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Streamflow response to the Nisqually earthquake

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Abstract

An extensive network of stream gages documents regional streamflow response to the M6.8 Nisqually earthquake wherein almost half of the gages analyzed within 115 km of the epicenter exhibited changes in baseflow within 13 h after the earthquake. Rapid streamflow response indicates that the impetus for the increased discharge originated within 100 m of the water table. Distance to the epicenter explained only 13% of the variance in streamflow response and the maximum modeled ground acceleration within 5 km of each gage location was not correlated with increased streamflow. Of those rivers that responded, post-seismic increases in discharge were correlated with pre-earthquake discharge; larger rivers exhibited greater absolute increases in streamflow. Analysis of baseflow recession in the periods 1 month before and 1 month after the earthquake indicates no systematic detectable changes in aquifer properties. Locations with seismically induced increases in streamflow were closer to the epicenter than an empirical limit to the area susceptible to liquefaction based on observations reported for previous earthquakes. In addition, the spatial pattern of streamflow response corresponds to the pattern of near-surface volumetric strain, with decreased streamflow in areas that dilated and substantial increases in streamflow in areas of greatest compression and subsidence. Together these observations suggest that settling and compaction of surficial deposits of the Seattle Basin and liquefaction of partially saturated valley-bottom deposits were responsible for post-seismic increases in streamflow. Compilation of distance–magnitude data for streamflow responses to a wide range of earthquakes show that streamflow changes generally occur in areas susceptible to liquefaction.

Keywords: streamflow; earthquake; hydrologic; liquefaction

1. Introduction

Numerous accounts of hydrological response to earthquakes describe changes in both surface water discharge and subsurface groundwater levels in wells. Documented hydrological responses to earthquakes include changes in the water level in wells, spring discharge, and streamflow [1,2]. Various workers attribute such changes to expulsion of fluids from the seismogenic zone [3], pore-pressure diffusion following co-seismic strain in the upper crust [1,4,5], compression of confined aquifers [6], enhanced permeability of surficial materials due to either shaking of near-surface

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deposits [7–9] or opening of bedrock fractures [10–13], and liquefaction of surficial deposits [14]. Here we report new observations from an extensive network of gaging stations in the Puget Sound region, Washington, to document the regional pattern of streamflow response to the February 28, 2001, Nisqually earthquake (local time of 10:54 a.m. Pacific Standard Time). Our observations demonstrate an asymmetric pattern of streamflow changes that implicate compaction of near-surface aquifers and liquefaction of surficial deposits as the causes of observed streamflow increases. We also compile observations on the distance from the epicenter for streamflow response to previous earthquakes to further evaluate general mechanisms for such response.

2. Nisqually earthquake

The M6.8 Nisqually earthquake was a deep intraslab event within the subducting Juan de Fuca plate with a hypocenter 52 km below the ground surface, 18 km northeast of Olympia, WA [15]. Shaking lasted about 45 s, with felt intensity of up to Modified Mercali Intensity VII. The event involved normal-style displacement on a N–NW trending fault, with relative subsidence east of the epicenter. The Nisqually earthquake provides an unusual opportunity to investigate seismically induced changes in streamflow because of an extensive regional network of active stream gages and a fortuitous lack of rainfall on the day of the earthquake.

3. Methods

Analysis of discharge records from 222 U.S. Geological Survey, state, county, and city gaging stations shows both that earthquake-triggered streamflow changes were widespread in western Washington, and that there was a broad range in the magnitude of streamflow effects among gaging stations that recorded a response to the earthquake. We examined each gage record for clear changes in streamflow trends after the earthquake and evaluated the percentage change in baseflow discharge between the time of the earthquake and midnight that night, 13 h later, so as to normalize for the wide range of stream sizes and to avoid the influence of rainfall the following day that would mask evidence for seismically triggered changes in streamflow. We screened from the record those sites where the influence of dams precluded evaluation of streamflow response, as well as a few sites influenced by seismically triggered landslides and stations noted to be influenced by river ice at the time of the earthquake. In addition, several stations were omitted because they displayed cryptic, short-lived changes many hours after the earthquake. For a subset of the gages that demonstrated response to the earthquake we also analyzed streamflow records during periods of sustained baseflow recession in the month before and after the Nisqually earthquake.

4. Results

On the morning of the earthquake, discharge in most streams in western Washington was gradually decreasing, as is typical for baseflows between winter storms. Although minor discharge increases occurred in some channels on February 27, February 28 was a clear sunny day. At some of the gages that exhibited a response, streamflow increased within minutes after the 10:54 a.m. (local time) earthquake (Fig. 1A). At other gages the response was delayed, with a gradual rise that started in the minutes after the earthquake continuing to build through the day (Fig. 1B). Some gages peaked and began to decline before midnight, whereas others sustained response to the following day when runoff from a typical winter storm obscured recognition of seismically induced changes in baseflows.

Stream gages exhibiting no apparent response to the earthquake were distributed throughout the state and included locations near the epicenter. From the time of the earthquake to midnight that night, changes in streamflow varied from 1% to >100% at the stations in western Washington that exhibited identifiable response. Given the resolution of the hydrologic records and the magnitude of the variability in pre-earthquake

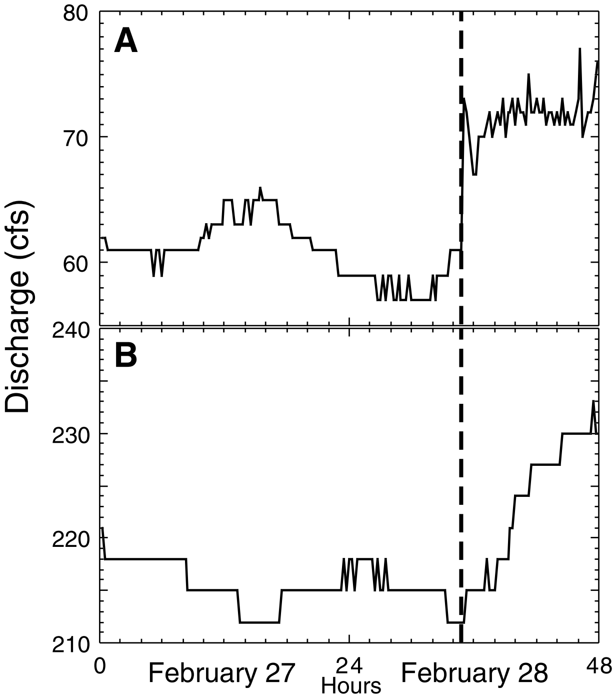

Fig. 1. Examples of hydrographs from gaging stations for February 27 and 28, 2001, showing stations that span the range of response to the Nisqually earthquake on February 28 (10:54 a.m. local time): (A) Issaquah Creek, USGS gage 12121600 (20% increase in discharge); (B) Nisqually River near National, USGS gage 12082500 (9% increase in discharge). Vertical bars indicate time of the earthquake.

discharges, we consider the significance of streamflow changes of 1–5% as uncertain using this approach. Within 115 km of the epicenter, 67 out of 161 stream gages analyzed responded to the earthquake, including three gages west of the epicenter that recorded decreased streamflow; none of the 61 gages farther than 115 km (and up to 414 km) from the epicenter exhibited any discernable response (Fig. 2).

Strong spatial coherence is apparent in the distribution of gages that recorded changes in discharge associated with the Nisqually earthquake

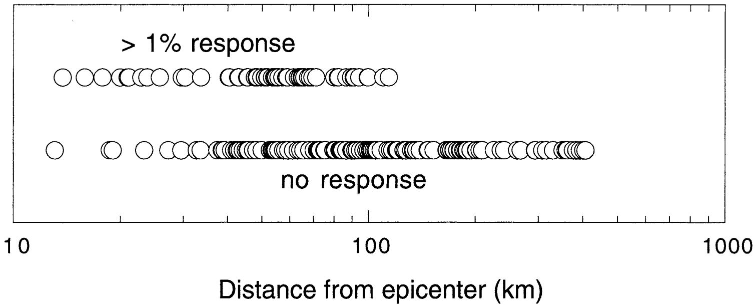

Fig. 2. Distance from the epicenter for stream gages that exhibited discernable response (upper) or no apparent response (lower) to the earthquake.

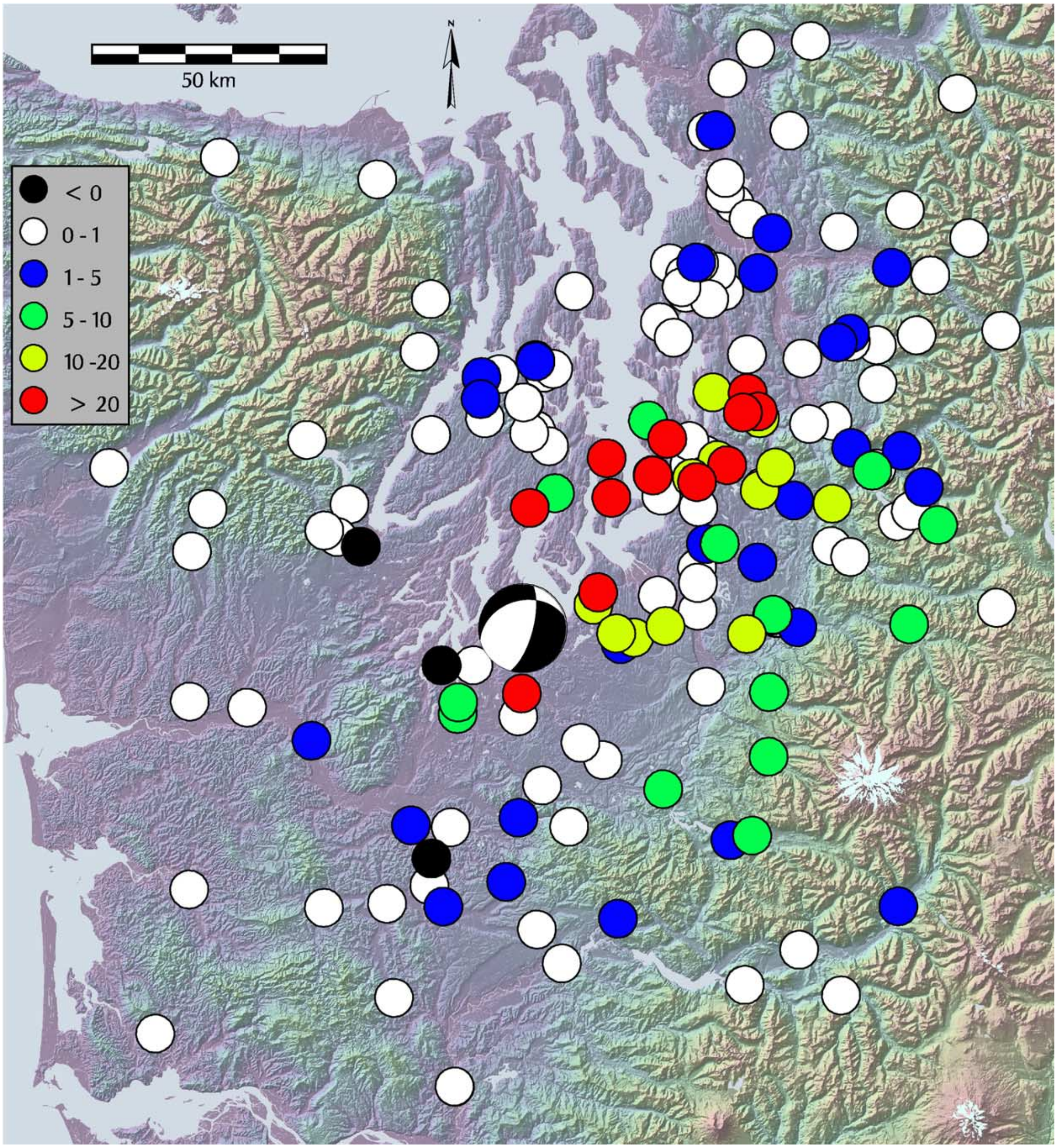

Fig. 3. Map showing the percentage change in flow from the time of the Nisqually earthquake to midnight that night for 161 gaging stations in the Puget Sound region. Data are derived from discharge records from U.S. Geological Survey gaging stations and gages maintained by King, Snohomish, Pierce, Thurston, and Kitsap Counties, the cities of Seattle and Olympia, and the Washington State Department of Ecology. White circles indicate gages with no discernable response (i.e. $< 1\%$). Black circles represent stations where streamflow decreased. Colored circles indicate gages for which $> 1\%$ increase was identifiable; color coding corresponds to the percentage change in baseflow. For a few stations for which only stage data were available, the change represents changes in stage rather than discharge. Beachball at the epicenter location represents focal solution for the earthquake. None of the 51 analyzed gages located beyond the area shown and up to 400 km from the epicenter exhibited any discernable response to the earthquake.

(Fig. 3). Discharges east of the epicenter increased, with the strongest hydrologic response concentrated in the area northeast of the epicenter. West of the epicenter, increases in discharge $>5\%$ were restricted to proximal locations, and three gages recorded reduced discharge. Even though the stream gage network is not uniformly dispersed throughout the region, there is sufficient coverage to conclude that streamflow response was asymmetrically distributed with respect to the earthquake's epicenter. Moreover, least-squares linear regression indicates that distance from the epicenter explained only 13% of the variance in normalized streamflow response among those gages that exhibited identifiable response to the earthquake (Fig. 4). The post-seismic increase in discharge was better correlated with discharge at the time of the earthquake, which explained just under half the variance in the absolute change in discharge, indicating that the degree of response scaled with the size of the river (Fig. 5).

Two types of mechanisms could explain increased streamflow in response to earthquakes: temporary changes in total head such as those due to dynamic strain during liquefaction, and permanent changes in hydraulic conductivity or storativity due to aquifer compression, settling, and/or compaction. Following Manga [14], analysis of baseflows sustained by groundwater flow between runoff producing storm events can be used to evaluate the degree of seismically induced changes in aquifer properties. Consider a shallow, one-dimensional, confined aquifer wherein, in the absence of recharge, changes in hydraulic head, h, follow a diffusion model:

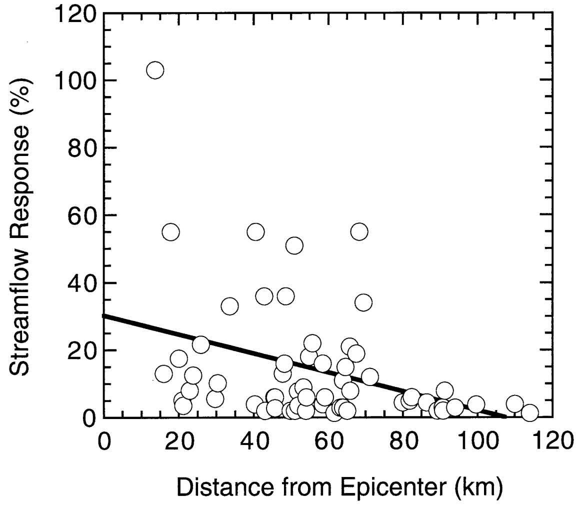

Fig. 4. Percent increase in streamflow versus distance to epicenter. Least-squares linear regression yields $y = 30-0.28x$ ($R^2 = 0.13$).

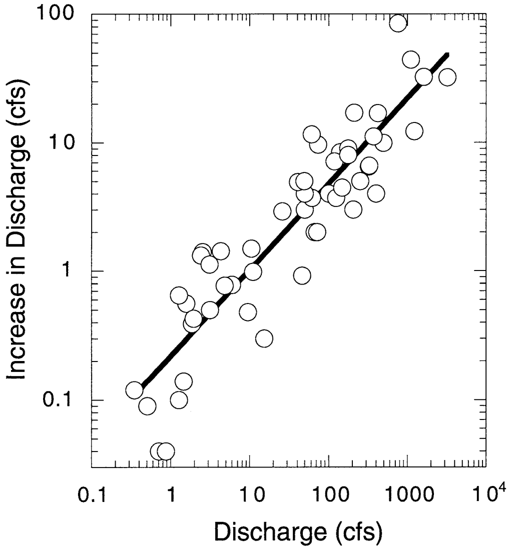

Fig. 5. Post-seismic increase in discharge versus discharge at the time of the earthquake. Power function regression yields $y = 0.21x^{0.67}$ ($R^2 = 0.45$).

$$\delta h/\delta t = D\delta^2 h/\delta x^2 \tag{1}$$

where D is hydraulic diffusivity, t is time, and x is the distance from the aquifer boundary. Adopting the linearized one-dimensional form of the Boussinesq equation, the discharge per unit width (q) is given by:

$$q = -bK\delta h/\delta x \tag{2}$$

where b is aquifer thickness and K is hydraulic conductivity. At long times after surface runoff and recharge events, the recession of baseflow discharges for such a system is given by:

$$\mathrm{dlog}Q/\mathrm{d}t = -\alpha D \tag{3}$$

where Q is stream discharge, α is a constant that characterizes the geometry of the aquifer, and for a confined aquifer $D = K/S_s$ where S_s is the specific storage, whereas for a horizontal unconfined aquifer $D = bK/S_y$ where S_y is the specific yield [16]. This simple 1-D model is justified because there typically is not enough information available on aquifer properties to justify a more sophisticated and complicated model for interpreting hydrological responses to earthquakes.

The slope of a least-squares linear regression of $\log Q$ versus time for periods of falling baseflow allows determining $-\alpha D$, and therefore estimating aquifer-scale hydrologic properties. If seismically induced changes in streamflow result from non-recoverable changes in aquifer properties (i.e. K, S_s, or S_y), then αD should differ for periods of baseflow from before and after the earthquake. Recoverable changes, such as those due to dynamic strain during ground shaking, would not be expected to result in sustained changes in baseflow response characteristics.

Periods of baseflow recession within a month of the Nisqually earthquake (February–March, 2001) were identified from plots of $\mathrm{d}\log Q/\mathrm{d}t$ versus time for the USGS gaging stations that responded to the earthquake. The slope defined by least-squares linear regression of $\log Q$ versus t was used to determine $-\alpha D$ for each period of falling discharge characterized by steady $\mathrm{d}\log Q/\mathrm{d}t$ for a month both before and after the earthquake. As found previously for other earthquakes [14], discharge recession constants from periods before and after the Nisqually earthquake do not exhibit any consistent pattern of change that would indicate non-recoverable alteration of aquifer properties (Fig. 6). Although mean recession constants (i.e. αD) decreased for some gages, others increased and the error bars defined by the range of observed values overlap the 1:1 line for all but three gages. Hence, any change due to seismically induced static strain or changes in permeability was minor or of limited spatial extent, and did not systematically affect streamflow in the same way among gaging stations.

The time scale of the observed response provides independent evidence for a near-surface source for the post-seismic increases in streamflow. Roeloffs [17] derived a relation between depth below the water table (z), hydraulic diffusivity, and the time scale (T) of pore-pressure diffusion to the water table in near-surface aquifers that can be approximated by:

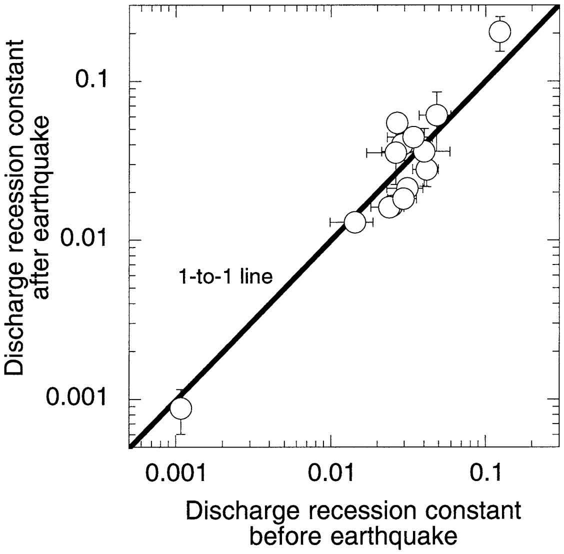

Fig. 6. Pre-earthquake versus post-earthquake discharge recession constants (αD) for a subset of streamflow gages that exhibited response to the earthquake. Data shown are mean values of αD (Q in cfs and time in days) for those gages for which both pre- and post-earthquake values could be determined. Error bars show range of values for individual events at stations where multiple events were suitable for determining αD. Power function regression yields $y = 1.5x^{1.1}$ ($R^2 = 0.93$): 1-to-1 line shown in figure for reference.

$$T = 11z^2/D \tag{4}$$

Rearranging Eq. 4, the maximum depth below the water table that a hydrologic response observed at a time T after an earthquake could have originated may be estimated by:

$$z = (TD/11)^{0.5} \tag{5}$$

Incorporating typical hydraulic diffusivities of unconsolidated sands ($D \approx 1$–10 m^2 s^{-1}) and the observed streamflow response within hours of the earthquake into Eq. 5 indicates that excess streamflow generated by the earthquake originated within 100 m of the water table.

The distance from the epicenter to stream gauges that responded to the Nisqually earthquake is consistent with Manga's [14] interpretation of dynamic strain due to liquefaction as responsible for streamflow response to earthquakes.

Papadopoulos and Lefkopoulos [18] reported an empirical relation that describes the maximum distance from earthquake epicenters at which liquefaction has been documented:

$$M = -0.44 + 3 \times 10^{-8} D_e + 0.98 \log D_e \quad (6)$$

where M is the earthquake magnitude and the distance to the epicenter (D_e) is given in cm. Manga [14] showed that locations of observed streamflow response to the 1964 Alaksa, 1952 Kern County, 1959 Hebgen Lake, 1983 Borah Peak, and 1989 Loma Prieta earthquakes occurred close enough to the epicenters for those locations to have experienced liquefaction according to Eq. 6. Stream gages that responded to the Nisqually earthquake also were close enough to the epicenter for liquefaction to have occurred in their watersheds (Fig. 7), whereas sites without detectable response extended to beyond the range where liquefaction could be expected. We also compiled additional data for other earthquakes that caused increases in streamflow. The composite data set reinforces Manga's [14] finding that the maximum distance at which co-seismic streamflow response has been reported corresponds to the maximum distance at which liquefaction has been observed.

The area within which surficial evidence for liquefaction was observed after the Nisqually earthquake extends to approximately the same distance as the area within which streamflow increases $>5\%$ were observed. Some of the major valley bottoms in which no evidence for liquefaction was observed correspond to large alluvial rivers in which no evidence for increased streamflow was detected. Ground shaking was highly variable over short distances in the Puget Lowland, and due to differences in the distribution of data we cannot relate field evidence for liquefaction directly to streamflow changes. Neither the percentage increase nor the absolute increase in streamflow were correlated with modeled ground accelerations extrapolated from the rela-

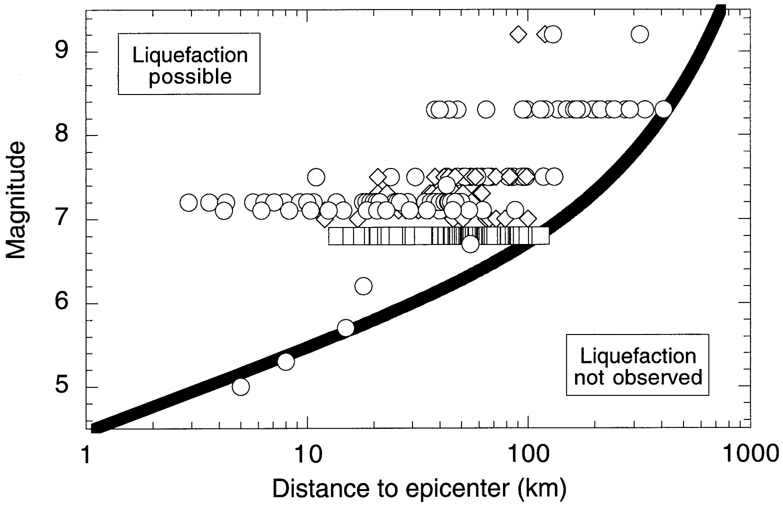

Fig. 7. Distance from epicenter versus earthquake magnitude for locations that exhibited seismically induced streamflow response. Line represents the empirical relation reported by Papadopoulos and Lefkopoulos [18] to describe the distance from the epicenter beyond which liquefaction has not been observed (i.e. Eq. 6). Diamonds represent data compiled by Manga [14], squares represent data from the Nisqually earthquake, and circles represent additional data compiled on increases in spring flow or streamflow at Alum Rock Park, CA, reported by King et al. [9]; response of Waddell Creek to the Loma Prieta earthquake reported by Briggs [10]; the Kern County earthquake derived from figures 1 and 2 in Briggs and Troxell [7]; the Loma Prieta earthquake derived from figure 1 of Rojstaczer et al. [12]; spring and river flow changes from the 1995 Kobe earthquake derived from figure 1 of Sato et al. [21]; surface water response reported for the 1992 Landers [22] and 1994 Northridge earthquakes [23]; the distance to which streamflow effects were reported by Waller [8,24] for the 1964 Alaska earthquake; and the 1906 San Francisco earthquake based on anecdotal accounts of changes in stream and spring flow reported in Lawson [25].

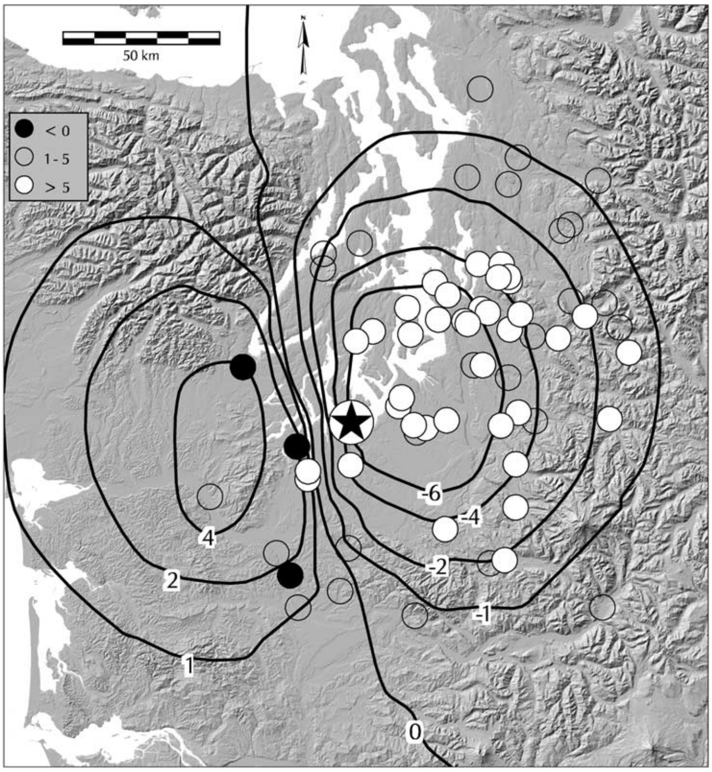

Fig. 8. Preliminary vertical displacement field modeled for the Nisqually earthquake showing contours of uplift and subsidence [26] and the location of stream gages that decreased (black), increased more than 5% (white) or had between 1 and 5% response (open circles). Contours from http://www.panga.cwu.edu/olympia_eq/nisqually.jpg.

tively sparse pattern of instrumentally determined ground motion [19,20] (R^2 of 0.05 and 0.04, respectively). However, the influence of channel size on the post-seismic increase in streamflow suggests the influence of the size of unconfined aquifers along riverine valley bottoms. In addition, it is likely that the asymmetry in streamflow response reflects to some degree the distribution of potentially liquefiable near-surface deposits in the Puget Lowland. In particular, sandy deposits of the Seattle Basin to the northeast of the epicenter should be more susceptible to liquefaction than coarser, predominantly gravel deposits found west of the epicenter.

However, areas with streamflow response $>5\%$ also correspond to areas to the northeast of the epicenter predicted to have subsided >1 mm on the down-dropped hanging wall of the triggering fault (Fig. 8). All of the observed drops in streamflow occurred on the upthrown side of the fault. This broad spatial correspondence points to a connection between the style and magnitude of streamflow response and the pattern of near-surface crustal strain.

5. Discussion

The simplest explanation for the observed streamflow response to the Nisqually earthquake is that it reflects both expulsion of water from shallow aquifers due to compaction of unconsolidated near-surface deposits and potentially liquefiable surficial deposits in response to ground shaking. Locations near the epicenter that did not respond to the earthquake presumably reflect local geologic conditions less susceptible to settling and liquefaction. However, the correspondence of areas exhibiting the greatest streamflow response with areas that subsided indicates a substantial role for settling and compaction of surficial deposits. Given that the baseflow recession analysis shows no systematic evidence for changes in basin-scale hydraulic conductivity, we conclude that the increased streamflow following the earthquake must have originated either from dynamic strain accompanying liquefaction, or settling and compaction of near-surface aquifers that did not strongly influence baseflows. The strong influence of the pre-earthquake baseflow discharge on the magnitude of observed response argues in favor of the interpretation that streamflow changes were caused by shaking of variably saturated near-surface deposits along river valleys and by compaction of shallow aquifers developed in Pleistocene outwash sands of the Seattle Basin.

Other potential explanations for the increased streamflow in response to the Nisqually earthquake are not supported by our observations. In particular, the rapid response indicates a shallow source within 100 m of the water table for the increased flow. This precludes both expulsion of over-pressured fluids in the seismogenic zone and pore-pressure diffusion following co-seismic strain in the upper crust as dominant mechanisms for streamflow changes associated with the earthquake. The near-surface origin of the hydrologic response is consistent with the deep focus of the Nisqually earthquake because low-frequency, non-directional shaking at the ground surface would tend to favor liquefaction as a mechanism for streamflow changes. We note, however, that frequent runoff-producing events in the region limited our ability to detect any signature of delayed response from deeper sources.

6. Conclusions

The magnitude of hydrologic response to earthquakes is inherently site-specific due to local geological conditions such as the presence of unconsolidated or liquefiable deposits. But our findings indicate that local near-surface strain and response to strong ground shaking can explain streamflow response to the Nisqually earthquake. Moreover, our analysis provides further support for the observation that, given earthquake magnitude, post-seismic changes in streamflow are consistent with empirical limits on the distance to which liquefaction occurs from epicenters. For the Nisqually earthquake, the influence of pre-earthquake discharge on the response together with the spatial correspondence between increased streamflow and near-surface volumetric strain support the interpretation that streamflow response was caused by settling or compaction of unconsolidated shallow aquifers and dynamic response to shaking of saturated valley-bottom deposits.

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