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Key Points:
- Earthquakes can increase the transmissivity and hydraulic diffusivity of well-aquifer systems
- Earthquakes can change confined aquifers to semiconfined aquifers

Supporting Information:
- Supporting Information S1
- Figure S1

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Aquifers switched from confined to semiconfined by earthquakes

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Abstract Earthquake-induced aquifer parameter changes (e.g., permeability and hydraulic diffusivity) have been documented in many studies. However, changes in the confinement of an aquifer from confined to semiconfined following an earthquake have not been reported. Here we focus on the tidal response of the water level in four wells following the 2008 Wenchuan M_w 7.9 and 2013 Lushan M_w 6.6 earthquakes to show that earthquakes can change confined aquifers to semiconfined aquifers by reopening of preexisting vertical fractures (and later healing). This study has important implications because a switch from confined to semiconfined means a change of vertical hydraulic connection, which may affect the vulnerability of an aquifer, the integrity of underground waste repositories, and the safety of groundwater supplies.

1. Introduction

Changes in groundwater level [*Shi et al*., 2015a; *Wang and Chia*, 2008], stream flow [*Manga et al*., 2003; *Mohr et al*., 2012], water temperature [*Wang et al*., 2012], and chemical composition [*Claesson et al*., 2004; *Skelton et al*., 2014] are the most widely documented hydrological responses to earthquakes. Various mechanisms have been proposed to explain these phenomena: (1) groundwater level changes are always associated with changes in aquifer parameters (permeability or storativity) through unclogging/clogging of temporary barriers [*Brodsky et al*., 2003], elastic deformation [*Jang et al*., 2008; *Wang and Chia*, 2008], or rupture of the aquifer [*Wang et al*., 2004b; *Ward*, 2015]; (2) stream flow changes following earthquakes are associated with permeability enhancement [*Rojstaczer et al*., 1995; *Wang and Manga*, 2015; *Wang et al*., 2004a] or coseismic consolidation/liquefaction of sediments [*Manga et al*., 2003; *Montgomery et al*., 2003]; (3) water temperature changes are attributed to earthquake-induced permeability changes and the resultant mixing of different water [*Mogi et al*., 1989; *Shi and Wang*, 2014]; and (4) changes in chemical composition have been attributed to the rupturing of hydrological barriers between chemically distinct aquifers, permitting rapid mixture [*Claesson et al*., 2007; *Skelton et al*., 2014].

Most of the mechanisms proposed above are associated with earthquake-induced aquifer parameters change and can be divided into two groups according to whether the aquifer structure was changed. The mechanisms related to changed aquifer structures include rupture of the aquifer/aquitard or consolidation of the aquifer, causing vertical groundwater movement between aquifers. Mechanisms with unchanged aquifer structures include the clogging/unclogging of temporary barriers, which changes the velocity of groundwater movement. It is possible to identify whether the aquifer structure has changed following an earthquake by analyzing the water level variation before and after the earthquake [*Liao et al*., 2015]

Here we use the tidal response of the water level in wells following the 2008 M_w 7.9 Wenchuan earthquake and the 2013 M_w 6.6 Lushan earthquake to show that earthquakes may change both the horizontal permeability of the aquifer and the well-aquifer system, changing the aquifer from confined to semiconfined.

2. Geological Setting and Observations

Both the 2008 M_w 7.9 Wenchuan earthquake and 2013 M_w 6.6 Lushan earthquake occurred on the Longmenshan fault zone along the eastern margin of the Qinghai-Tibet Plateau (Figure 1). The two earthquakes had similar focal mechanisms, with thrust and right-lateral components for the Wenchuan earthquake and a thrust fault component for the Lushan earthquake. The M_w 7.9 Wenchuan earthquake produced a unilateral 340 km rupture, while the Lushan earthquake occurred ~85 km southwest of the

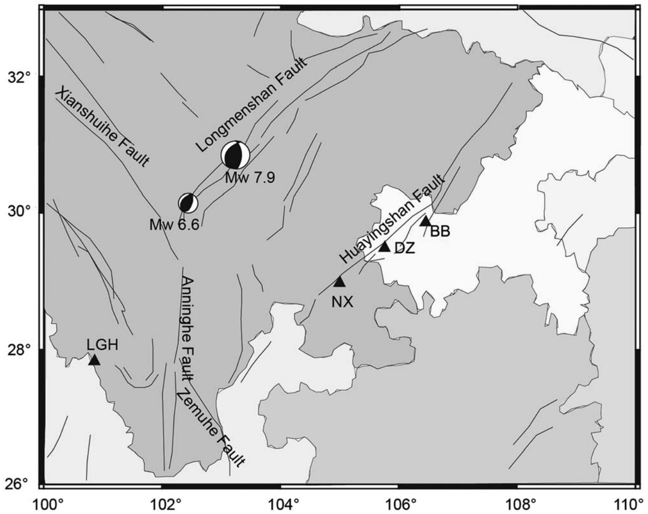

Figure 1. Geological setting and locations of groundwater monitoring wells (black triangles) and epicenters of the Wenchuan (M_w 7.9) and Lushan (M_w 6.6) earthquakes. Beach balls show the lower hemisphere projection of the focal mechanism. Black lines show mapped faults.

Wenchuan earthquake, with a rupture length of approximately 66.5 km along the strike of the Longmenshan fault zone [*Liu et al*., 2013; *Xu et al*., 2009]. The similarity of the focal mechanisms and the fault zone geology eliminates one of the variables when comparing the properties of well-aquifer system responses to earthquakes [*Shi et al*., 2014].

Groundwater level monitoring is an important part of the earthquake prediction program in China, and a nationwide groundwater monitoring well network has been constructed for this purpose [*Shi et al*., 2015b]. Twelve wells recorded the coseismic responses following both the Wenchuan and Lushan earthquakes, with sampling rates of 1 min or 1 h [*Shi et al*., 2014]. In this paper, we consider only the four groundwater monitoring wells that show a clear tidal signal (NX, DZ, BB, and LGH: Figure 1 and Table 1). The water levels were recorded by an LN-3A digital instrument developed by the Institute of Earthquake Science, China Earthquake Administration. The measurement range is from 0 to 10 m with a resolution of 1 mm. Water level data collected from December 2007 to September 2013 were analyzed. Coseismic and postseismic water level changes caused by the Wenchuan and Lushan earthquakes were clearly identified (Figure 2); the water level response showed gradual and step changes with sustained postseismic variation. Using an empirical scaling relation from *Wang* [2007], we found that the seismic energy density required to trigger the hydrological response for those wells ranged from 4.5×10^{-3} to 1.0 J/m^{-3} (Table 1), consistent with global observations [*Wang and Manga*, 2010]. The seismic energy density is calculated from the equation [*Wang*, 2007]:

$$\log(r) = 0.48M - 0.33\,\log e(r) - 1.4 \tag{1}$$

where r is the actual epicentral distance in kilometers, M is the earthquake magnitude, and e is the seismic energy density (in J m^{-3}). This relation was derived using data from southern California. No similar relationship for the studied area is currently available. We use the empirical relation as an approximation in the absence of a better relationship.

3. Analysis

3.1. Tidal Analysis

Tidal signals were decomposed by the widely used tidal analysis program Baytap-G [*Tamura et al*., 1991]. Steps and spikes caused by instrument malfunctions or maintenance work were removed manually before

Table 1. Coseismic Response to Wenchuan and Lushan Earthquake in the Wells[a]

Well Name	Aquifer Lithology	Depth (m)	Wenchuan Earthquake				Lushan Earthquake			
			EP (km)	Coseismic Response	WL (m)	e (J m^{-3})	EP (km)	Coseismic Response	WL (m)	e (J m^{-3})
NX	Quartz sandstone	101	267	Gradual drop	−1.1	0.79	237	Gradual drop	−0.752	1.5×10^{-2}
BB	Sandstone	105	328	Step drop	−0.95	1	347	Step rise	0.042	1.1×10^{-2}
DZ	Mudstone and sandstone	109	284	Gradual drop	−0.68	0.5	290	Gradual rise	0.12	7.8×10^{-3}
LGH	Limestone	200	435	Step rise	0.034	0.2	353	Step drop	−0.086	4.5×10^{-3}

[a] e in the table represents the seismic energy density, calculated from $\log(r) = 0.48\,M - 0.33\log e(r) - 1.4$ [*Wang*, 2007], where r is the actual epicenter distance in kilometers, M is the magnitude of the earthquake, and e is the seismic energy density in (J m^{-3}). EP is epicenter distance, and WL is water level.

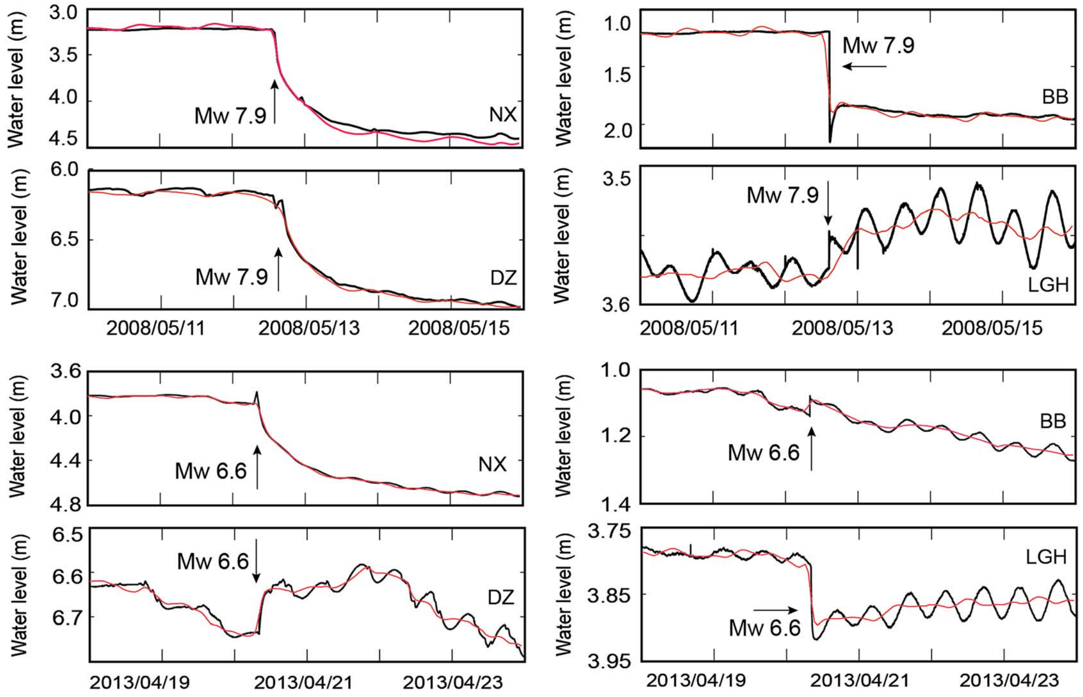

Figure 2. Water level fluctuations before and after the Wenchuan and Lushan earthquakes. The black curves show the measured groundwater level changes, while the red curves show the corrected water level with tidal signal removed.

the analysis. The 1 min water-level data were resampled as hourly data. For the analysis, we set a data span of 30 days with an overlap of 15 days. Then, we used the average value of the phase shifts 3 months before and after the Wenchuan and Lushan earthquakes to determine the phase changes in response to these events (see Table 2 and Figure 3). In Figure 3, the yellow error bars indicate the root-mean-square error (RMSE) of the tidal analysis; we can see the clear phase shift changes caused by the two earthquakes in these wells: the changing magnitudes of the coseismic phase shift are greater than 2 times than the RMSE. Although the phase shift change of the NX well following the Lushan earthquake is smaller than the RMSE, the phase shifts (−5.48° before and −4.72° after the Lushan earthquake) are larger than the RMSE (~0.97°); we consider that the changes in the phase shift are caused by the earthquake rather than by the analysis error.

The phase shifts of the tidal response of the water level increased after both earthquakes. The phase changes can be classified into three categories: (1) negative phase before the earthquake that becomes less negative after the earthquake, (2) negative phase before the earthquake that becomes positive after the earthquake, (3) positive phase before the earthquake that becomes more positive after the earthquake.

3.2. Estimation of the Aquifer Property Changes Following Earthquakes

Many studies have employed the tidal response of the water level as a proxy to study the permeability change of well-aquifer systems [*Elkhoury et al.*, 2006; *Lai et al.*, 2014; *Shi and Wang*, 2014; *Shi et al.*, 2015b; *Xue et al.*, 2013; *Yan et al.*, 2014]. The most commonly used method for this analysis is Hsieh's horizontal flow

Table 2. Phase Changes in Wells Caused by Wenchuan and Lushan Earthquake

	Wenchuan Earthquake			Lushan Earthquake		
Well Name	Preseismic Phase (deg)	Postseismic Phase	Phase Change	Preseismic Phase (deg)	Postseismic Phase	Phase Change
NX	−1.4	3.9	5.3	−5.48	−4.72	0.78
DZ	−13.7	−5.2	8.5	−21.5	−18.27	3.23
BB	11.7	22.9	11.2	12.64	17	4.36
LGH	−10.1	5.7	15.8	2.12	3.21	1.09

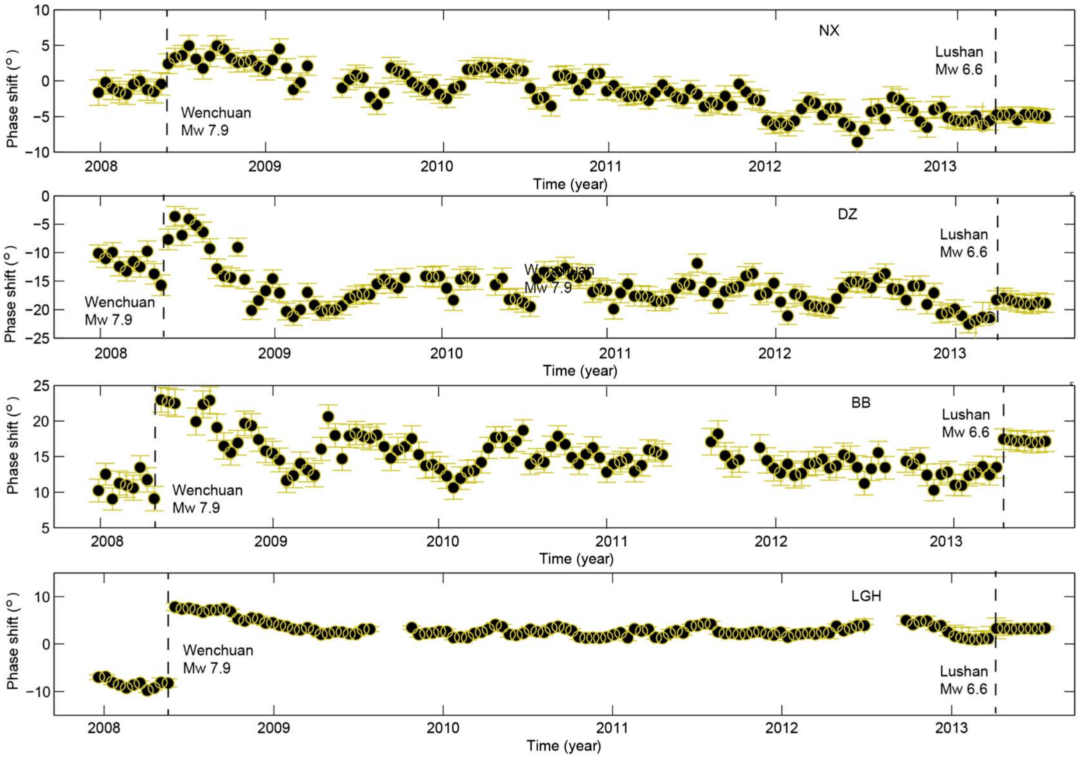

Figure 3. Phase shift variation during 2007–2014 of the four wells. The yellow error bars indicate the root-mean-square error (RMSE) of the tidal analysis.

model [*Hsieh et al*., 1987]. The assumption of Hsieh's model is that aquifers are single, horizontal, homogeneous, isotropic, and well confined. Under these circumstances, the phase shift between Earth tide and the water level should be negative, due to the time required for water to flow in and out of the well. The phase shift is also related to the aquifer properties [*Hsieh et al*., 1987]. We focused on the tidal response before and after the Wenchuan and Lushan earthquakes and extracted the M_2 tidal signals for analysis [*Doan et al*., 2006; *Kinoshita et al*., 2015].

When the aquifer is well confined, the permeability can be determined using Hsieh's horizontal flow model using the negative phase shift between the water level and the tidal strain (see Text S1 in the supporting information). However, the Hsieh model does not apply when the phase shift between the water level and the tidal strain is positive (a positive phase shift indicates that the water level response precedes the tidal strain [*Roeloffs*, 1996]). *Roeloffs* [1996] proposed that a positive phase shift results from the diffusion of pore pressure to the water table (the aquifer is not well confined); the degree of confinement controls the frequency response of the pore pressure to tidal loading [*Kinoshita et al*., 2015]. In addition, the relationship between phase shift and hydraulic diffusivity can be written as [*Doan et al*., 2006] (see more details in Text S2 in the supporting information):

$$p(z,\omega) = BKu\ \varepsilon\left(1 - e^{-(1+i)z/\sqrt{2D/\omega}}\right) \tag{2}$$

where $p(z, \omega)$ is the pore-pressure fluctuation at depth z; B is Skempton's coefficient; K_u is the bulk modulus of the saturated rock under undrained conditions; ε is the change in the volumetric strain; D is hydraulic diffusivity; and ω is the frequency of fluctuation.

Based on Hsieh's horizontal flow model and Roeloffs' vertical diffusion model, we can estimate the transmissivity and hydraulic diffusivity of aquifers (see Table S1 in the supporting information). Because transmissivity is related to the hydraulic diffusivity and storage coefficient ($T = D / S$), we can also obtain the transmissivity from the vertical model. To differentiate the transmissivity from the two models, we use T_h to indicate the transmissivity calculated using the horizontal model and T_v for the transmissivity calculated using the vertical model. The results are listed in Table 3 and show that Hsieh's horizontal flow model applies to the DZ well for

Table 3. Transmissivity Based on the Tidal Response[a]

	Wenchuan Earthquake				Lushan Earthquake			
	Pre-Earthquake		Postearthquake		Pre-Earthquake		Postearthquake	
Well Name	T_h (m^2/d)	T_v (m^2/d)	T_h (m^2/d)	T_v (m^2/d)	T_h (m^2/d)	T_v (m^2/d)	T_h (m^2/d)	T_v (m^2/d)
NX	17.40	—	—	1.09	4.89	—	5.77	—
DZ	1.75	—	3.56	—	0.598	—	0.734	—
BB	—	1.30	—	4.38	—	1.34	—	2.23
LGH	3.43	—	—	1.44	—	2.59	—	3.06

[a] The em-dash sign means it is not applicable, T_h is transmissivity calculated using the horizontal model, and T_v is transmissivity calculated using the vertical model.

both the Wenchuan and Lushan events and that the vertical flow model applies in the BB well for both the Wenchuan and Lushan events. For the other two wells, the two events require different models.

4. Discussion

As mentioned in the tidal analysis section, a negative phase shift indicates dominant horizontal groundwater flow in a confined well-aquifer system, while a positive phase shift indicates vertical diffusion in an unconfined (or semiconfined) well-aquifer system. For a specific well-aquifer system, a phase shift change from negative to positive after an earthquake indicates that the well-aquifer system may have changed from confined to semiconfined and that the dominant effect on the tidal signal has switched from horizontal to vertical flow. Thus, we can infer that the Wenchuan and Lushan earthquakes had little influence on aquifer confinement changes at the DZ and BB wells. The DZ well remained well confined, and the BB well remained semiconfined. At the NX well, the well-aquifer system was well confined before the Wenchuan earthquake but became semiconfined after the Wenchuan earthquake. This switch may have been caused by a reopening of vertical fractures [*Liao et al.*, 2015], which will reseal over time. The aquifer at the NX well appeared confined before the Lushan earthquake (almost 5 years after the Wenchuan earthquake). The horizontal permeability was enhanced by the Lushan earthquake, but vertical fractures remained sealed. Thus, there was no change in the aquifer type. At the LGH well, a confined aquifer became semiconfined after the Wenchuan earthquake and did not recover before the Lushan earthquake; there was no change in aquifer type following the Lushan earthquake. The enhancement of the hydraulic diffusivity (or vertical permeability) following the Lushan earthquake may have been caused by the unclogging of preexisting fractures due to the shaking of seismic waves.

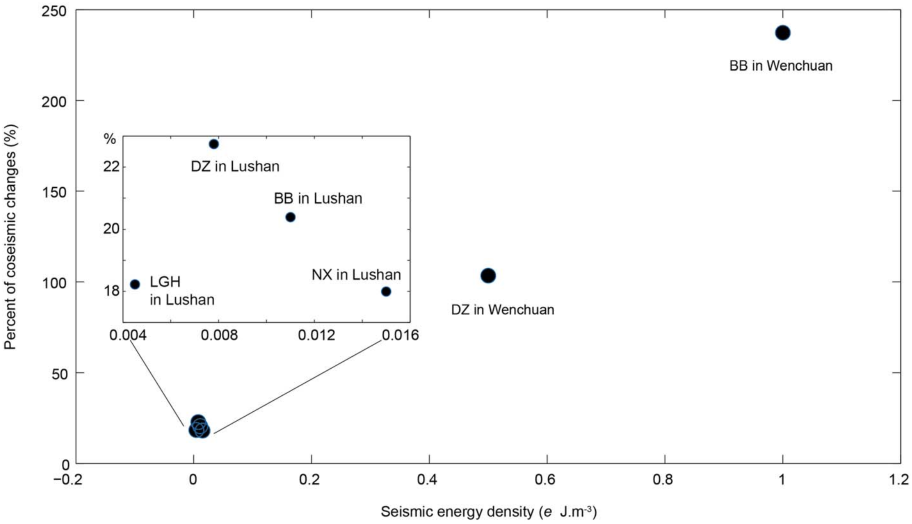

Figure 4. Relationship between seismic energy density and percent of coseismic transmissivity changes. Because of the confinement changes of NX and LGH well during Wenchuan earthquake, we do not include them in the figure.

Many previous studies have documented that earthquakes can enhance vertical permeability [*Liao et al.*, 2015; *Manga and Rowland*, 2009; *Rojstaczer et al.*, 1995; *Wang and Manga*, 2015; *Wang et al.*, 2004a] and that the permeability will recover through the healing or reclogging of fractures [*Faoro et al.*, 2012; *Manga et al.*, 2012; *Shi and Wang*, 2015; *Xue et al.*, 2013]. There are also reported cases in which large earthquakes disrupted the original aquifer system and created new systems [*Wang et al.*, 2016; *Ward*, 2015]. The seismic energy density of the Wenchuan earthquake at these wells ranged from 0.2 to 1.0 J/m^3, and it ranged from 0.0045 to 0.015 J/m^3 for the Lushan earthquake, capable of triggering different kinds of hydrological responses [*Wang and Manga*, 2010].

Therefore, it is reasonable to deduce that the vertical fracture permeability increased following the Wenchuan earthquake at the NX and LGH wells. No aquifer-type change occurred following the Lushan earthquake, and the aquifer parameter (transmissivity and hydraulic diffusivity) changes may reflect unclogging of preexisting flow pathways. *Elkhoury et al*. [2006] noted a roughly linear relation between peak ground velocity and coseismic permeability change. In this study, we try to relate the transmissivity with the seismic energy density. We use the percentage of coseismic changes in transmissivity as a function of the seismic energy density in Figure 4, and no relationship is observed.

Comparing the aquifer parameters in Table 3, we see suggestive evidence of a healing process during the 5 year period between the 2008 Wenchuan earthquake and the 2013 Lushan earthquake (Figure 3). For example, the vertical transmissivity in the BB well changed from 1.30 m^2/d to 4.38 m^2/d after the 2008 Wenchuan earthquake but had recovered to 1.34 m^2/d before the 2013 Lushan earthquake. At the DZ well, the horizontal transmissivity changed from 1.75 m^2/d to 3.56 m^2/d after the Wenchuan earthquake and decreased further (0.598 m^2/d) before the Lushan earthquake. This decrease may have been caused by the blocking of preexisting fractures that were open before the Wenchuan earthquake [*Lai et al.*, 2014; *Shi and Wang*, 2015]. Aquifer-type changes induced by earthquakes can either recover (NX) or not recover (LGH) within a 5 year period, indicating that the local hydrogeological conditions (e.g., permeability, aquifer lithology, and fracture aperture) are important to the recovery process.

This is the first published documentation of a coseismic aquifer-type change from confined to semiconfined. Since the confinement change is related to the change of hydraulic connection, it may affect the postseismic groundwater flow and solute transport. Thus, such change should be considered as a significant factor in the management of groundwater supply and underground waste isolation and also in earthquake precursor monitoring in the seismic active areas.

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