Permeability changes associated with large earthquakes: An example from Loma Prieta, California

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ABSTRACT

The Loma Prieta (California) earthquake (October 17, 1989; M 7.1) caused significant changes in the hydrology of the San Lorenzo and Pescadero drainage basins, northwest of the epicenter. Streamflow increased at most gauging stations within 15 min after the earthquake. Ionic concentrations and the calcite saturation index of the stream water also increased. Streamflow and solute concentrations decayed significantly over a period of several months following the earthquake. Ground-water levels in the highland parts of the basins were locally lowered by as much as 21 m within weeks to months after the earthquake. The spatial and temporal character of the hydrologic response suggests that the earthquake increased rock permeability and temporarily enhanced ground-water flow rates in the region.

INTRODUCTION

Hydrologic changes associated with moderate- and major-scale earthquakes have long been noted (Carnegie Institution of Washington, 1908; La Rocque, 1941). Some changes are short term and are associated with the dilatational waves generated by earthquakes (Eaton and Takasaki, 1959; Cooper et al., 1965; Liu et al., 1989); other changes are long term and have a less obvious explanation. Postseismic changes in spring flow and streamflow were noted in response to such seismic events as the Arvin-Tehachapi earthquake (M 7.1) of 1952 (Briggs and Troxell, 1955), the Borah Peak earthquake (M 7.0) of 1983 (Whitehead et al., 1985), and the Matsushiro earthquake swarm of 1968 (Nur, 1974); the changes, whose net effects were increases in fluid discharge following the earthquake, persisted for a period of months to years. Postseismic changes in ground-water level have also been observed (Waller, 1966; Bell and Katzer, 1987); many of these changes are too large to be explained by the static compression or extension induced by the earthquake (Bower and Heaton, 1978).

Various mechanisms have been postulated to explain these long-term changes in ground-water level and rate of surface discharge. The changes have been attributed to the expulsion of overpressured fluids in the seismogenic zone (Sibson, 1981) and the collapse of a broad network of pre-earthquake-induced dilatant fractures (Nur, 1974). Streamflow and spring-flow changes have been attributed to elastic compression of confined aquifers (Wood et al., 1985). Changes in water level in wells may be due to seismically induced ground failure around the borehole (Bredehoeft et al., 1965). Streamflow and ground-water changes have also been related to permeability changes in near-surface materials (Waller, 1966; Bell and Katzer, 1987).

The Loma Prieta (California) earthquake (October 17, 1989; M 7.1) provides a unique opportunity to examine hydrologic changes associated with earthquakes. Long-term changes in both surface discharge and ground-water levels were observed in the region following the earthquake. Minor changes were also noted in response to the Lake Elsman earthquake (August 8, 1989; M 5.2), an event that has been described as a foreshock to the Loma Prieta earthquake (Lisowski et al., 1990). In this paper we examine the surface-water and ground-water response of the Pescadero and San Lorenzo drainage basins to the Loma Prieta earthquake. Our analysis indicates that the observed surface and subsurface hydrologic changes are due to extensive permeability changes within the basins.

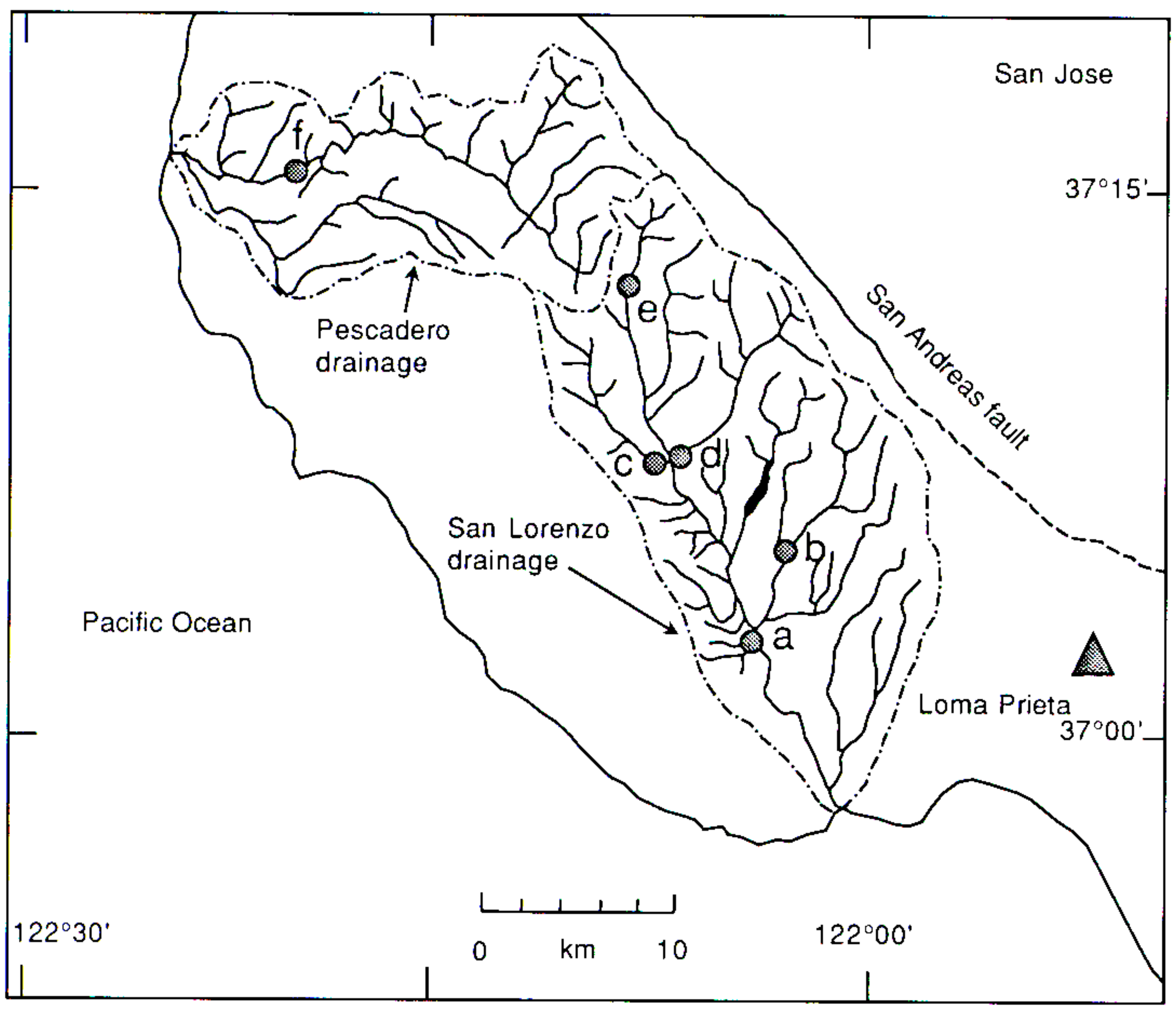

Figure 1. Location of study area in relation to San Andreas fault, Loma Prieta epicenter (triangle), and northern part of Loma Prieta rupture zone (heavy dashed line). Stream gauging stations (circles): a—Big Trees, b—Zayante Creek, c—Boulder Creek, d—Bear Creek, e—San Lorenzo Park, f—Pescadero Creek.

STUDY AREA

The San Lorenzo and Pescadero drainage basins define a region greater than 600 km^2 in area; they are west of the ruptured segment of the San Andreas fault associated with the Loma Prieta earthquake (Fig. 1). The basins are mountainous; their slopes commonly exceed a 30% grade. Elevation increases to over 900 m along the boundary of the basins closest to the San Andreas fault. Stream gradients range from 0.003 to 0.2 m/m (Nolan et al., 1988). Mean annual rainfall ranges from about 500 mm near the coast to about 1500 mm in the higher elevations (Rantz, 1971). Rainfall is generally absent from May through September, although fog is common during these months. In the high elevations of the basins, the San Lorenzo sandstone, Vaqueros sandstone, and Lambert shale are the most common bedrock formations. These formations are heavily fractured at the surface, and the degree to which they are permeable and are used as unconfined aquifers is highly variable and dependent on the degree to which they are fractured at depth (Johnson, 1980; Akers and Jackson, 1977). The region contains many extensive zones of structural weakness, both in the near surface and at depth. In the highlands, many ancient and active landslides can be found in the Tertiary formations (Hector, 1976). In addition to the San Andreas fault, major active faults in the basins include the San Gregorio and Butano and perhaps parts of the Zayante (Clark, 1981). Most folds and faults in the area follow the northwest-southeast trend of the San Andreas fault.

STREAMFLOW RESPONSE TO LOMA PRIETA

Streamflow has been monitored in the region by the U.S. Geological Survey since the 1930s, and the stream gauging stations shown in Figure 1 have all been operating for at least 13 yr. Regulation and diversion of these rivers and their tributaries are minor upstream of all of the gauging stations (Markham et al., 1988).

In all drainage areas monitored, there was an increase in streamflow associated with the earthquake, indicating the greatly enhanced contribution of ground water to the streams (Fig. 2). Except for the Bear Creek station, streamflow increases were observed at the first sampling following the earthquake (within about 15 min of the earthquake) at all stations that were not temporarily disabled by the ground motion. At Bear Creek, streamflow increases were preceded by a postseismic decrease, which persisted for 22 h. The San Lorenzo Park station was not recording for a period of 70 h following the earthquake. Streamflow increases were monotonic for several days following the earthquake, but were slightly masked by rainfall that began on October 21. Peak increases due to the earthquake were generally an order of magnitude greater than prequake streamflow.

Although there were large increases in streamflow due to the earthquake, the long-term postseismic response indicates that these increases were generally short-lived. We estimated the longer term effects of the earthquake on streamflow by comparing the base flow over the period following the earthquake with the base flow of the previous year. Base flow for each year was estimated by straight-line hydrograph separation. The excess base flow produced by the earthquake was determined by calculating the difference between the postearthquake base flow and the base flow 1 yr prior at the same station. This base flow was adjusted by subtracting or adding any differences between the base flow on October 17, 1988, and that on October 17, 1989 (the day of the earthquake).

In determining excess base flow, we made the assumption that, independent of the earthquake, the seasonal character of the base flow would not vary greatly from water year 1989 (July 1, 1989–July 1, 1990) to water year 1990 because the seasonal character and annual amount of precipitation for both years were very similar (72 cm for 1989 and 76 cm for 1990). The inferred excess flow produced by the earthquake is shown in Figure 3. Excess base flow decayed rapidly at all but the Boulder Creek station. After 45 d, excess base flow was roughly half that of peak flow. After 150 d, excess flow is difficult to identify in the records.

Stream chemistry at two of the stream gauging stations in the San

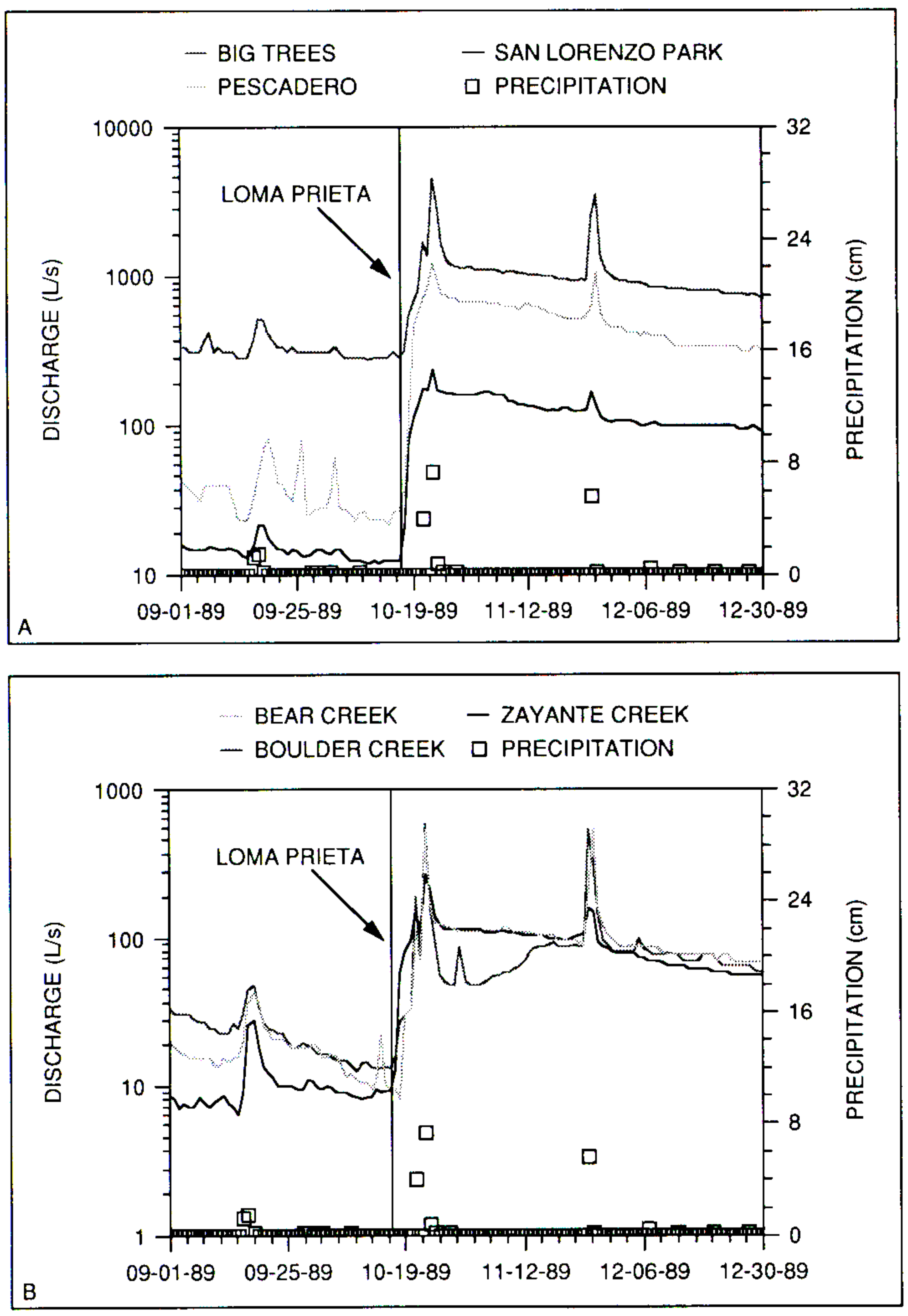

Figure 2. Streamflow response to Loma Prieta earthquake (October 17, 1989) at (A) Big Trees, Pescadero, and San Lorenzo Park and at (B) Bear, Boulder, and Zayante creeks. Streamflow is in terms of a daily mean. Precipitation is in terms of a daily total. Dates (*x* axis) are in order of month-day-year.

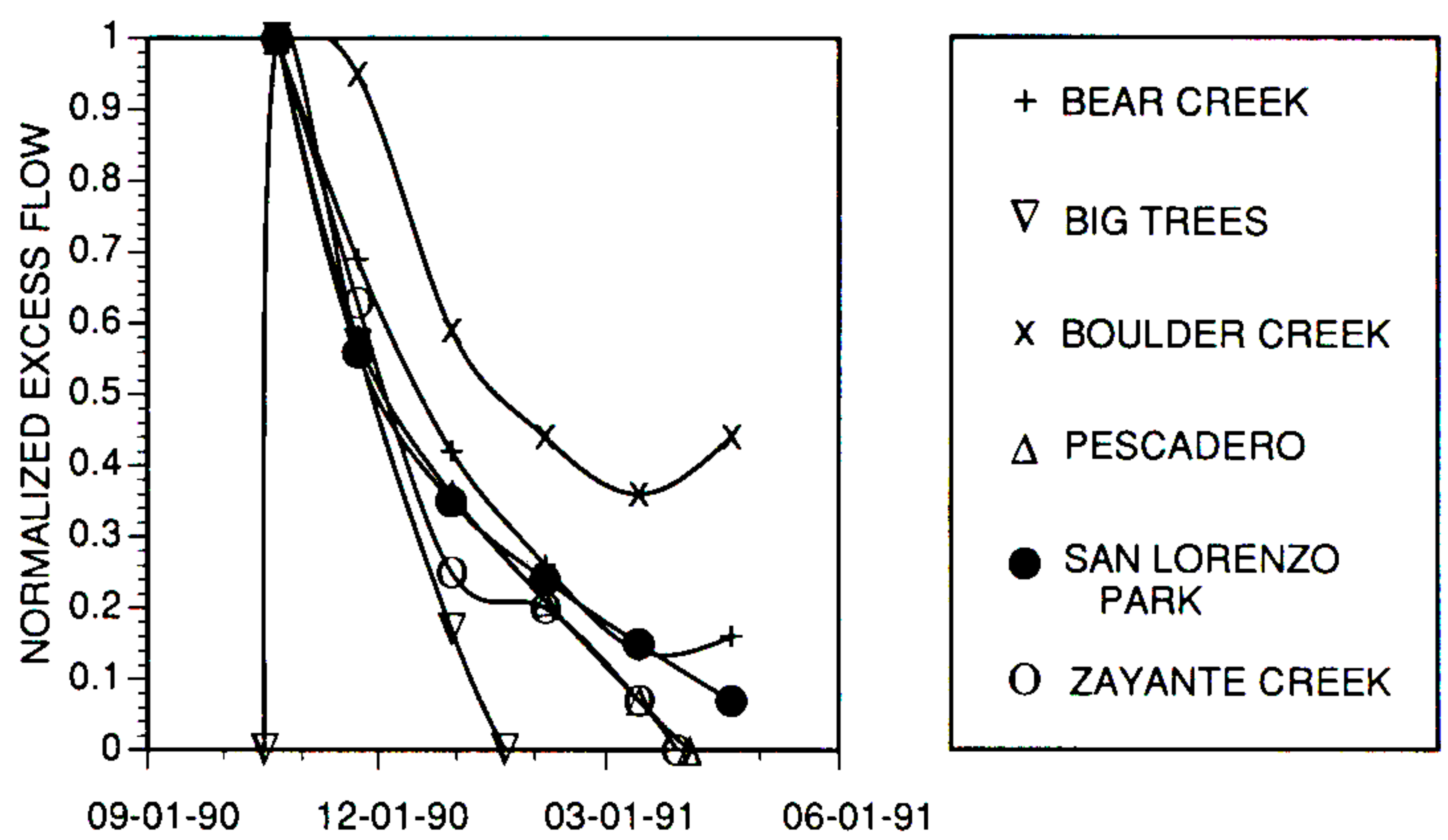

Figure 3. Base flow as function of time at gauging stations. Base flow is normalized by peak excess base flow at each station: Bear—110 L/s; Big Trees—920 L/s; Boulder—40 L/s; Pescadero—690 L/s; San Lorenzo Park—170 L/s; Zayante—110 L/s.

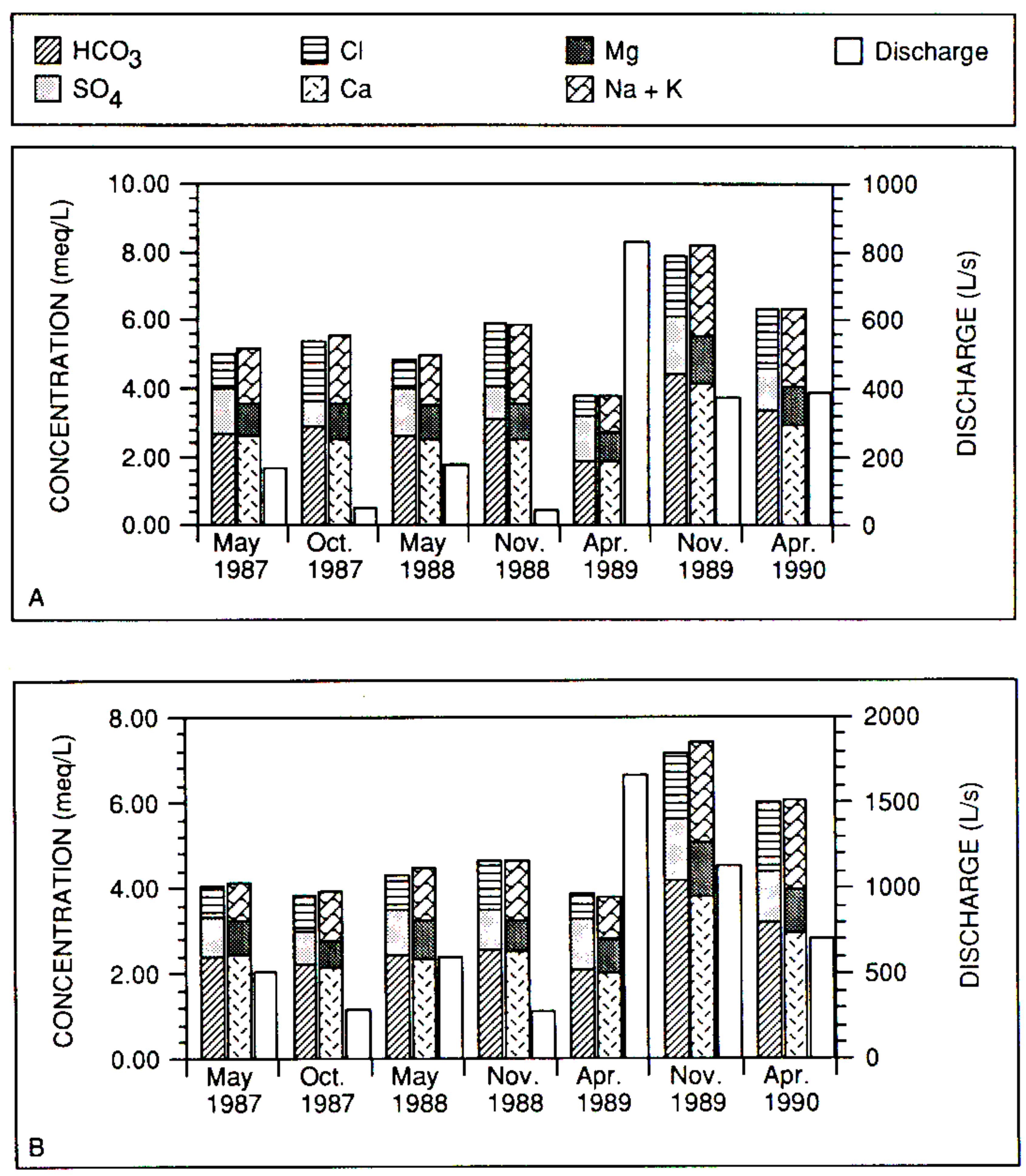

Figure 4. Major-ion stream chemistry as function of time and streamflow at (A) San Lorenzo Park and (B) Big Trees.

Lorenzo drainage basin (Big Trees and San Lorenzo Park) has been monitored on a biannual basis (Fig. 4). In response to the earthquake, stream chemistry showed a marked increase in overall ionic strength, but the overall proportions of the major ions were nearly the same as in prequake conditions. The increase in bicarbonate and calcium caused the calcite saturation index to increase from 0.4 to 0.8. Water temperature in early November 1989 was 7 °C at both stations, nearly 4 °C cooler than any previous measurement either in spring or fall. By April 1990, the stream chemistry had begun to approach prequake conditions at both locations. The changes in temperature and chemistry suggest that the additional water flow caused by the earthquake was derived from ground water from the surrounding highlands.

The response of the region's streams was similar to, but much larger in extent and magnitude than, their response to the Lake Elsman earthquake of August 8, 1989. The earlier earthquake produced a twofold increase in flow at the San Lorenzo Park and Pescadero stations. At the other stations, any changes were too small to be detectable.

GROUND-WATER RESPONSE

There were numerous anecdotal reports of earthquake-related changes in water level and water quality of wells in the study area as well as reports of changes in spring flow. Exact measurements of prequake water levels, however, are generally not available for the region. One well, which taps an unconfined aquifer located in the eastern headwaters of Pescadero Creek, has been monitored weekly since 1976 (Fig. 5; location shown in Fig. 6A). Drought has had an influence on the hydrograph, but the earthquake caused the water level to drop 4 m within several weeks after the earthquake.

Although changes in water level in the recharge areas of these basins are generally difficult to quantify, we infer that similar drops in water level occurred in a significant part of the basin highlands. Numerous wells either went dry or underwent a significant reduction in their capacity to pump water within several weeks after the earthquake. We focus on measured and inferred changes in ground-water levels in two areas of the Santa Cruz Mountains. One area (Fig. 6A) includes the water well mentioned above and is along the crest of the Santa Cruz Mountains. The other area (Fig. 6B) is near the headwaters of the San Lorenzo River. The wells shown in Figure 6 are used by single homes and range in depth from 40 to 140 m.

Of the wells shown in Figure 6A, about half showed a reduced capacity to deliver water for domestic use or were completely dry by January 1990. In general, the wells that were most affected were in the southern part of the area (where elevation is highest). In most of the wells that were adversely affected (wells that either went dry or no longer provided enough water for home use), changes were noted within several weeks after the earthquake. It is difficult to relate quantitatively the adverse impact of the wells to a water-table decline. Wells in the region that were not adversely affected generally have water levels greater than 7 m above the well bottom. If these conditions existed prior to the earthquake in the affected wells, then the water-table declines produced by the earthquake would be at least on the order of several metres.

In the San Lorenzo headwaters area (Fig. 6B), wells that are adversely affected are largely confined to two ridge tops. Wells along the northeast edge of the area as well as wells located near the valley floor were not adversely affected. Although no extensive prequake water-level records exist for this area, there is limited anecdotal information on prequake levels in some wells. In one well that became dry, the water level was 21 m above the bottom of the hole on October 11, 1989. In another well that became dry, the water level was 40 m above the bottom during February 1989. Subsequent measurements in the region of unaffected and affected (but not dry) wells over the time period January–July 1990 indicated that water levels declined gradually in many wells (on the order of 1.5 m/month or less). The rates of decline during 1990 are too gradual to be identified as having been due directly to the Loma Prieta earthquake. They may also have been due to the effects of drought in the region. The water-level data suggest that the impact of the earthquake on ground-water levels in this area had either greatly diminished or had virtually disappeared after several months following the earthquake.

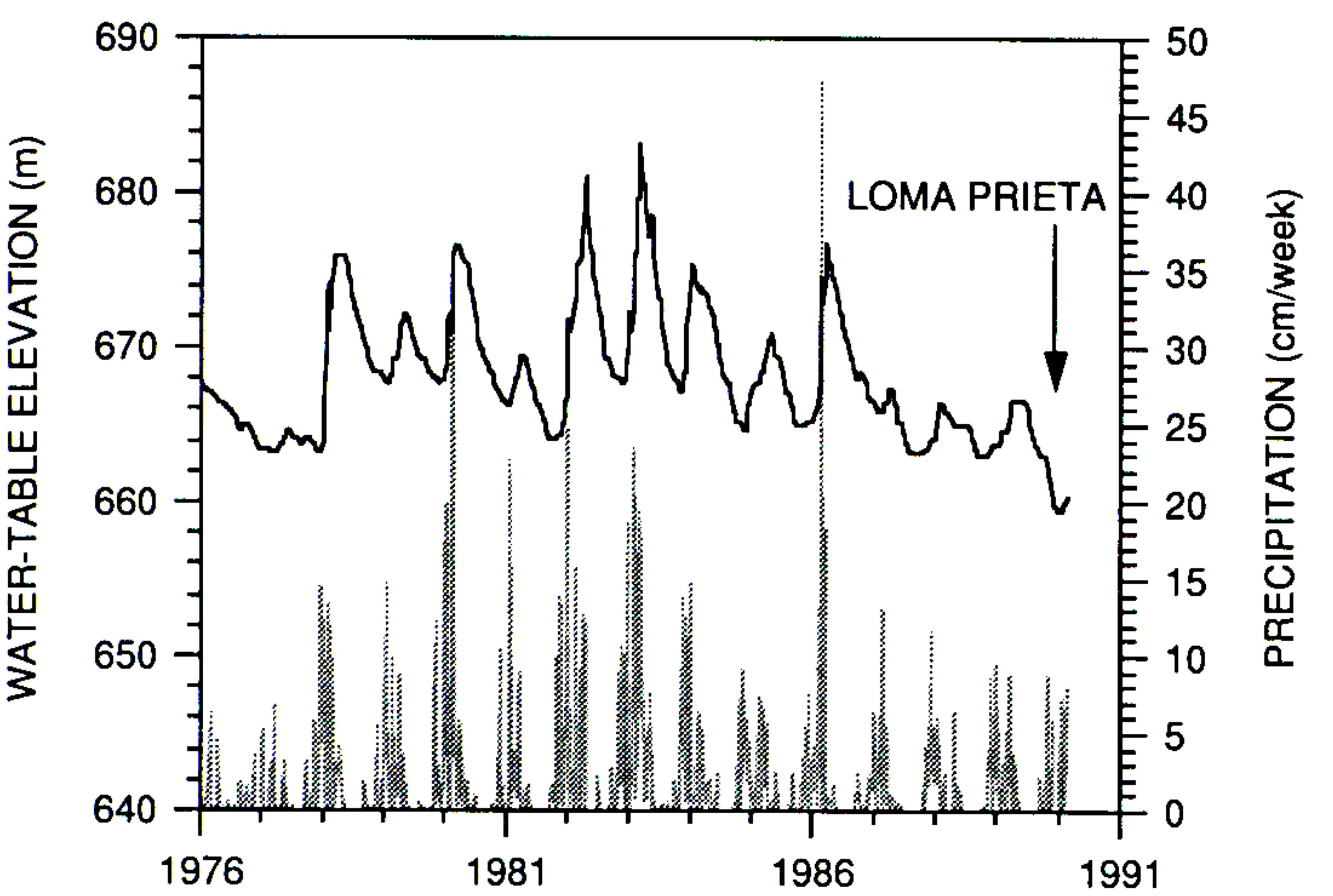

Figure 5. Water-table elevation as function of precipitation from 1976 to 1990 in well on eastern edge of Pescadero basin. Well is northernmost one in Figure 6A.

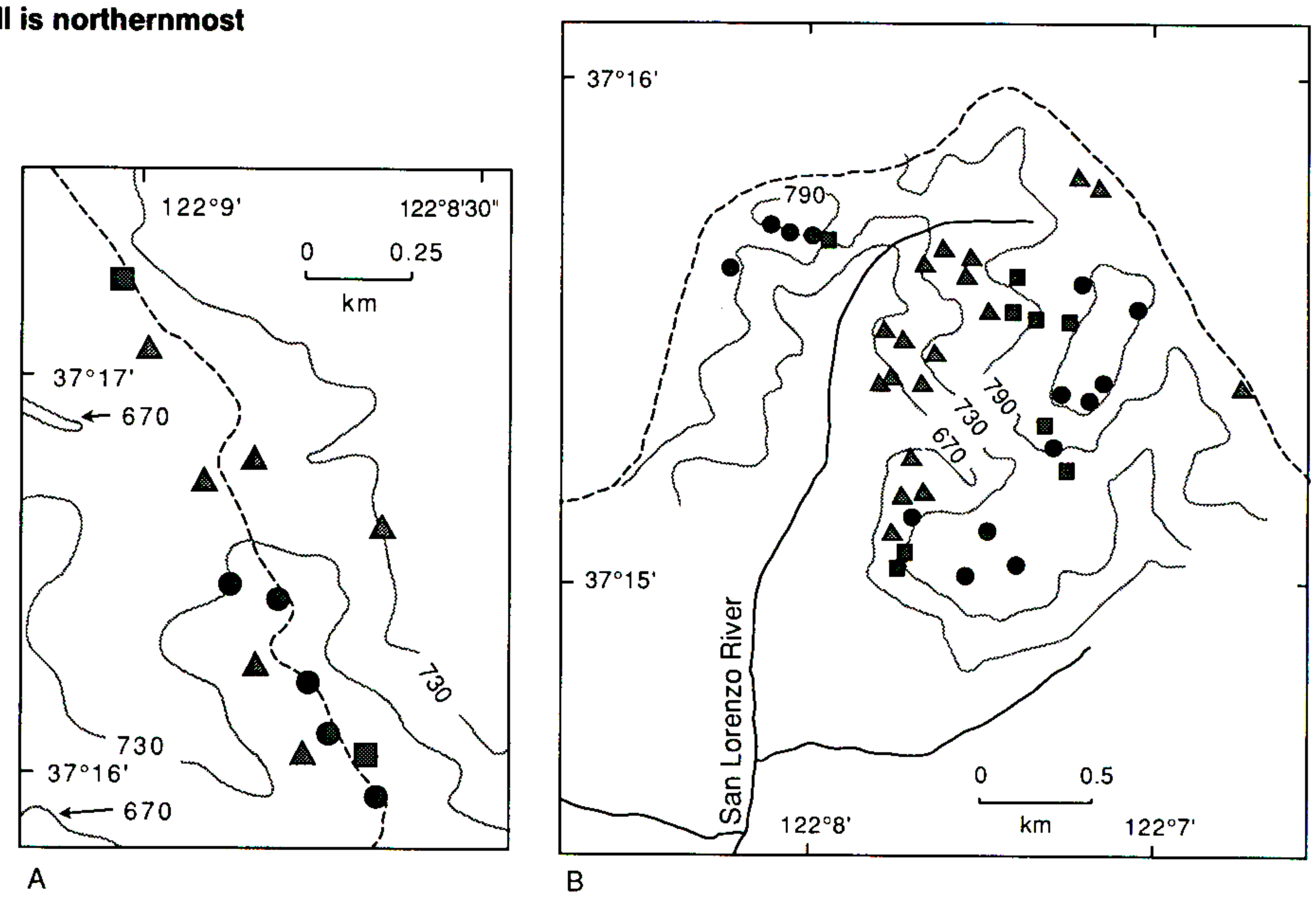

Figure 6. Impact of Loma Prieta earthquake on wells in areas of (A) Pescadero headwaters and (B) San Lorenzo headwaters. Circle—well went dry; square—well's ability to yield water for supply decreased; triangle—well was unaffected. Elevation contours (light lines) are in metres. Dashed line is boundary of drainage basin.

PROBABLE CAUSE OF RESPONSE

The observed hydrologic changes—temporary excess streamflow, dropping water table, and changes in stream chemistry—were probably due to a common cause. The mechanism that most likely explains the postseismic hydrologic observations is a permeability increase caused by seismically induced fractures and microfractures. If the fracture networks that control ground-water flow in the region were enhanced by the earthquake, ground-water flow rates would initially increase in proportion to the permeability increase. The water table would drop because the ground-water system would be effectively drained by the increased discharge. Areas of high elevation would be most susceptible to water-table drops because these would be areas that would tend to have the highest water-table elevations prior to the earthquake.

The increased fractures and microfractures in the ground-water system would also be expected to alter temporarily the chemistry of the ground water. They would tend to expose previously near-stagnant water in small pores to enhanced ground-water flow paths. This near-stagnant pore water, because it has had much time to interact with rock-mineral surfaces, would have a relatively high concentration of solutes. As a result of the generation of new flow paths, a greater proportion of water with a high solute concentration would be expected to enter the major ground-water flow paths, and the ionic strength of the exiting ground water would increase.

To account for the initial surge in discharge, the fracturing would have to effectively increase the permeability in parts of the aquifers and aquitards in the highlands by about one order of magnitude. Streamflow would decay rapidly because the hydraulic gradient that drives fluid flow would decay as the water table dropped. The declines in water-table elevation would be expected to decay at a rate similar to the decay of streamflow.

The relatively shallow depth of the water table in the highland parts of the region suggests that permeability increases and concomitant water-table drops are temporary. If they were permanent, the numerous historic and prehistoric earthquakes in the region would likely have lowered the water table to great depths. Between earthquakes, the fracture networks probably heal, and the water table at least partly recovers to its pre-earthquake level. We propose that permeability in this region is a time-dependent parameter, increasing during times of seismicity and decreasing during interseismic periods.

CONCLUSIONS

This study has focused on the ground-water and surface-water response of two basins to the Loma Prieta earthquake. The signature of the hydrologic response is consistent with earthquake enhancement of ground-water flow paths. This enhancement may also be responsible for hydrologic changes seen in response to other earthquakes. This mechanism may explain why the general response of streams to earthquakes is one of increased flow. Because streams are usually the exit area for ground-water flow, significant increases in ground-water flow rates would be readily detected in the base-flow signature of the stream.

The hydrologic response suggests that the shallow materials in the highland areas of these basins are in a state of incipient failure. Dynamic or static shear strains produced by both the Loma Prieta and Lake Elsman earthquakes are large enough to generate new cracks and microfractures in the upper 200–300 m of the crust. The fractures generated must be able to form a new continuous flow path or enhance an old continuous flow path. The weak nature of the near surface is evidenced by the numerous active and ancient landslides in the area. It can also be inferred from the influence that fracture permeability had on the preearthquake state of ground-water flow in the region. This area has been subjected to repeated earthquakes, and it is likely that these seismic events, both historic and prehistoric, have had a large impact on the geologic evolution of permeability and ground-water flow patterns and rates in the region.

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