was mostly horizontal before the earthquake (Fig. 3A). Formation of the subvertical fractures during the earthquake breached the impervious shales and greatly enhanced the vertical permeability, allowing rapid downward draining of water to recharge underlying aquifers (Fig. 3B). The horizontal conductivity of the aquifers, however, was essentially unaffected. Draining of the foothills creates excess water in the aquifer that dissipates as base flow following the earthquake with a duration characteristic of the aquifer.

We use the diffusion equation for a one-dimensional leaky aquifer (de Marsily, 1986) to examine the consequence of this model (Fig. 3C); here the recharge to the aquifer is treated as a source:

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial x^2} + A, \quad (1)$$

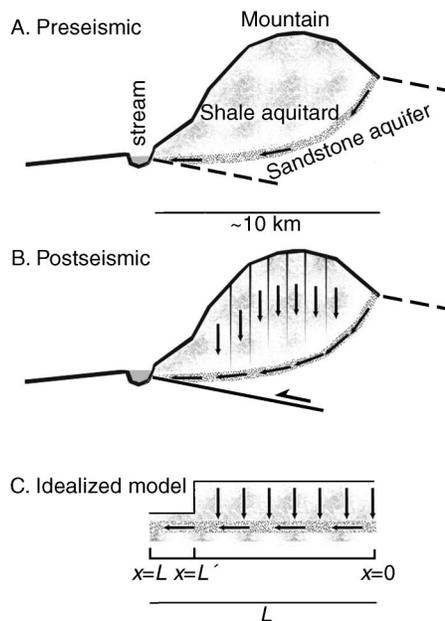


Figure 3. Conceptual model. A: Interseismic period. Groundwater in mountains flows along sandstone aquifers; vertical flow is impeded by impervious shale beds. Eastern boundary of model is located 10 km east of Chelungpu fault at outcrop of Shuangtung fault; both faults are indicated by dashed lines. B: Coseismic extensive fractures breach impervious shales, allowing subvertical draining of water through shale beds. Ruptured Chelungpu fault is indicated by solid line. C: Idealization of one-dimensional leaky aquifer used in calculation.

where h is the excess hydraulic head above the background value, K is the horizontal hydraulic conductivity, S_s is the specific storage, and A is the rate of water recharge per unit volume of the leaky aquifer across its boundary. Even though this model is highly simplified, it has been shown to agree with data in several studies (e.g., Roeloffs, 1998; Manga, 2001; Manga et al., 2003; Brodsky et al., 2003; Montgomery et al., 2003) that characterize the first-order hydrological system response to earthquakes.

Coseismic drops of water level occurred in many wells in the foothills. Sudden downpour

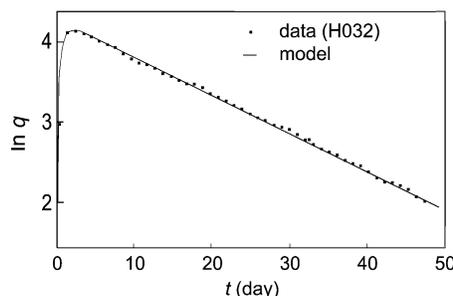


Figure 4. Diagram comparing excess discharge (q_{ex} , in m^3/s) predicted by model (curve) with daily average data (dots) for stream gauge H032. See text for details.

also occurred in a tunnel beneath the foothills immediately after the Chi-Chi earthquake (Lin, 2000). Thus, we may treat the recharge of the leaky aquifer as coseismic. If we further simplify the problem by assuming the amount of the coseismic recharge per unit volume as constant Q_0 for $x \leq L'$ and 0 for $x > L'$, the excess discharge from the aquifer to the stream at time t is (Wang et al., 2004):

$$q_{ex} = \frac{2DVQ_0}{L^2(L'/L)} \sum_{r=1}^{\infty} (-1)^{r-1} \times \sin\left[\frac{(2r-1)\pi L'}{2L}\right] \times \exp\left[-\frac{(2r-1)^2\pi^2 D}{4L^2}t\right], \quad (2)$$

where $D = K/S_s$, V is the volume of the aquifer between $x = 0$ and L' (Fig. 3C), and VQ_0 is the total excess water recharging the aquifer. As an example, Figure 4 compares the data for stream gauge H032 (Fig. 2, adjusted to $q_{ex} = 0$ just before earthquake) with the excess discharge q_{ex} determined by equation 2. An excellent fit is obtained with $D/L^2 = 2.4 \times 10^{-7} s^{-1}$ (Table 2) and $L'/L = 0.8$. The former is consistent with the results from analyzing the postseismic decrease in the groundwater level in the foreland following the Chi-Chi earthquake (Wang et al., 2004), and the latter is consistent with the fact that gauge H032 is located in the mountains, where the width of the floodplain is small. With the values of DVQ_0/L^2 from model fitting and the values of D/L^2 in Table 2, we obtain the amount of excess water, VQ_0 , for several stream gauges (Table 2). By summing the excess discharges in the Choshui Stream and in the Wushi Stream, we obtain a total amount of 0.7–0.8 km^3 of the excess water released from the mountains after the Chi-Chi earthquake, which is the largest amount of earthquake-released water ever reported.

DISCUSSION

We propose a model of fracture-related anisotropic permeability such that only the vertical permeability of the groundwater system is enhanced by the earthquake, while the horizontal permeability remains nearly constant. This model removes the apparent controversy between the hypothesis of permeability increase in the shallow crust and the results from recession analysis that evaluates mostly the horizontal permeability of a groundwater system.

Lowering of the water level in mountainous terrane was also reported after the Loma Prieta earthquake in California (Rojstaczer et al., 1995) and after the Kobe earthquake in Japan (Tokunaga, 1999). Both earthquakes occurred on strike-slip faults, even though there was a

significant thrust component in the Loma Prieta earthquake. Thus, the release of water from mountains in earthquakes may not be restricted to a fold-and-thrust tectonic setting, as in this study, but may also occur in other tectonic settings. The variability in the volume of excess flow in different regions following different earthquakes, as cited earlier, may reflect the differences in regional precipitation, i.e., ~2.5 m/yr in Taiwan vs. <0.5 m/yr in the Santa Cruz area. Other factors, such as differences in topography (affecting hydraulic gradient) and tectonic settings (affecting stress orientation), may also change the volume of excess flow.

The vertical permeability of the foothills may readily return to its preearthquake state owing to active biogeochemical processes, and vertical flow of groundwater will again be impeded. The time scale of this process, however, is difficult to determine.

Recurrent large earthquakes may repeatedly induce subvertical flow to flush the low-permeability regions in the mountains. By using the 40 m digital elevation map of Taiwan, we calculate a volume of 301 km³ for the foothills above the surface trace of the Chelungpu fault (Fig. 3B) and within 10 km east of the fault. Assuming an average porosity of ~10% for the impervious shales, we estimate the amount of stored water to be ~30 km³, or ~43 times that released in the Chi-Chi earthquake. Given a recurrence interval of 350–600 yr for large earthquakes on the Chelungpu fault, we estimate the residence time of the stored water in the foothills to be 1.5–2.5 × 10⁴ yr. Thus, the low-permeability regions in the mountains may be completely flushed by meteoric water in a geologically short time.

Because advective transport may strongly influence groundwater temperature and chemical composition, the use of temperature and geochemical data may provide effective tests for the proposed model (e.g., Bredehoeft and Papadopoulos, 1965; Ingebritsen et al., 1989; Deming, 1993; Kharaka et al., 1999; Saar and Manga, 2003). Moreover, a time-dependent change in gravity may occur because of the draining of the water. We suggest active monitoring of such data after future large earthquakes.

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