RESPONSE OF ALASKAN WELLS TO NEAR AND DISTANT LARGE

EARTHQUAKES

By

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A

THESIS

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Abstract

We observed water level changes in groundwater wells in Alaska following the large 2002 Nenana Mountain and the Denali fault earthquakes. Multiple mechanisms must be responsible for the variable temporal pattern and the magnitude of the observed water level changes. For the wells in a consolidated confined aquifer system, poroelastic theory explains the water level changes. However for the wells in a partially confined unconsolidated aquifer, 1) fracture formation due to an earthquake which changes the permeability of the aquifer, or 2) consolidation of the unconfined aquifer in host rock by earthquake induced dynamic strain (liquefaction) are both important mechanisms. For each well the dominant mechanisms are the same for both earthquakes. For the group of wells where dynamic strain is the cause of water level changes, we also observed water level changes due to the 2004 great Sumatra-Andaman earthquakes. Though more than 10000 km away, the Sumatra earthquake induced water level changes that are very consistent with the changes due to the local large earthquakes. Along with the determination of the mechanics of the well water level changes in Alaska, we also determined general hydrological parameters of the wells which can be helpful for future studies.

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1. Introduction

During the winter of 2002, central Alaska experienced two major earthquakes (Figure 1.1). The Mw 6.7 Nenana Mountain earthquake, on 23 October 2002, created a 40 km long aftershock zone along the western part of the Denali fault. Focal mechanisms and InSAR and GPS data suggest that the earthquake ruptured a 21.5 km long vertical right-lateral fault at shallow depth [Wright et al., 2003, Hreinsdottir et al., 2006]. Eleven days later, the 3 November 2002 Denali fault earthquake (Mw 7.9) ruptured about 340 km of the surface along three major faults (Figure 1.1). It first ruptured 40 km along the Susitna Glacier thrust fault, then with nearly pure right-lateral strike slip motion it ruptured 220 km of the Denali fault and 80 km of the Totschunda fault [Eberhart-Phillips et al., 2003, Hreinsdóttir et al., 2003]. Hreinsdóttir et al. [2006] used 232 GPS coseismic displacements to develop a high resolution slip distribution model for the Denali earthquake.

After more than a year, in the winter of 2004, the whole earth experienced the largest earthquake in the history of digital earthquake recording (Figure 1.2). The 26th December 2004 Sumatra-Andaman earthquake (Mw 9.1-9.2) shook the whole earth and created a rupture zone more than 1500 km long with an average slip of 15 m [Lay et al., 2005]. West et al. [2005] reported that surface waves from the Sumatra-Andaman earthquake triggered seismic activity at Mount Wrangell in Alaska.

Groundwater level changes due to an earthquake are a common phenomenon and have been studied for several decades. These studies are mainly important for disaster management, earthquake prediction, aquifer characterization, and for understanding the
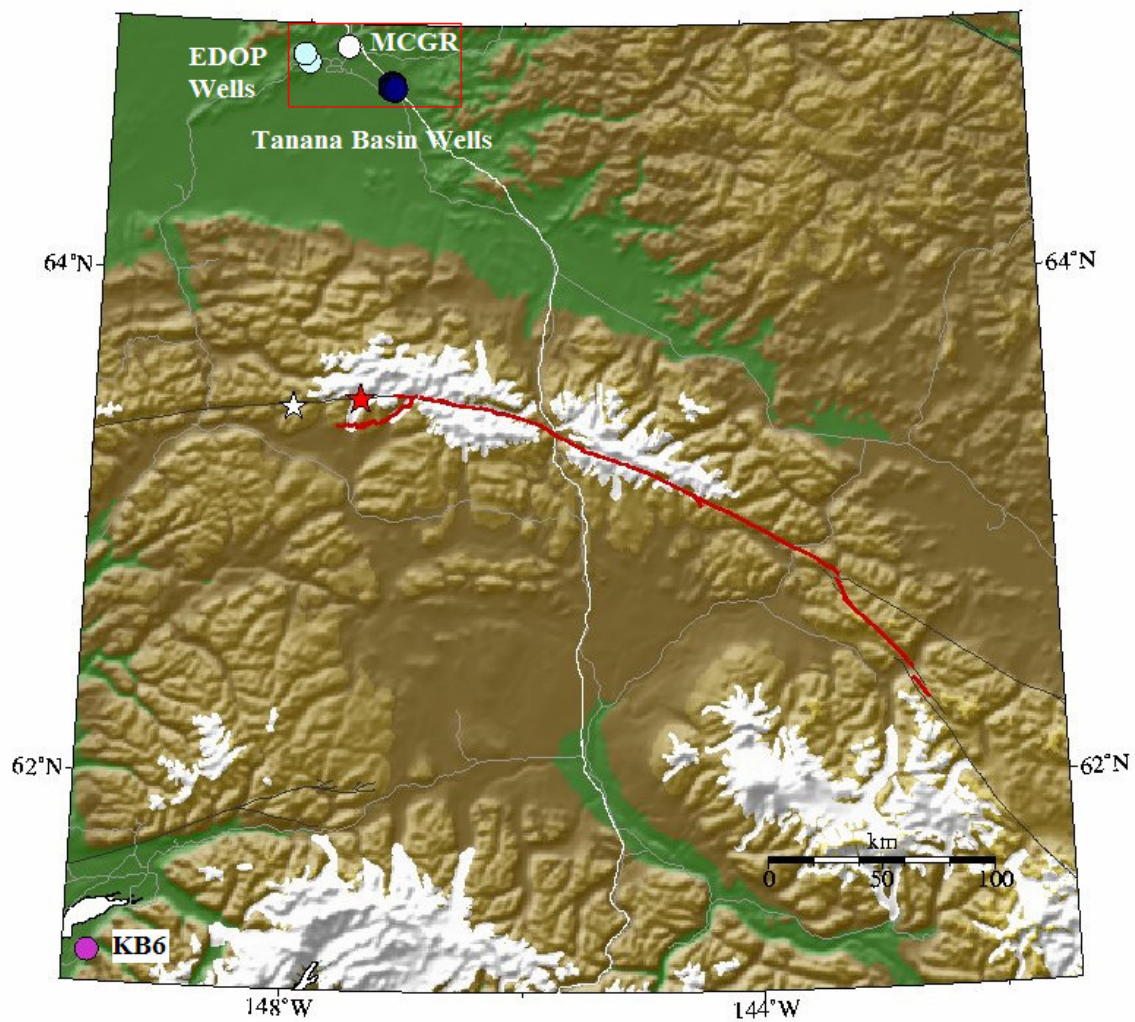
Figure 1.1: General location map. The epicenter of the Nenana Mountain earthquake is shown by a white star and the epicenter of the Denali fault earthquake by a red star. The red line is the rupture length of the Denali earthquake. The white line is the Trans Alaska Pipeline and the gray lines are roads. The well locations are also plotted. Different colored dots represent wells in different geographic locations.
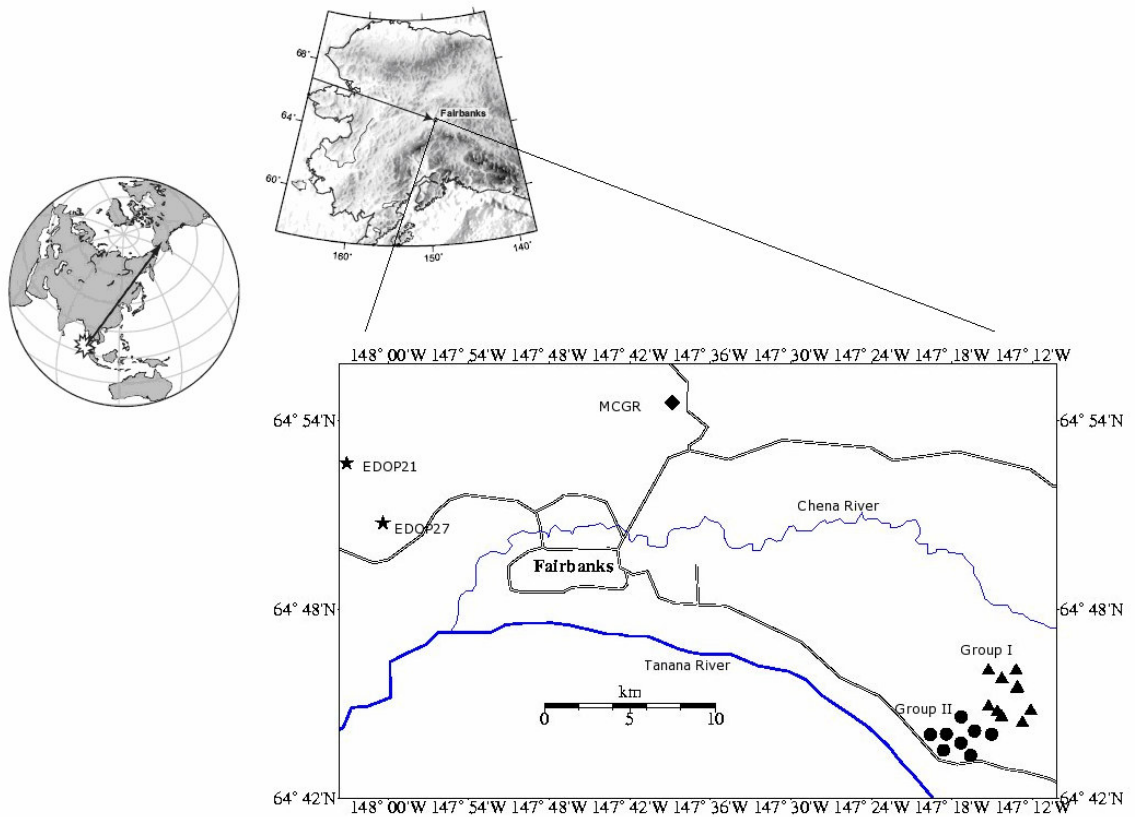
Figure 1.2: Well locations near Fairbanks. Zoomed pictures of Tanana basin wells (rectangular area of Figure 1.1) along with the ray path of seismic waves of the Sumatra-Andaman earthquake from Sumatra to Alaska [after West et al., 2005]. These wells can be classified into two groups according to their response patterns to different earthquakes and their variations of water level with the variations of water level of nearby rivers (see text for details).

tectonic settings of the studied areas [Roeloffs, 1996]. We studied the responses of the ground water from several wells in Alaska to these 3 earthquakes. In this study we report the response pattern of water levels, quantify the changes and identify the causes of water level changes following the Nenana Mountain, the Denali Fault and the Sumatra-Andaman earthquakes.

Water level changes from the Denali earthquake were reported in several newspapers from all over the USA. Water sloshed in Seattle's Lake Union and in Lake Pontchartrain of New Orleans. Muddy tap water turned up in Pennsylvania, where a 6 inch water level drop was observed in some places [Stricherz, 2003]. Water level oscillations were also observed in several lakes in western Canada. In southern Manitoba (epicentral distance 3500 km), deep water wells started producing muddy water [Cassidy and Rogers, 2004]. A sudden water level drop followed by oscillation was observed and modeled in the NVIP-3 well in Oregon [Brodsky et al., 2003]. In Alaska, several studies were made on liquefaction caused by the Denali earthquake [Harp et al., 2003; Kayen et al., 2004]. Those studies found good agreement between peak ground velocity and the extent of liquefaction.

Water level changes after the great 2004 Sumatra-Andaman earthquake were reported in newspapers from all over the world. We personally observed a sudden increase in water level in local ponds and wells in India. Water level changes were observed in China as well [Wang, 2006]. Kitagawa et al. [2006] reported coseismic and postseismic water level changes in wells in Japan. In the USA, several reports have been made on water level changes due to this great earthquake. Nelms and Powell [2005]

reported water level changes in a well at Christiansburg, Virginia, almost 10000 km away from the epicenter of the earthquake. Water level changes in a well in Missouri were also observed [http://www.dnr.mo.gov/env/wrc/sumatranEQ.htm].

There was no analysis of groundwater level changes in Alaska after the Nenana and the Denali earthquakes prior to our study. We observed groundwater level changes in 22 wells in Alaska following the 2002 Nenana Mountain and the Denali fault earthquakes (Figures 1.1 and 1.2). Comparing the distance from the source to the well, to the rupture length of the earthquakes, these wells can be considered far field for the Nenana and near field for the Denali earthquake. Since these wells are situated in diverse aquifer systems, we find different mechanisms responsible for the changes in the water level in each aquifer system. Generally in a near field well, with a confined aquifer system, we expect to see a coseismic step in water level changes proportional to induced volumetric static strain by the earthquake [Wakita, 1975; Quilty and Roeloffs, 1997]. However, fracture formation due to an earthquake, thus changing the permeability of the aquifer [Rojstaczer et al., 1995; Brodsky et al., 2003], and consolidation of an unconfined aquifer by earthquake induced dynamic strain [Wang et al., 2001; Manga et al., 2003], are also widely reported mechanisms of seismically generated water level changes. During our study of the wells in Alaska, we find, for the wells in a confined aquifer system, the coseismic water level changes can be explained by the response to static strain as described by poroelastic theory [Roeloffs, 1996]. For unconsolidated partially confined aquifer systems, dynamic strain and fracture formation due to seismic wave propagation are the major causes of water level changes.

For the group of wells where dynamic strain is the cause of water level changes, we also observed water level changes due to the 2004 great Sumatra-Andaman earthquake [Sil and Freymueller, 2006]. On the basis of the dominant water level change mechanism and the geological/geographical settings, we classify the observed wells into a few groups and discuss the possible causes of the water level changes. We also determine the general hydrological parameters of the wells, which will be helpful for future geohydrological studies of Alaska. We expect our work will help to understand some of the effects of earthquakes in Alaska and also can gain some insight into general water level changing mechanisms due to other earthquakes anywhere in the world.

2. Mechanisms of water level changes due to earthquakes

Water level anomalies have been observed after many major earthquakes. Based on more than a decade of studies, researchers have identified and documented several causes of water level changes due to earthquakes. Roeloffs [1996] and Montgomery and Manga [2003] summarized the major process of water level changes associated with earthquakes. From their studies, we can classify the mechanisms into two groups: changes due to volumetric static strain induced by the earthquake (following poroelastic theory), and changes due to the passage of seismic waves. In this section we shall explain these two mechanisms and some of the case studies associated with them, in order to provide background for our own studies.

To verify and understand the mechanisms of water level changes, precise measurement of water level due to the earthquake is required. The postseismic response of the water level is also an important component for understanding the responses of aquifers to earthquakes. Water level can also be affected by nontectonic effects like changes in atmospheric pressure. To study these effects, we must remove all nontectonic effects from the water level time series for a considerable time period including the day of the earthquake. All the case studies we shall discuss here are based on corrected water level data only. So before discussing the case studies we shall discuss the standard correction process for water level data.

2.1. Poroelastic theory

A poroelastic material is a material consisting of an elastic matrix containing interconnected fluid saturated pores. Fluid saturated crust behaves as a poroelastic material to a very good approximation.

For an ordinary isotropic, linearly elastic solid, the stress strain relationship can be written as:

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} \tag{2.1}$$

Where ε_{ij} is the strain tensor, σ_{ij} is the stress tensor, δ_{ij} is the Kronecker delta function, G is the shear modulus and ν is the Poisson ratio, and there is an implied summation over repeated indices. But if a medium is porous (and pores are filled with fluid) then the stress strain relationship will be different. Biot [1941] first proposed a new stress-strain relationship by modifying equation 2.1 for the effect of fluid pressure in the pore spaces. Rice and Cleary [1976] summarized the following equations for a linearly elastic isotropic porous medium, which are the building blocks of poroelastic theory:

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)}p\delta_{ij} \tag{2.2}$$

$$m - m_o = \frac{3\rho(\nu_u - \nu)(\sigma_{kk} + 3p/B)}{2GB(1+\nu)(1+\nu_u)} \tag{2.3}$$

Here $m - m_o$ is the fluid mass change, ρ is the density of the fluid, B is the Skempton's coefficient, p is the pore pressure and ν_u is the "undrained" Poisson's ratio. The pore pressure, density and fluid mass are measured in the same reference frame as the stress and strain tensors. Rice and Cleary described equation 2.2 as a stress balance equation

and equation 2.3 as a mass balance equation. Equation 2.2 is the modified version of equation 2.1, where an additional term has been added to account for the effect of pore pressure p and changes in Poisson's ratio with applied stress.

We can see here that a new concept of "drained" and "undrained" conditions has been introduced to explain the poroelastic behavior of the materials. The "drained" condition is the one in which there is no change in fluid pressure. The "undrained" condition is the one in which there is no change in fluid mass [Roeloffs, 1996]. These two conditions may not be achieved in reality, but to a good approximation the introduction of sudden stress in the crust by an earthquake in a relatively short time can be considered as an "undrained" condition [Roeloffs, 1996; Wang, 2000]. Similarly, the "drained" condition is reached after relatively long duration pore fluid flow equalizes the fluid pressure gradients caused by the earthquake.

So for an earthquake the coseismic poroelastic effect on the crust can be obtained by putting $m - m_o = 0$ in the equation 2.3. Thus we obtain:

$$p = -B\,\sigma_{kk}/3 \quad \text{or} \quad \Delta p = -B\Delta\,\sigma_{kk}/3 \tag{2.4}$$

Equation 2.4 says under "undrained" condition, change in fluid pressure (Δp) is proportional to the change in mean stress ($\Delta\sigma_{kk}$). This is the mechanism of water level changes for poroelastic material. We can define Skempton's coefficient B qualitatively now. In the "undrained" condition, B is the ratio of the induced pore pressure (p) divided by the change in mean stress ($\sigma_{kk}/3$) (a negative sign indicates compressive stress) [Wang, 2000]. B governs the magnitude of water level changes due to an applied stress, as pore pressure is directly proportional to water level (p=hρg, where h is the water

column height). The value of B is always between 0 and 1. When B is 1, the applied stress is completely transferred into changing pore pressure. B equal to 0 indicates no change in pore pressure after applying the stress. When an aquifer is not confined, an applied stress can be easily transferred outside the aquifer system without increasing the pore pressure. Thus a low B value indicates a poorly confined aquifer system. Laboratory studies indicate the value of B depends upon the fluid saturated pore volume of the sample [Wang, 2000].

Equation 2.4 can also be expressed in terms of volumetric strain [Roeloffs, 1996]:

$$p = -\frac{2GB(1+\nu_u)}{3(1-2\nu_u)}\varepsilon_{kk}$$
(2.5)

Equation 2.5 shows that fluid pressure changes proportionally in a poroelastic material under the influence of an induced volumetric strain (ε_{kk}).

Apart from earthquake induced water level changes, poroelastic theory can also explain typical fluctuations observed in continuously recorded water level data due to changes in atmospheric pressure and tidal strain. These two are the major noise sources while studying water level changes due to earthquakes. Since atmospheric pressure is unidirectional, in the z (vertical) direction, putting $\varepsilon_{xx} = \varepsilon_{yy} = 0$ and $m - m_0 = 0$ in equations 2.2 and 2.3 respectively, we can obtain the ratio between pore pressure change and barometric pressure change as [Roeloffs, 1996]:

$$\frac{\Delta p}{\Delta b} = (B/3)\left(\frac{1+\nu_u}{1-\nu_u}\right)$$
(2.6)

Here Δb is the change in barometric pressure and Δp is the change in pore pressure. Since Δp is directly proportional to water level changes ($p=h\rho g$, where h is the water column height, g is the acceleration due to gravity and ρ is the density of water) equation 2.6 can be modified in terms of the relationship between the water level changes (Δh) and the atmospheric pressure changes (Δb) as:

$$\frac{\Delta h}{\Delta b} = (B/3\rho g)\left(\frac{1+v_u}{1-v_u}\right) \tag{2.7}$$

Once Skempton's coefficient has been determined, the equation 2.7 can be used to correct the water level data for atmospheric pressure effects.

Tidal strain can also influence water level. The effect of tidal strain will be the same as described by equation 2.5. If we replace p with $h\rho g$ in equation 2.5, then the relationship can be written as:

$$\Delta h = -\frac{2GB(1+v_u)}{3\rho g(1-2v_u)}\Delta\varepsilon \tag{2.8}$$

where Δh is the change in height of water level, and $\Delta\varepsilon$ is the corresponding tidal strain change. Equation 2.8 is used to correct water level fluctuations due to variation in tidal strain. Figure 2.1 shows a few typical uncorrected and corrected water level data from atmospheric pressure and tidal strain using equations 2.7 and 2.8.

2.2. Shaking induced water level changes

In numerous cases of water level changes due to earthquakes, poroelastic theory could not explain all observed water level changes [Quilty and Roeloffs, 1997]. So it can
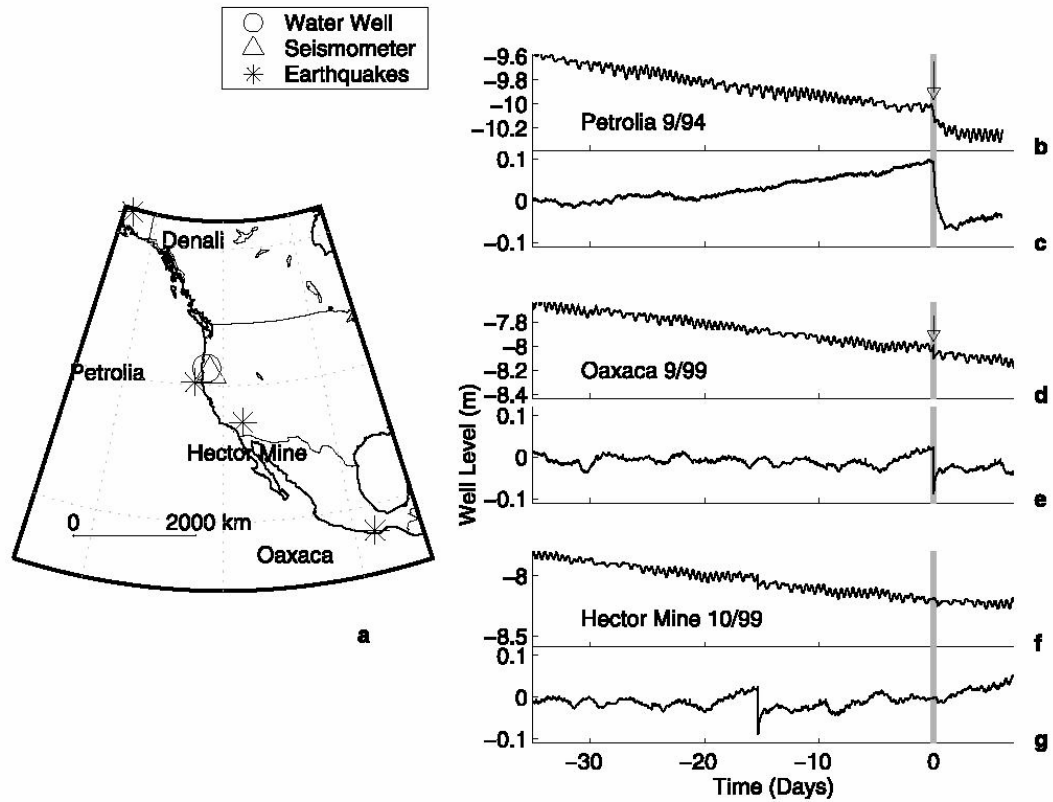
Figure 2.1 Example of correction of water level data using equation 2.6 and 2.7 In (a) earthquake locations and well locations are shown. In (b), (d) and (f) are the uncorrected water level data with a linear trend. (c), (e) and (g) are the corrected water level data using equations 2.6 and 2.7 Before correction, the linear trends were removed. The gray vertical line indicates the occurrence of the earthquake. Source, Brodsky et al. [2003].

be inferred that other mechanisms also must affect water level changes in some cases. Shaking by the seismic waves from an earthquake (especially high amplitude surface waves) can change the characteristics of an aquifer, for example by opening or closing fractures or by inducing compaction. Opening and closing of fractures changes the existing pore pressure gradient in the aquifer system by changing the flow paths of the water. The changes in pore pressure gradients can then be considered as new pseudo pressure sources, which cause water level changes. Generally in wells that are far from earthquake sources and where the aquifers are unconsolidated or filled with fractures, shaking induced changes in water level are more dominant than poroelastic changes.

Whether a change in water level is either due to static strain (typically a step like coseismic change followed by a gradual decay) or due to shaking (either a gradual change or a step-like change in water level), the induced pore pressure obeys the standard diffusivity equation of the form [Wang, 2000]:

$$\frac{\partial p}{\partial t} - c\frac{\partial^2 p}{\partial z^2} = 0 \qquad (2.9)$$

The simplest solution for equation 2.9 is the standard Kelvin solution [Roeloffs, 1996; Wang, 2000; Brodsky et al., 2003]:

$$\Delta p(z,t) = p_o erf(z/\sqrt{4ct}) \qquad (2.10)$$

Where Δp (z,t) is the change in pore pressure, p_o is the amplitude of the change, z is the depth where pore pressure has evolved or diffused and c is a hydrological parameter known as the hydraulic diffusivity. Based on this equation we can define

$$\tau = z^2/4c \qquad (2.11)$$

as the characteristic decay time of the water level. Shaking induced changes are identified based on the fitting of gradual changes in water level (either coseismic or postseismic) using equation 2.10.

Equation 2.10 also describes the recovery of water level to its steady state from a perturbed state. A perturbation can be caused by an earthquake or by a cultural event like pumping of the well. Equation 2.10 can help to estimate the steady state condition of the water level when it is recovering from a perturbation such as pumping.

So we can say there is not a single composite theory of shaking induced water level changes, but there are many observations supporting these mechanisms. We shall also discuss a few case studies that demonstrate shaking induced water level changes.

2.3 Case studies supporting the poroelastic theory of water level changes

Several case studies have shown that coseismic water level changes are proportional to the volumetric strain induced by the earthquake, as would be expected from equation 2.5. Here we shall briefly describe a few such observations.

Quilty and Roeloffs [1997] observed coseismic water level changes in nine wells near Parkfield, California after an M_D 4.7 earthquake on 20 December 1994 (M_D is the duration magnitude). They developed a dislocation model for the earthquake, which also predicted the volumetric strain at the well sites. Their predicted strain was in good agreement with observed strainmeters. Using equation 2.7 and from the observed water level changes due to atmospheric pressure, they obtained the B values for each well. They showed that water level changes in five wells out of the nine could be explained by equation 2.5 (Figure 2.2). Among the other 4 wells, two wells followed the same
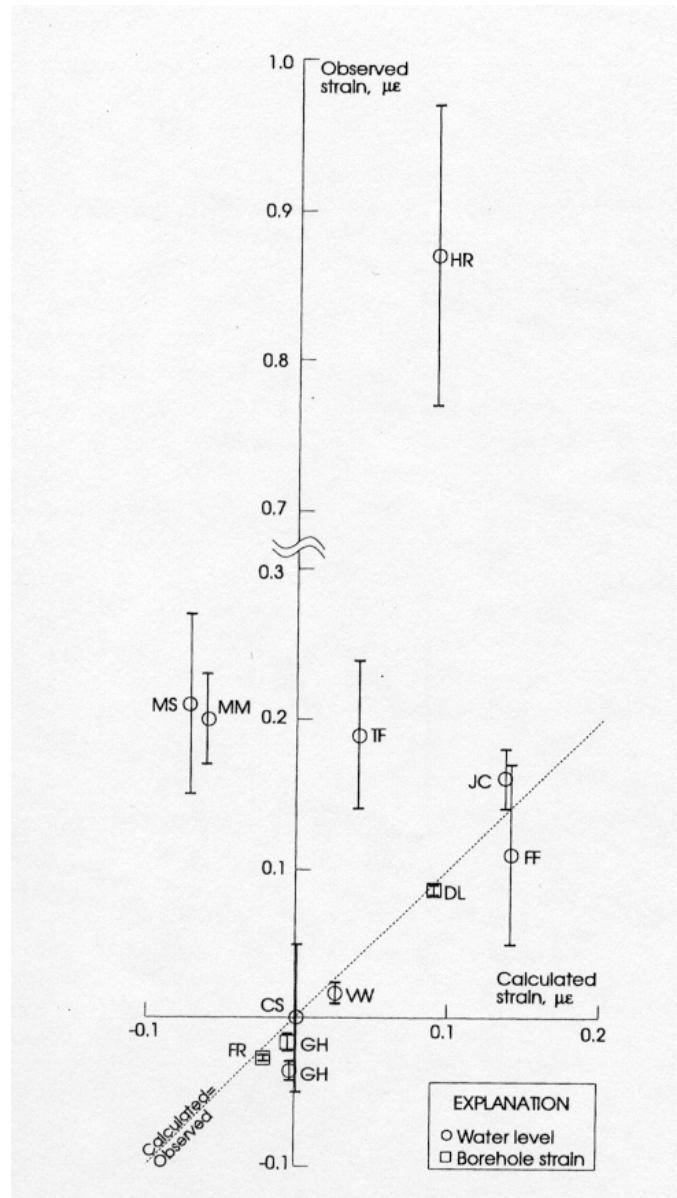
Figure 2.2: Graphical comparison between observed strain and the strain calculated using the best fitting dislocation model by Quilty and Roeloffs, 1997. Strain is directly observed by borehole strainmeters (square), and inferred using poroelastic theory from water level (circle). Apart from the two wells in the upper left quadrant, the sign (and magnitude in most of the cases) of coseismic water level changes can be explained by poroelastic theory.

direction of water level changes as predicted by poroelastic theory, but had a larger magnitude. The other two wells could not be explained by the poroelastic theory at all.

A similar observation was made by Jónsson et al. [2003], after an Mw 6.5 earthquake in Iceland in June 2000. The earthquake was strike slip. Around the fault they observed a four-lobed pattern of water level rise and fall proportional to the induced stress pattern of the earthquake obtained from a standard dislocation model. The postseismic decay of the induced pore pressure (as observed from the water level decay) also led to poroelastic deformation of the crust.

2.3 Case studies supporting shaking induced changes

Just like with poroelastic phenomena, there are several case studies supporting shaking induced water level changes. There are two major types of observations that suggest that some water level changes can not be due to poroelastic effects. In these cases, the wells are either too far from the source, so the static volumetric strain is negligible and cannot be responsible for changes the water level, or the changes are gradual, and appear long after the introduction of static volumetric changes.

Roeloffs [1996] observed persistent water level changes in a well near southern California, after any distant major earthquake. The water level always increased irrespective of the focal mechanism of the earthquake (Figure 2.3). The magnitudes of water level changes were inversely proportional to the square of the source distance and directly proportional to the magnitude of the earthquakes, as determined empirically. Roeloffs speculated that the interaction between the seismic waves and a gas phase in the
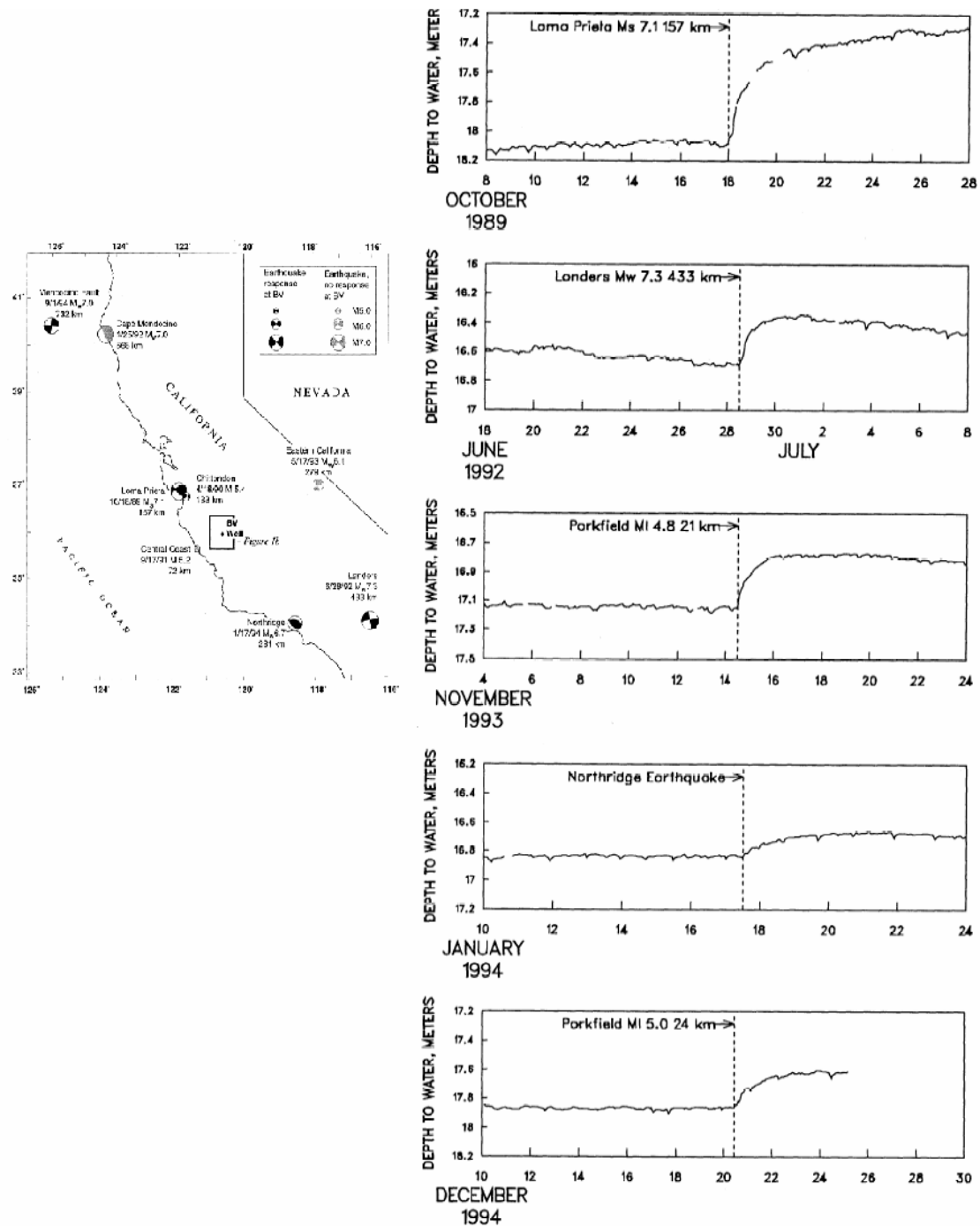
Figure 2.3: Water level increases in the BV well California for earthquakes at different locations and with different focal mechanisms. Here depth to water is the distance between land surfaces (at an elevated position) to the top surface of the water column in the well. From Roeloffs [1998].

pore spaces might explain these changes in water level. A similar observation was made by Matsumoto et al. [2003], in the Haibara well, Japan.

In another case study, Brodsky et al. [2003] observed several coseismic water level drops in a well near Grant's Pass, Oregon, irrespective of the focal mechanisms of the earthquakes. In this well, water level decreases were either gradual or sudden. Fitting the gradually changing water level data using equation 2.10, the value of c and z were determined (Figure 2.4). The value of c matched the value obtained from an independent study. The value of z was always greater than the depth of the well. Brodsky et al. [2003] concluded that the passage of seismic waves might clear some clogged fractures near the wells and change the hydraulic properties. The change in the water levels was a reflection of the change in the aquifer properties due to ground shaking. In a separate study, Woodcock and Roeloffs [1996] showed that the magnitude of water level changes followed an inverse square relationship with distance for this well also.

Ground shaking due to an earthquake generates dynamic strains. Manga et al. [2003] showed that the water flow of Sespe Creek, California always increases after any significant earthquake. They showed that the magnitude of the water flow increase is directly proportional to the peak horizontal ground velocity caused by the earthquake, with no effect below a threshold value (Figure 2.5). Since the peak horizontal velocity of an earthquake is directly proportional to the peak dynamic strain, they concluded that dynamic strain due to an earthquake can affect water flow. Earlier Bower and Heaton [1978] proposed the same theory to explain the water level changes in a well near Ottawa from the 1964 Alaska earthquake.
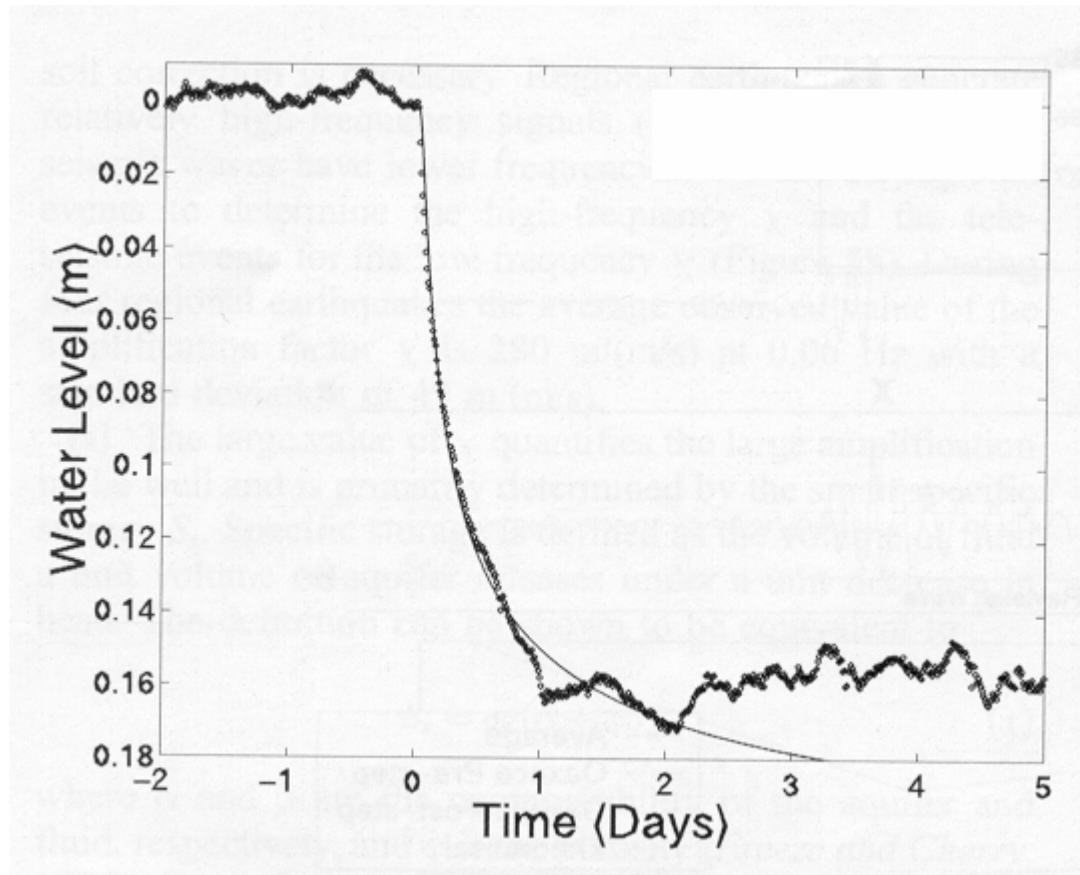
Figure 2.4: Gradual water level decrease in the Grant's Pass well after the Petrolia earthquake, fit using equation 2.10. The best fit curve has values of c=0.2 m^2/sec and z=70 m. The same value of c was obtained from an independent study. From Brodsky et al., 2003.
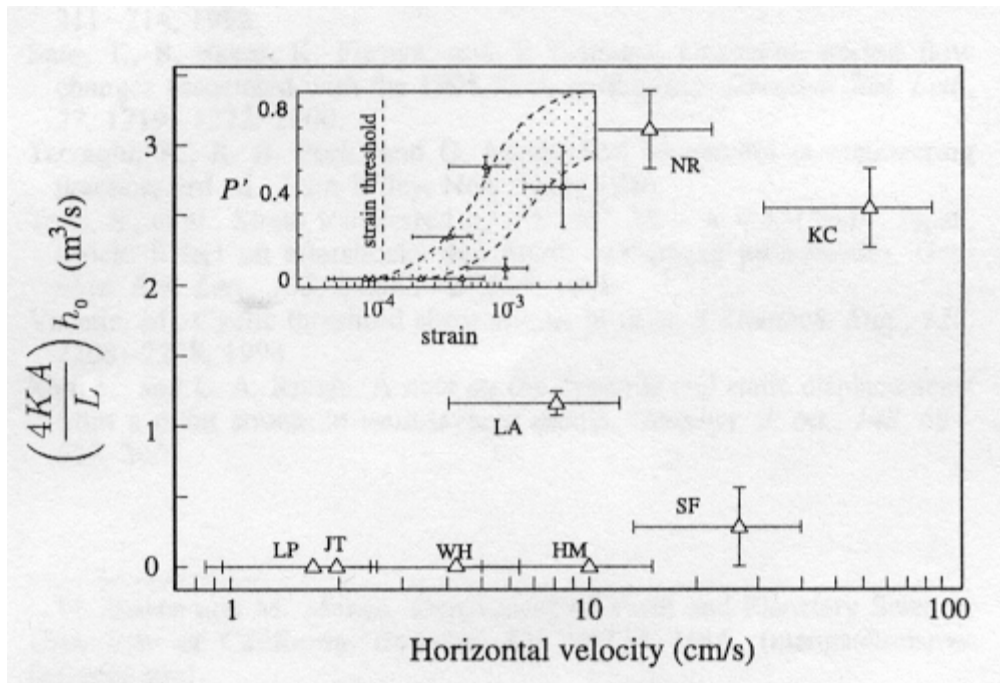
Figure 2.5: Relation between magnitudes of water level changes and horizontal ground velocities due to the earthquakes. The water level changes were found to be directly proportional to the peak horizontal velocities of the earthquakes. Source Manga et al., 2003.

Ground shaking by an earthquake can also cause the water level of a well to oscillate, a phenomenon known as "Hydroseismograms" [Roeloffs, 1996]. Cooper et al. [1965] and Bredehoeft et al. [1965] showed that the water column in a well of favorable dimensions and a very permeable surrounding rocks could resonate at periods comparable to seismic Rayleigh waves. High temporal resolution water level data can thus behave exactly like seismograms for a given earthquake. When the sampling interval of the water level is less frequent, the oscillations can be seen as spike like changes in water level.

3. Well locations, data processing and observations

In this section we shall discuss the locations, geological settings and basic characteristics of the wells from which we have collected data for our study. Then we will discuss the general and special corrections applied to the water level data. We then consider the corrected water level data to be our observation for modeling and interpretation. In the observation part, we will describe the observed anomalous behavior of water levels after the Nenana Mountain, the Denali fault and the Sumatra-Andaman earthquakes, respectively.

3.1 Studied groundwater wells

We obtained groundwater data from 22 wells all over Alaska (Figures 1.1 and 1.2). The wells are drilled into different aquifer systems. There may be more semi-continuously or continuously monitored wells in Alaska, but we consider only those wells which had data from at least one of the previously mentioned 3 earthquakes. In this section we will discuss the geological setting, instrumentation and Skempton's coefficient of the studied wells.

3.1.1 Well settings and instrumentations

Two studied wells, EDOP27 and EDOP21, are situated west of the city of Fairbanks (Figure 1.2). They are drilled into an upland aquifer system on Ester Dome which is a part of Yukon-Tanana terrane. The average depth of the wells is 67 meters. The aquifer is contained within highly fractured bedrock consisting of metamorphic and igneous rocks. The aquifer is considered as confined during the winter season because of the presence of seasonal frost layers below it [Youcha, 2003]. These two wells are

monitored by the Water and Environmental Research Center (WERC), University of Alaska. Occasional pumping of water from these two wells makes the water level data noisy. No tidal effect is observed in the water level. A very minute fluctuation is observed due to atmospheric pressure changes.

The well MCGR is situated almost 15 km east of the EDOP wells (Figure 1.2). This well is situated in the same terrane as the EDOP wells but the well depth is only 30 meters. The aquifer system is confined and consists of Quartz-mica schist of pre-Jurassic age.

A cluster of 18 wells (names starting with DSAP and USAP) is situated southwest of the city of Fairbanks (Figure 1.2) in the Tanana Valley, which is covered by thick deposits of alluvium and loess. The whole valley is surrounded by an upland consisting of fractured metamorphic schist bedrock [Anderson, 1970] of the Yukon-Tanana terrane. The 18 ground water wells we studied were all drilled into Quaternary Chena alluvial deposits. These wells are very shallow (average depth 5 meters). The aquifer system is unconsolidated and is considered to be confined during winter because of the presence of a permafrost layer and a seasonal frost layer [Personal communication with Edward Plumb, Hydrologist, National Weather Service]. During summer seasons, the aquifer is not confined and the hydrographs of the wells vary systematically with the variation of the water levels of the nearby Chena and Tanana rivers [Personal communication with Heather R. Best, Hydrologic Technician, USGS, Fairbanks]. These wells along with MCGR are monitored by the USGS water Resource Division office in Fairbanks. A

strong correlation between atmospheric pressure and water level variations is observed for these wells.

Another well, KB6, is situated 29 km north of Anchorage. This well is drilled into Quaternary sand and gravel to a depth of 40 meters. The USGS water Resource Division office in Anchorage occasionally monitors this well. Water level data vary with changing atmospheric pressure for this well.

Water level data were collected at an interval of one hour in all of the wells using a submersible pressure transducer. Periodically, water level data are checked manually to verify the performance of the automated pressure transducer. Since the year 2004, the water level has been monitored at 15 minute intervals for the DSAP and USAP wells. Resolutions of the water level measurements are 3 mm and 0.3 mm, for the wells monitored by WERC and USGS respectively.

3.2 Data processing

Numerous factors can perturb the original water level data. Rainfall/ precipitation, fluctuations in atmospheric pressure, periodic variations in tidal strain and even prior earthquakes can act as noise while trying to identify and quantify the changes in water level due to any particular earthquake of interest.

Another noise source we observed in our data is a general seasonal variation of water level due to some unidentified factor. Most likely this is a result of seasonal variations in precipitation and water usage. Since all of the studied earthquakes occurred during the winter season, the seasonal variation of the water levels behaved similarly. For our study we used a maximum of one month of water level data. For these short time

periods, the observed seasonal variation of water level can be estimated as linear (Figure 3.1.) and thus it is easy to remove this effect by fitting a linear trend to the data using least squares inversion.

We use equation 2.7 for correcting the water level data for the effect of variation of atmospheric pressure. Atmospheric pressure data from weather data stations near the well locations were collected from the Alaska Climate Research Center, Fairbanks, for the required time frame. For most of the wells (except the EDOP wells), water level variations (after removing the seasonal trend) can be explained by the variation of atmospheric pressure data (Figure 3.1).

Next we studied the effect of tidal strain on the water level data. The relation between variations of tidal strain and water level changes was already discussed in Chapter 2 (equation 2.8). We predicted the tidal strain at the well locations for a given time using a standard code (SPOTL) written by Dr. Duncan Agnew of Scripps Institution of Oceanography, California [http://igpphelp.ucsd.edu/~agnew/spotlmain.html]. We did not find any correlation between water level changes and tidal strain in any of the wells we studied.

In general there is no rainfall in interior Alaska during the winter season. There can be a lot of precipitation, but it falls as snow and remains on the surface until the spring thaw. Unlike many other places, here we do not find any correlation between water level changes and rainfall or snow fall, at least not in winter.
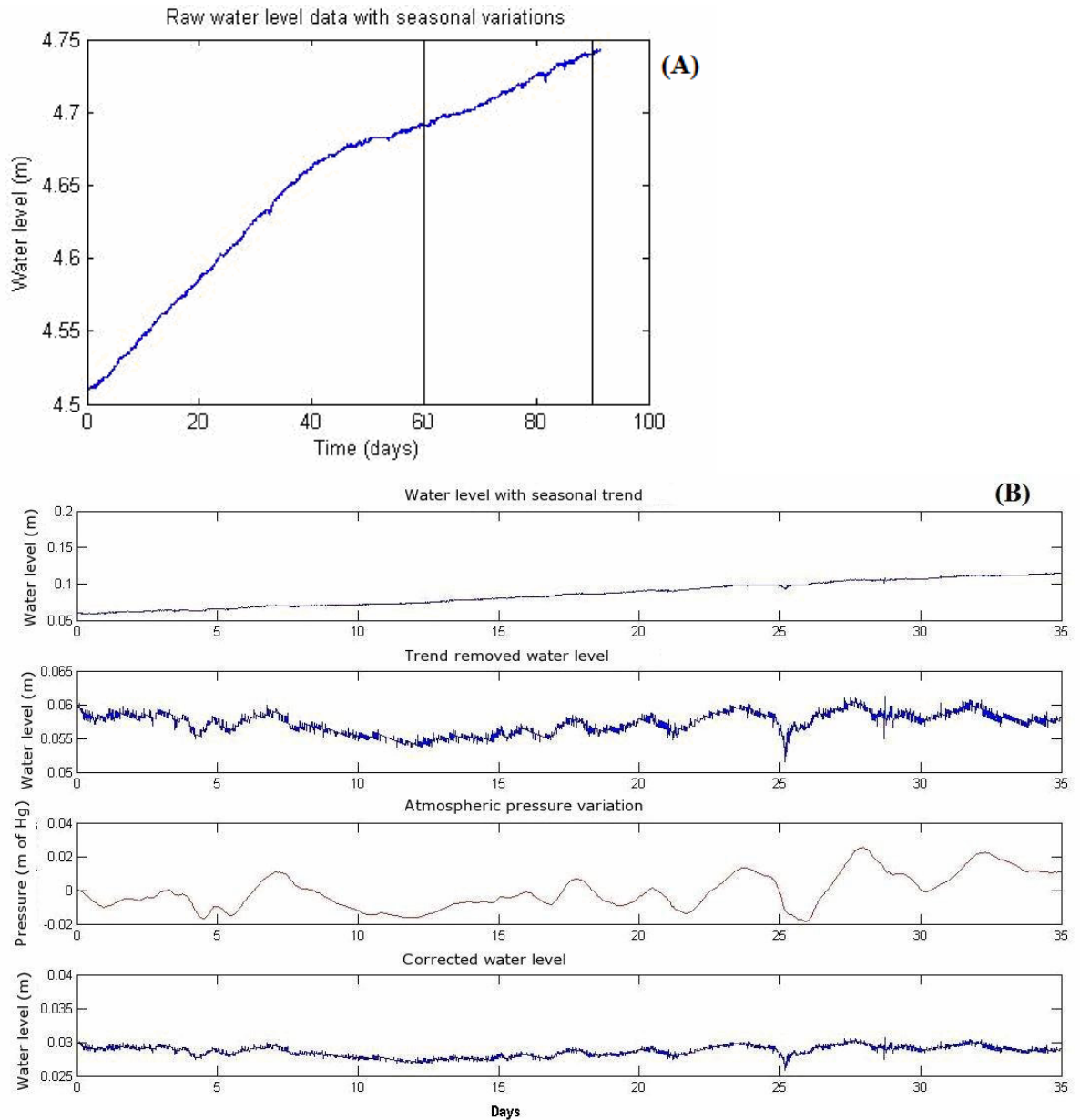
Figure 3.1.: (A) Raw water level data with a seasonal signal. (B) For a short time interval (nearly 30 days, inside two lines of the figure A) seasonal variation can be approximated by a linear trend (Top panel of B). The linear trend is due to seasonal variation of water level data. After removing the trend, the variation in water level data is more prominent (second panel). Much of the remaining variation can be explained by the changes in atmospheric pressure. Variation of atmospheric pressure at the same well is shown in the 3rd panel. The corrected water level using equation 2.7 is shown in the bottom panel. The atmospheric pressure data are from Fairbanks and the water level data are from DSAP8D well (one of the Group I wells of Figure 1.2)
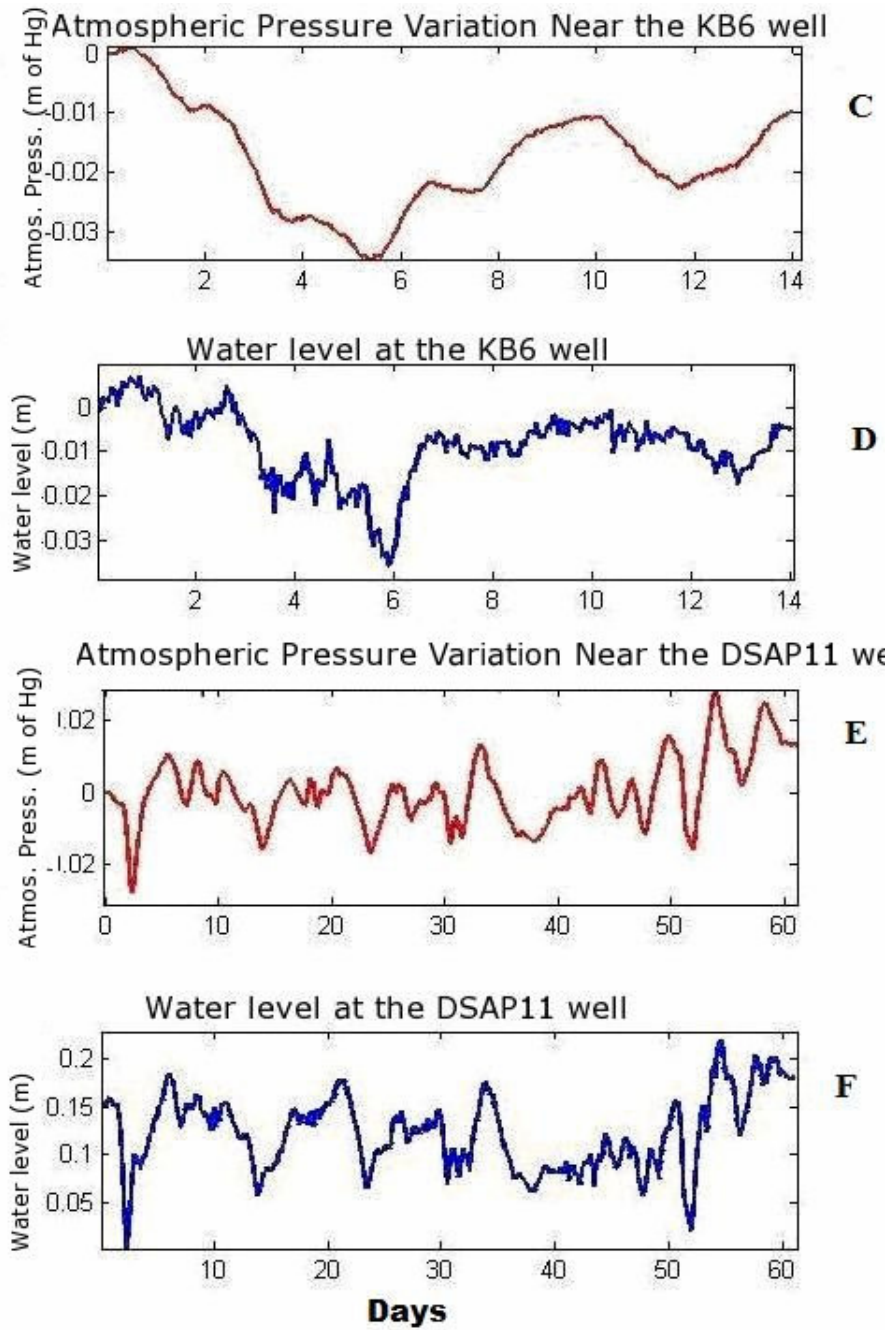
Figure 3.1 (continued): Atmospheric pressure and water level fluctuations. Fluctuations in water levels can mostly be explained by the variations in atmospheric pressure. Figure C shows atmospheric pressure changes in Anchorage during a specific time. During the same time frame, the variations in water levels in the well KB6 are almost the same (D). Similarly variations in water level of the DSAP11 well (E) (1 of the Group II wells of Figure 1.2) are correlated with atmospheric pressure variations of Fairbanks (F).

One last source of noise in the studied water level is from previous earthquakes. While we studied water level changes due to the Denali earthquake, previous water level changes due to the Nenana Mountain earthquake acted as noise. The response to the Nenana mountain earthquake changed the natural slope of the water level trend before the Denali earthquake. Again using a least squares fit we removed the effect of the Nenana earthquake to better estimate water level changes due to the Denali earthquake.

Apart from all these natural noise sources, there were a few man made sources which complicated the study of the effects of the earthquakes. Water was pumped from the well EDOP 21 a few hours before the Denali earthquake. At the time of the earthquake the water level in this well was still in the recovery phase. The reading of the water level value just after the Denali earthquake is also missing for this well. To predict the position of water level just before the Denali earthquake we used the solution to the diffusion equation of the following form which is a modified version of equation 2.10:

$$w(t) = -A * erfc\left(\sqrt{\tau/t}\right) \tag{3.1}$$

where w is the water level value after pumping at any given time t, A is the amplitude and τ is the decay constant defined in equation 2.11. Fitting the post pumping water level data to equation 3.1, using a least squares technique, helped us to predict the water level value right before the Denali earthquake. Similarly fitting the post Denali earthquake data using the same function and τ (and putting t=0) determined the coseismic water level value (Figure 3.2).

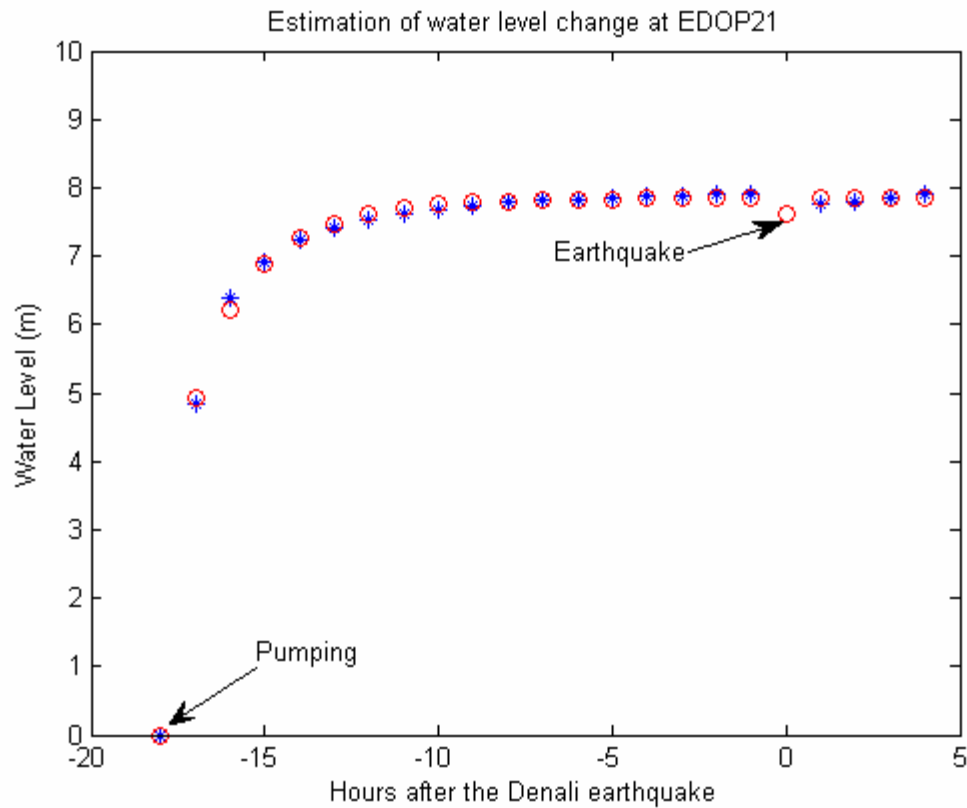Figure 3.2: Correction and estimation of water level changes at the well EDOP21. Post-pumping water level data were modeled to estimate the value of water level at the time of the earthquake. Postseismic data were modeled to estimate the original value of water level at the time of the earthquake. The difference gives the estimate of water level changes. Blue stars are the original water level data. Red circles are the modeled data.

3.2.1. Characteristic Skempton's Coefficients for the wells

Determination of Skempton's coefficient (B) for each well was necessary for understanding the mechanism of water level changes in them due to an earthquake. All the wells showed a good correlation between water level variations and atmospheric pressure changes (see Figures 3.1 and 3.2 for examples). While correcting the effect of atmospheric pressure, we determined B for each well using equation 2.7. Though our study span includes two separate years (2002 and 2004), we did not observe any significant changes in B values of the wells with time. The locations of each well along with their B values are presented in Table 3.1. The maximum B value is obtained from the well MCGR (0.8). For the 18 closely clustered wells in the Tanana valley, B values are very low. For the wells close to the Chena river (Group I of Figure 1.2) the B values range between 0.05 and 0.07, with an average of 0.062. The other group, situated northeast of the Tanana river and southwest of the Group I wells, (Group II of Figure 1.2), showed very low B values (ranging between 0.01 and 0.02 and with an average of 0.015). The low B values indicate poor confinement of the aquifer. This may result from the presence of leaks and fractures in the underlying permafrost layers. The B values for the other studied wells are also low (average 0.15), but still the value indicates better confinement of the aquifers than the Tanana basin area.

3.3 Observations

After removing the natural and cultural noise from the water level, we observed distinct signals of water level changes in the wells following each earthquake. The signals

Table 3.1 Well locations and Skempton's coefficients (B) values.

Well Name	Latitude	Longitude	Location comments	B Value
EDOP27	64º 50' 45" N	148 º 00' 23" W	Near Ester Dome, Aquifer: Bedrock	0.2
EDOP21	64º 51' 05"N	148 º 01'11" W		0.14
KB6	61º 17' 26"N	149 º 49' 35" W	Near Anchorage, Aquifer: Alluvium	0.17
MCGR	64º54'34" N	147º38'51" W	Near Fairbanks, Aquifer: Bedrock	0.8
DSAP1	64º46' 03" N	147º 13' 14" W	Southwest of the Chena river, Group I wells of Figure 1.2. Aquifer unconsolidated alluvium	0.062
DSAP3	64º 45' 47" N	147º 14' 18" W		0.065
DSAP4	64º 45' 31" N	147º 13' 08" W		0.07
DSAP6	64º 44' 54" N	147º 15' 17" W		0.05
DSAP7	64º 44' 44" N	147º 14' 39" W		0.07
DSAP8D	64o 44' 35" N	147º 14' 19" W		0.06
DSAP8S	64º 44' 35" N	147º 14' 19" W		0.062
USAP3	64º 44' 23" N	147º 12' 46" W		0.065
USAP5	64º 44' 50" N	147º 13' 12" W		0.06
DSAP9	64º 44' 35" N	147º 17' 20" W	Northeast of the Nenana river, Group II wells of Figure 1.2. Aquifer unconsolidated alluvium	0.02
DSAP10	64º 44' 08" N	147º 16' 20" W		0.01
DSAP11	64º 44' 02" N	147º 15' 04" W		0.02
DSAP12	64º 44' 02" N	147º 18' 26" W		0.02
DSAP13	64º 43' 45" N	147º 17' 21" W		0.02
DSAP14	64º 43' 21" N	147º 16' 38" W		0.01
DSAP15	64º 44' 01" N	147º 19' 38" W		0.01
DSAP16	64º 43' 31" N	147º 18' 39" W		0.01

were most prominent for the Denali fault earthquake and were observed in all the wells. The signals from the other two earthquakes were prominent but were not observed in all the wells. In some of the wells, data were not available during the Nenana Mountain earthquake. Due to availability of data from all the studied wells and very prominent signals, we shall discuss the observations from the Denali earthquake first. The observations from the Nenana Mountain and the Sumatra-Andaman earthquake will follow.

3.3.1 Water level observations following the Denali fault earthquake

We observed coseismic and postseismic water level changes following the Denali fault earthquake in all the studied wells except for DSAP2. The presence of severe uncorrelated noise in the well DSAP2 made it difficult to identify any water level changes after the earthquake.

The EDOP wells, which are drilled into the bedrock, showed a step-like coseismic water level drops and gradual postseismic recoveries in water levels (Figure 3.3). The pattern of changes is the same for both wells. The EDOP27 well, which is slightly closer to the fault, showed a larger water level drop than the EDOP21 well. As discussed earlier, the immediate coseismic water level data from EDOP21 were not available, but the missing data can be estimated from postseismic data using equation 3.1 (Section 3.2).

The DSAP and USAP wells in the Tanana basin (Figure 1.2) experienced two distinctly different types of water level changes. For one group consisting of 10 wells (Group I wells in Figure 1.2), a coseismic step-like water level rise was observed (Figure
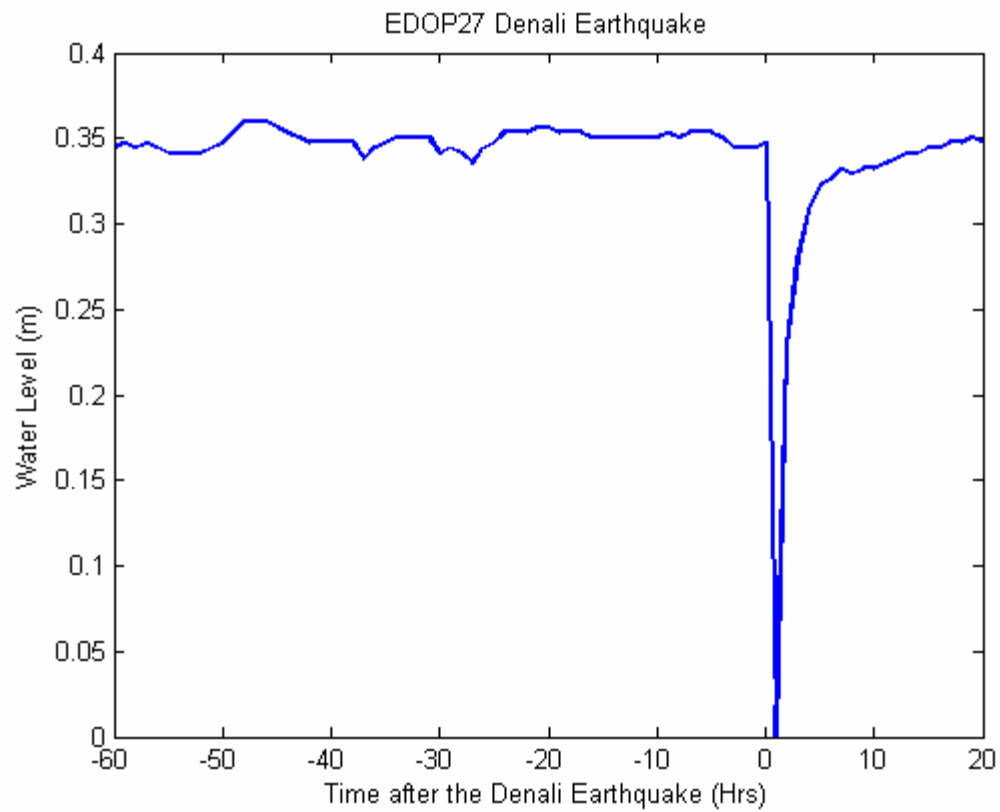
Figure 3.3: Observed water level changes at the well EDOP 27 on Ester Dome after the Denali Fault earthquake. A similar response is also observed from the well EDOP21.

3.4). The patterns of changes are the same as for the EDOP wells but opposite in sign. For the second group (Group II, consisting of 8 wells) transient changes (rise or fall) were observed after the earthquake with the occurrence of spikes in some wells (Figure 3.5). The transient changes lasted for more than a week after the earthquake. Apart from the hydrological responses to the earthquakes, these two groups behave differently during summer seasons with the variation of water levels of the two rivers (Chena and Tanana) situated on the northeast and southwest sides of the cluster of wells (Figure 1.2). This leads us to suspect the presence of a geological barrier between these two groups of wells.

For the well MCGR, we observed an increase in the water level after the Denali earthquake. The increment continued for two hours after the earthquake, and the level came back to its original position after that (Figure 3.6). The water level showed other fluctuations which we could not model using our general data processing scheme.

In the last well KB6, we observed a step-like coseismic increase in water level after the Denali earthquake. This change is the same as the step-like coseismic and gradual postseismic changes of the Group I wells of the Tanana basin area (Figure 3.7), except that the signal to noise ratio is much smaller.

3.3.2 Water level observations following the Nenana Mountain earthquake

Around the time of the Nenana Mountain earthquake, water level data were only available from the wells in the Tanana basin. All the wells in the Tanana basin area responded to the Nenana Mountain earthquake, except for DSAP1 and DSAP2, where
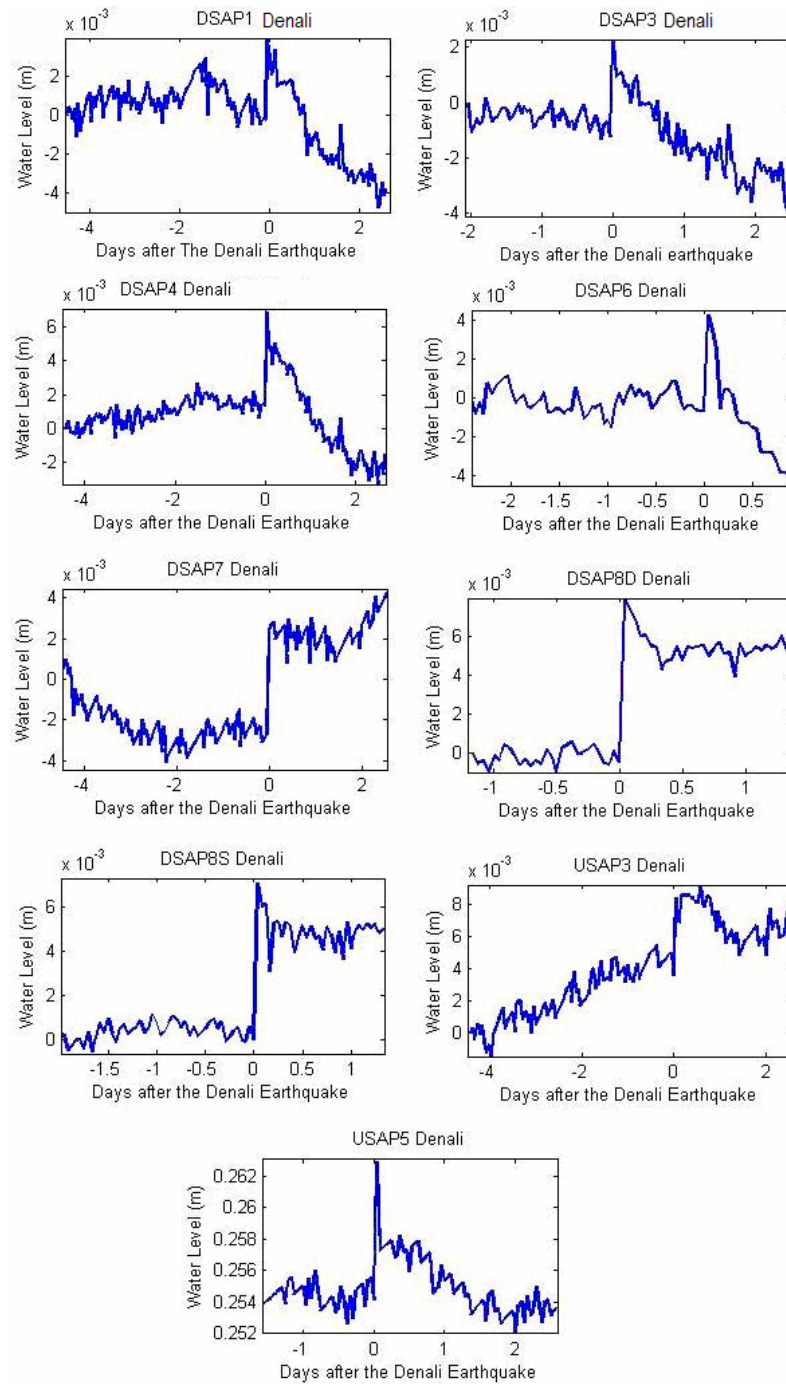
Figure 3.4: Coseismic step like water level changes observed in 9 out of 10 wells of the Tanana basin area after the Denali earthquake. These wells are close to the Chena River and are labeled as Group I in Figure 1.2.
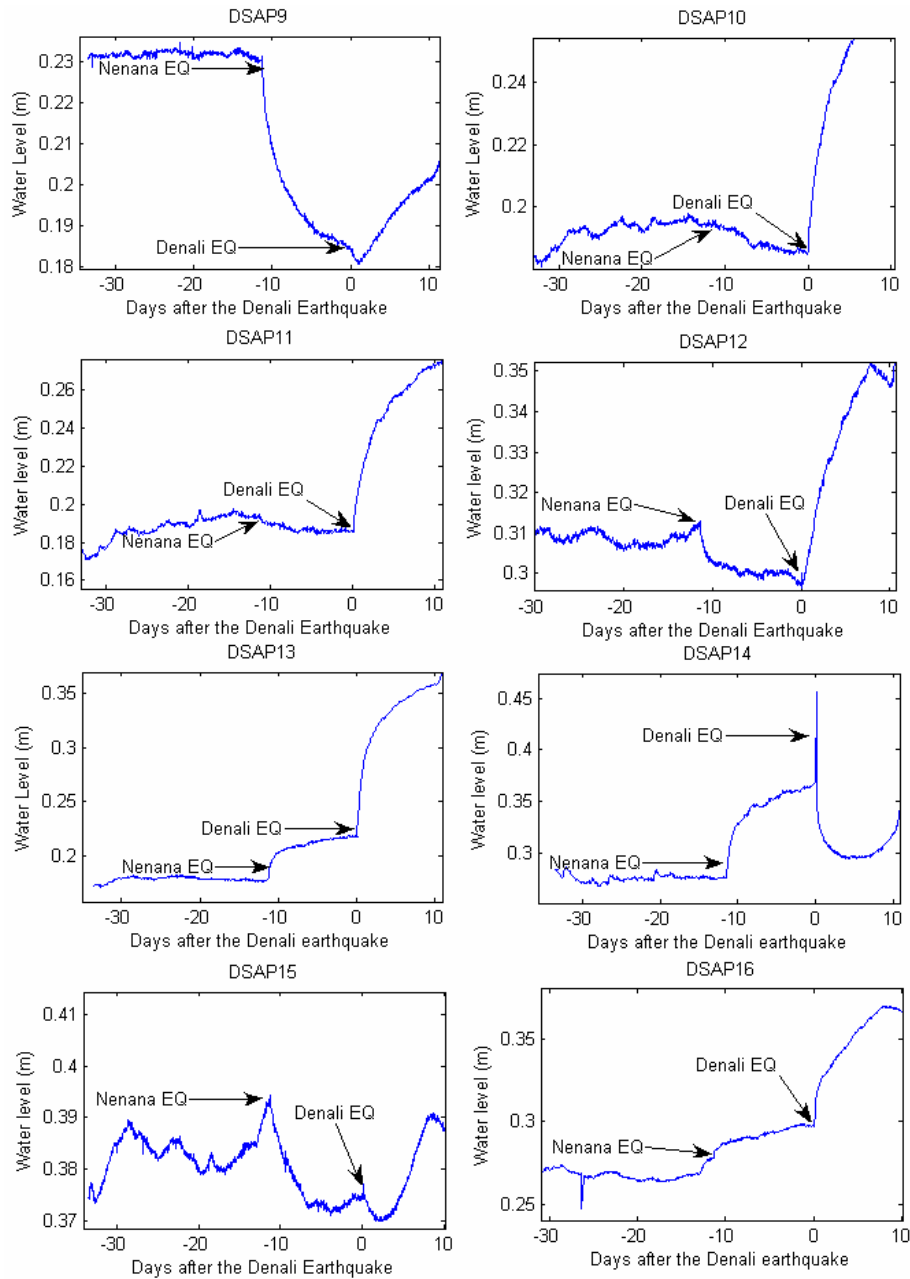
Figure 3.5: Transient water level rise or fall after the Nenana Mountain and the Denali fault earthquakes in the second group of wells of the Tanana basin (Group II). The rise and fall vary from well to well, and the responses to each earthquake have a different sign for different wells.
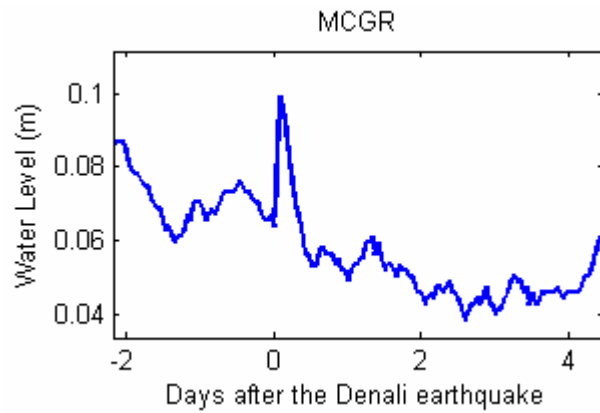
Figure 3.6: Spike-like water level changes in the MCGR well after the Denali earthquake. The increased water level persisted for two hours only.
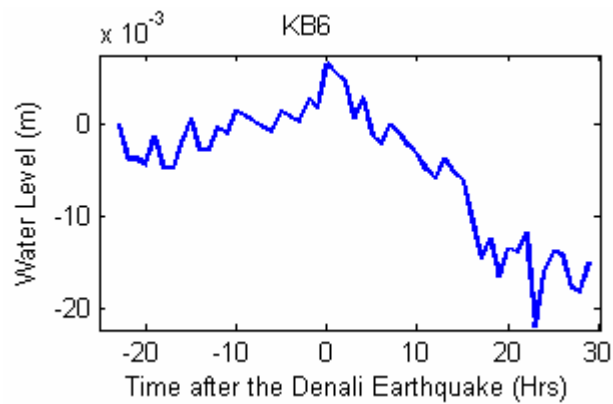
Figure 3.7: Step-like coseismic increase in water level and gradual postseismic decrease in the KB6 well after the Denali earthquake. Data are not are not available for any other earthquakes.

uncorrelated noise made it difficult to identify any changes in water level. The response pattern was similar to the response pattern of the Denali earthquake but different in magnitude. The Group II wells (Figure 1.2) near the Tanana river showed transient changes in water level after the earthquake (Figure 3.5). No apparent coseismic spike was observed in these wells. Just like those following the Denali earthquake, the Group I wells showed step-like coseismic water level increases followed by a gradual postseismic decay (Figure 3.8). No data were available for this earthquake from other studied wells.

3.3.3 Water level observations following the Sumatra-Andaman earthquake

Though the epicenter of the Sumatra earthquake was more than 10000 km away from the study area, we observed water level changes in some wells in Alaska. Water level data during this earthquake were available only from the Tanana basin area wells but with a higher temporal resolution (15 minute interval). The Group I wells (Figure 1.2) responded to the Sumatra-Andaman earthquake. No obvious changes in water level were observed in the group II wells in the Tanana basin area. We observed coseismic spikes followed by a small step-like increase in water level in the Group I wells [Sil and Freymueller, 2006]. Except for the frequent occurrences of spikes and the small magnitudes of the steps, the pattern of water level changes is the same as for the Nenana and the Denali earthquakes. Data from two wells of this group were so noisy that we cannot even identify any changes. The water level rise persisted for more than 2-3 days in all wells (Figure 3.9). Our paper detailing the observations of water level changes following the Sumatra-Andaman earthquake is presented in the Appendix.
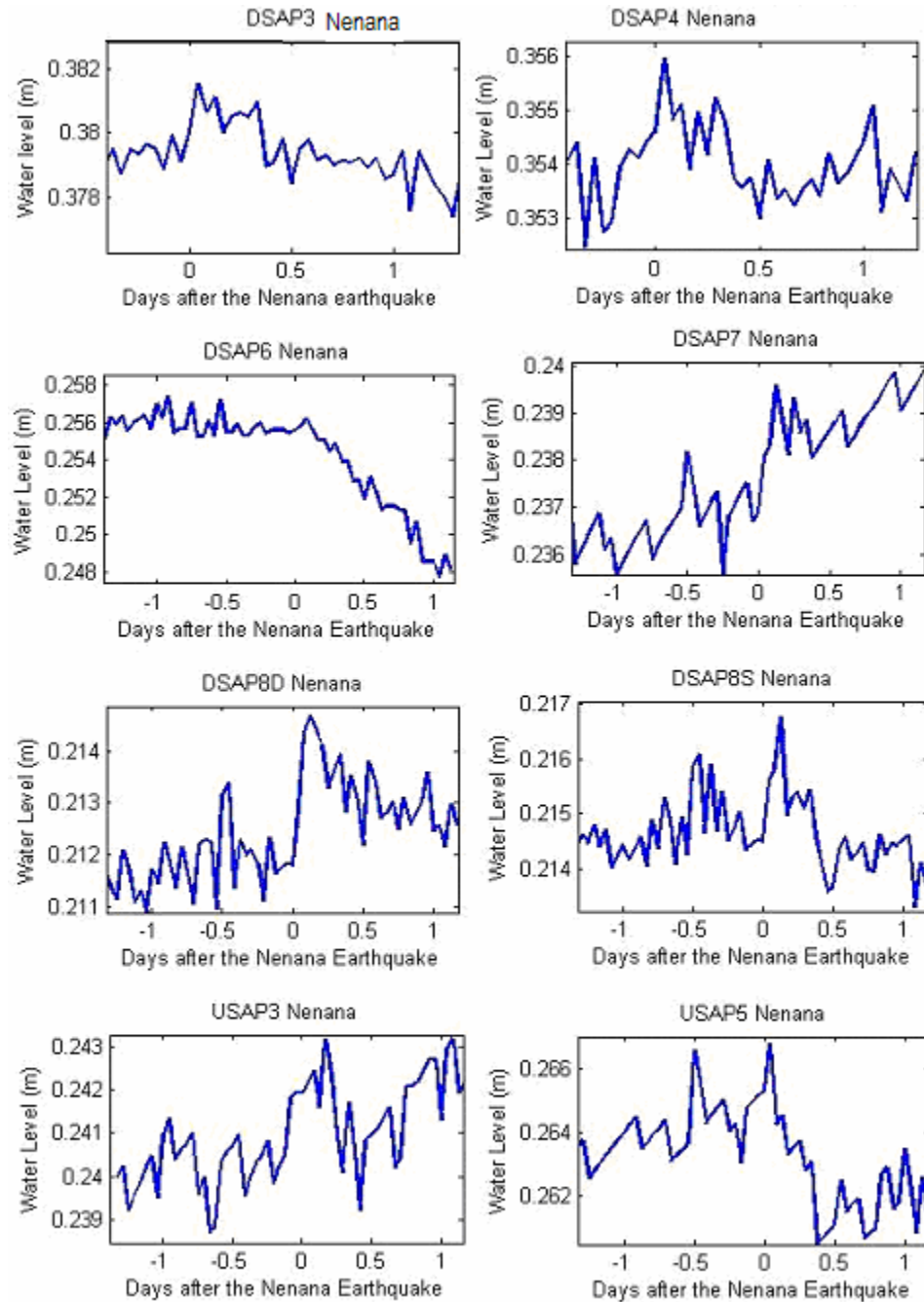
Figure 3.8: Step-like coseismic and gradual postseismic decay responses of 8 out of 10 wells of the Tanana basin area after the Nenana earthquake. These wells are the Group I wells of Figure 1.2.

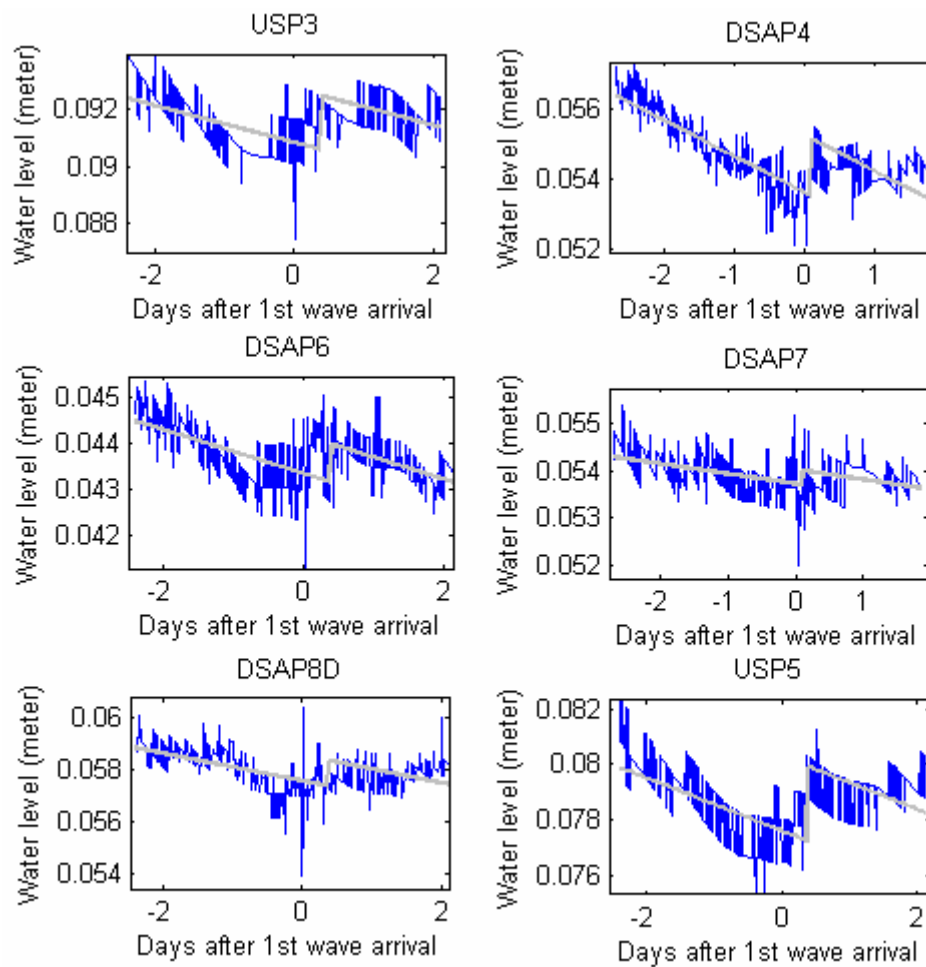Figure 3.9: Observed spike-like and step-like water level changes in Alaska after the Sumatra-Andaman earthquake. In these 6 wells water level changes were quite distinct and were used for further modeling analyses (gray lines). Source: Sil and Freymueller [2006].

4. Analysis of observed water level data

Analyses of the observed water level variations are required to understand the mechanisms behind them. From the observations we find mainly 3 types of water level changes associated with each earthquake. They are 1) coseismic steps followed by postseismic gradual decay, 2) gradual changes in water level following an earthquake, and 3) spike like changes. These kinds of changes have been observed in different cases after many different earthquakes all over the world. In Chapter 2 we have already discussed these mechanisms and the theory and hypotheses associated with them. In this section we quantify the changes in water level for the three studied earthquakes.

4.1. The Denali fault earthquake water level changes

Since changes in water level after the Denali earthquake are the most prominent and are observed in almost all the studied wells, we start our analysis with the Denali earthquake data.

As discussed earlier, for the EDOP wells, the KB6 well and for the Group I wells of Tanana basin (Figure 1.2) we observed step-like coseismic water level changes followed by gradual postseismic changes. We fit the water level time series using a combination of a linear trend (for presesimic), a step function (for coseismic) and an error function (for postseismic) of the form:

$$w(t) = I + St + CH(t - t_o) - Aerfc\left(\sqrt{\tau/(t - t_o)}\right) \tag{4.1}$$

where I (intercept) and S (slope) are constants that describe the linear pre-earthquake trend, C is a constant (magnitude of the step), H is the Heaviside (step) function, and erfc

is the complementary error function. The time of the earthquake is t_o and w(t) is the observed water level at any time t of our timeseries.

We use the least squares technique to fit the water level data from the Denali earthquake (Figure 4.1), and simultaneously estimate all parameters using data both before and after the earthquakes. The value of C obtained from the fitting is our estimate of the coseismic water level change and the values of τ can help us to determine the hydrological diffusivity, which we shall discuss later. We estimate a maximum drop of 0.35 m of water level at the EDOP27 well. The water level drop at the EDOP21 and KB6 wells are estimated to be 0.22 m and 0.0064 m respectively. For the Group I wells of the Tanana basin area, the estimated water level rises and values of τ (hour) are shown in Table 4.1. The maximum water level rise is observed in the well DSAP8D (0.0078 m) and minimum in the well DSAP3 (0.002 m). In this group the average water level rise is estimated to be 0.004 m.

For the other group of wells (Group II of Figure 1.2), we observed gradual changes in water level preceded by a spike (in some wells) following the Denali earthquake. In some wells water level increases, and in other cases it falls. The estimation of water level changes is made using least squares, fitting equation 2.8 to water level time series (Figure 4.2). The result is shown in Table 4.2. The maximum magnitude of water level changes (rise) is estimated at the well DSAP13 (0.167 m) and minimum (fall) at the well DSAP15 (-0.0053 m) for this group of wells. Note that for these wells the magnitude refers to the long-lived transients, not the coseismic step as with other wells.
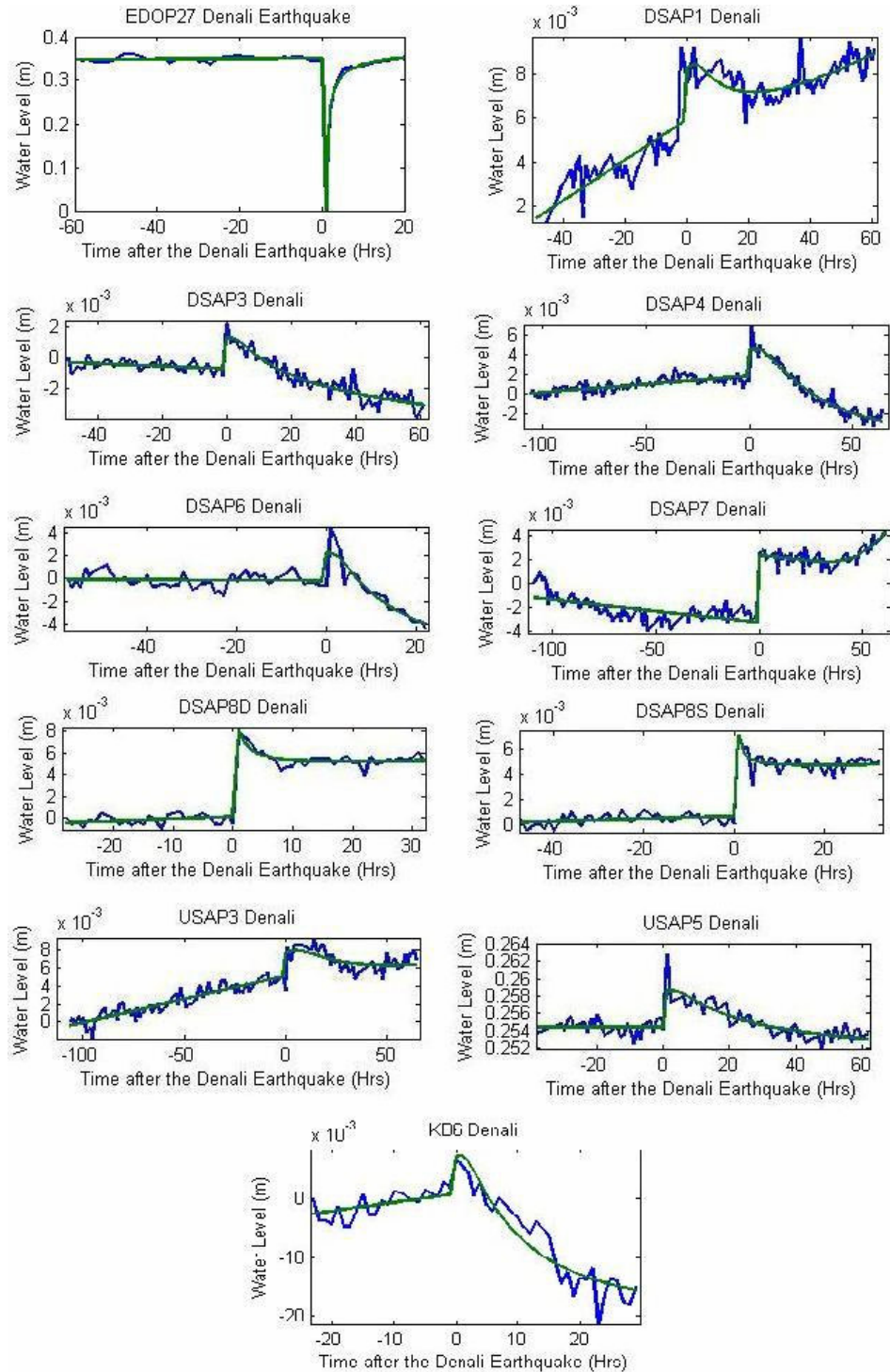
Figure 4.1: Modeled water level data for Group-I wells where coseismic step-like changes were observed, followed by gradual changes in water level, from the Denali earthquake. Blue lines are the observed data and green lines are the model.

Table 4.1: Steps (C) and decay constants (T) of the Group I wells

Well	Denali C (meter)	T- Denali (hour)	Nenana C (meter)	T- Nenana (hour)	Sumatra C (meter)
DSAP1	0.0023	35	0.0017	22	-----
DSAP3	0.002	35	0.0013	22	0.002
DSAP4	0.0027	75	0.0011	12	0.0016
DSAP6	0.0025	27	0.0007	30	0.0008
DSAP7	0.0056	972	0.0014	282	0.0003
DSAP8D	0.0078	3	0.0029	25	0.001
DSAP8S	0.0065	1	0.0022	13	0.0013
USAP3	0.0026	82	0.0007	8	0.0019
USAP5	0.0026	44	0.0018	3	0.0027
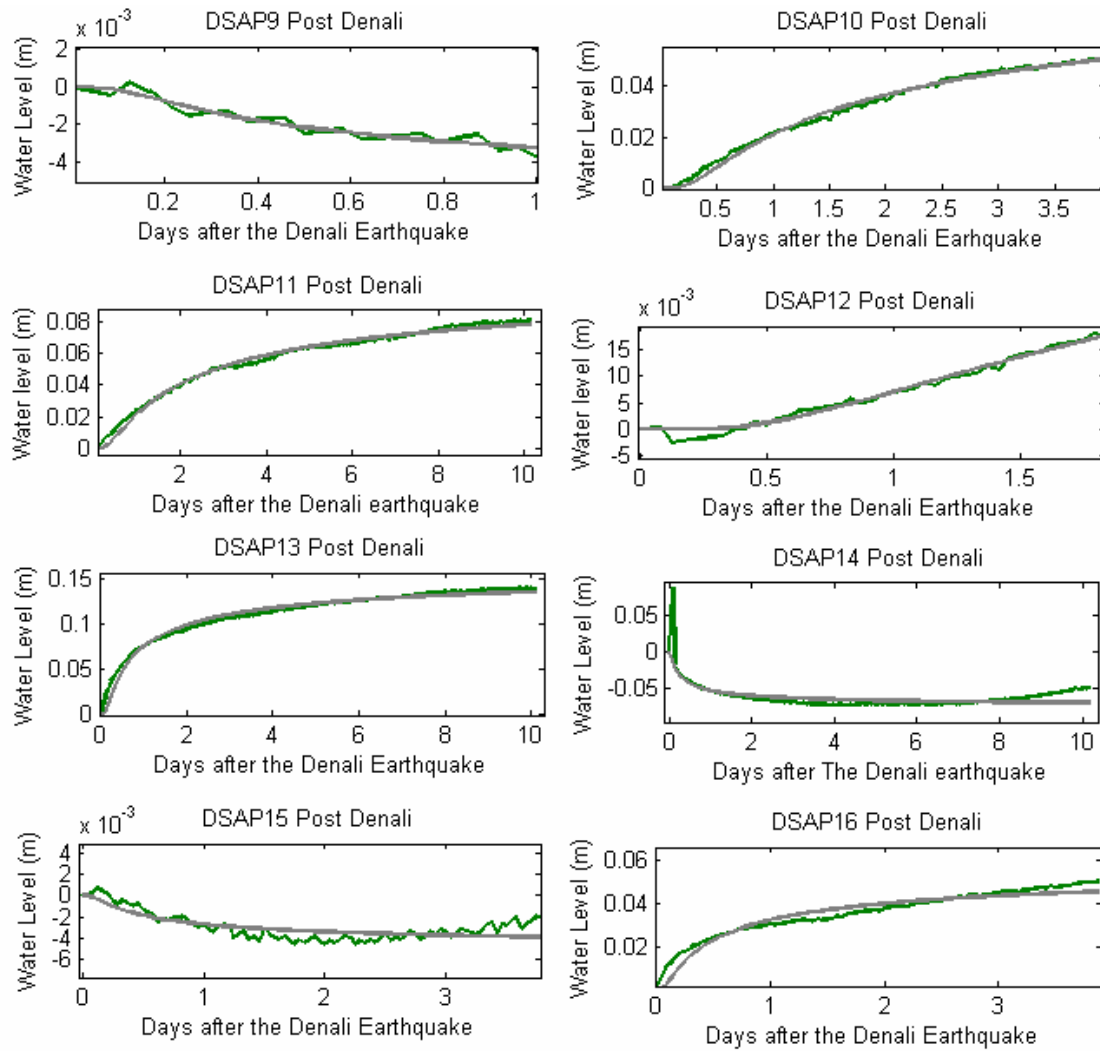
Figure 4.2. Fitting of gradual changes in water level for Group-II wells following the Denali earthquake.

Table 4.2: Amplitude and decay constants (T) of the Group II wells.

Well	Amplitude Nenana earthquake (meter)	T-Nenana (hour)	Amplitude Denali earthquake (meter)	T-Denali (hour)
DSAP9	-0.0602	3091	-0.0067	1444
DSAP10	-0.0033	552	0.0933	4160
DSAP11	-0.0102	2970	0.1157	5112
DSAP12	-0.0153	1056	0.092	9216
DSAP13	0.0461	1681	0.1678	1681
DSAP14	0.1025	1849	-0.0781	625
DSAP15	-0.0296	2916	-0.0053	1260
DSAP16	0.0251	4489	0.0601	1089

We did not fit the water level data from the well MCGR. Because only two data points showed water level changes after the Denali earthquake, we assume those are spike-like signals. Since data from this well are not of very high resolution, we are not able to do any further analysis of the spike-like signals.

4.2 The Nenana Mountain earthquake water level changes

We also estimate the water level changes from the Nenana Mountain earthquake water level data. The estimation procedure is the same as for the Denali earthquake processes. We observed water level changes from the Tanana basin area wells only. The Group I wells showed step-like water level increases followed by gradual water level decreases just like in the case of the Denali earthquake (Figure 4.3). The least squares estimated water level step and the value of τ are shown in Table 4.1. The maximum water level increase is observed in the well DSAP8D (0.0029 m) and the minimum in the well DSAP6 (0.0007 m) with an average of 0.0015 m of water level rise.

For the Group II wells, water level changes were estimated using equation 2.10 just like in the case of the Denali earthquake (Figure 4.4). The maximum water level change was estimated at the well DSAP14 (0.10 m), and the minimum at the well DSAP10 (-0.0033 m). Again these are the magnitudes of the long-lived transient changes.

Water level data were not available from any other studied wells for the Nenana Mountain earthquake.

4.3 The Sumatra-Andaman earthquake water level changes

We analyzed the water level data from the Sumatra-Andaman earthquake using the same technique discussed for the other earthquakes. Obvious step-like water level
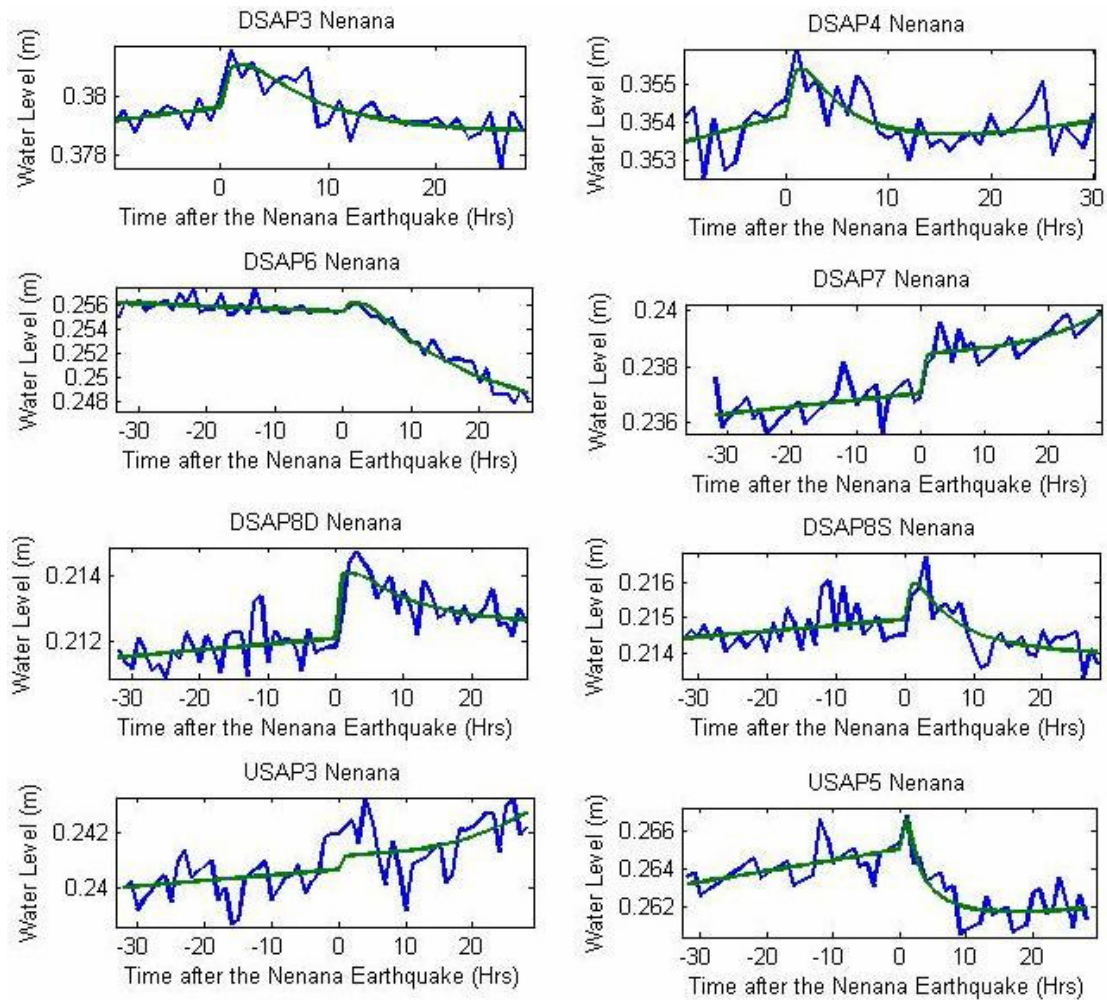
Figure 4.3. Fitting of step-like changes in water level in Group-I wells following the Nenana earthquake. The same group of wells showed step like changes after the Denali earthquake too.
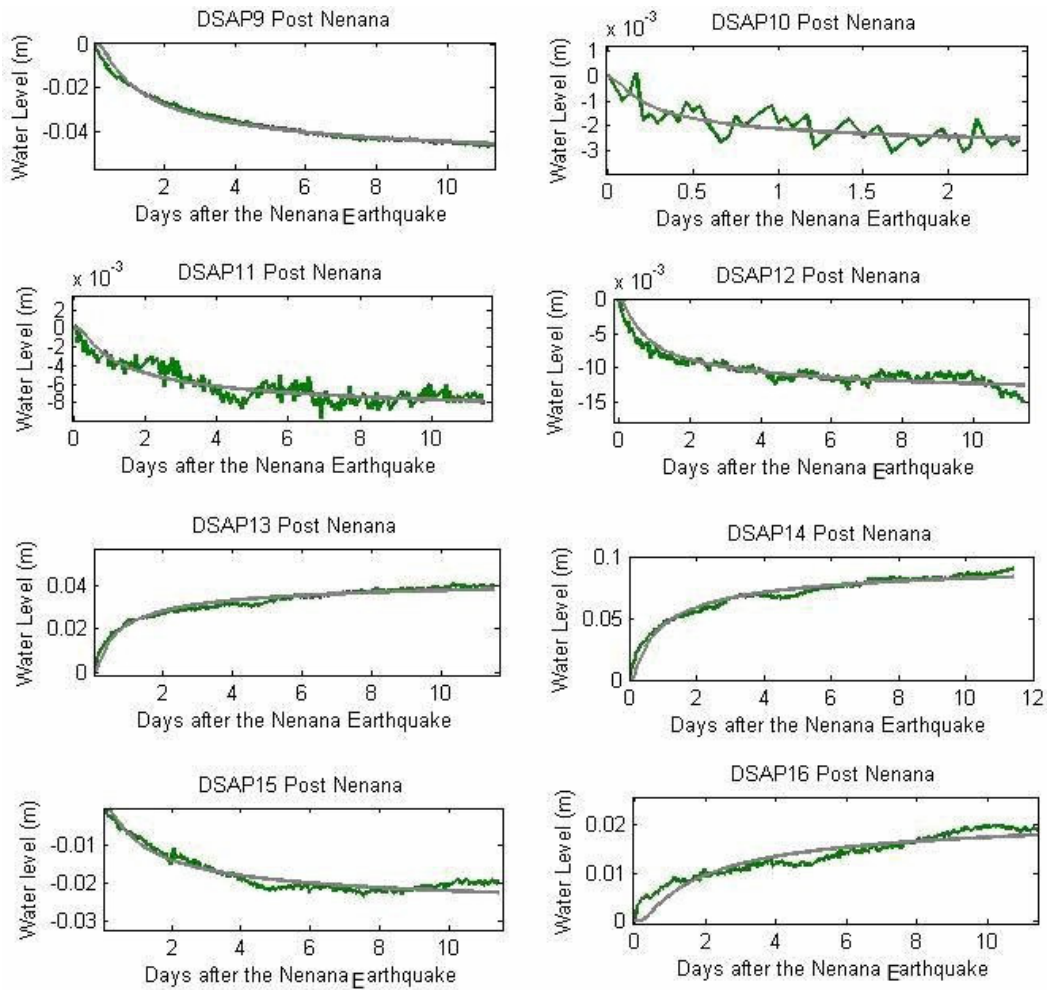
Figure 4.4: Gradual water level changes following the Nenana Mountain earthquake are modeled from the Group II wells of the Tanana basin area. This group also showed gradual changes following the Denali earthquake.

changes were observed only in the Group I wells of the Tanana basin area after this earthquake. But during the Sumatra earthquake water level data were collected at an interval of 15 minutes. The data were also associated with some inherent noise. The presence of this inherent noise and the small signal made it very difficult to estimate the time and magnitude of water level changes. The process of estimation of time and magnitude of step-like water level changes after the Sumatra-Andaman earthquake is discussed by Sil and Freymueller [2006] (Appendix 1). The magnitude of steps varied between <0.001 to 0.0027 m with an average of 0.0014 m (Figure 3.9).

5. Discussion

From our observations and analyses we can conclude that all of the studied wells responded to the Denali earthquake. The Group I and the Group II wells of the Tanana basin area responded to all three earthquakes and the responses to all earthquakes were similar (step-like changes in the Group I wells after all three earthquakes, and transient changes in the Group II wells after the Nenana and the Denali earthquakes). These patterns of water level changes lead us to believe that multiple mechanisms are responsible for changing water level. We also infer that the mechanisms are location dependent (that is aquifer property dependent). In this section we shall discuss the possible mechanisms of water level changes.

5.1. The Denali fault earthquake water level changes

As discussed earlier, we observed step-like water level drops at the EDOP wells, step-like water level rises in the Group I wells of the Tanana basin area and in the KB6 well, transient changes in water level in the Group II wells, and a spike-like increase in the well MCGR after the Denali earthquake.

We first test whether the changes in water levels after the Denali earthquake are due purely to the poroelastic effect. Based on equation 2.5, we expect to see a water level rise where the volumetric strain is compressional, and a water level fall where the strain is dilatational. To test this, we calculated the coseismic volumetric strain (Figure 5.1) based on a high resolution slip model of the Denali earthquake [Hreinsdóttir et al., 2006] and an elastic dislocation model [Okada, 1992]. The EDOP wells lie in the zone of dilatation, and we observed a water level fall after the Denali earthquake. The well KB6
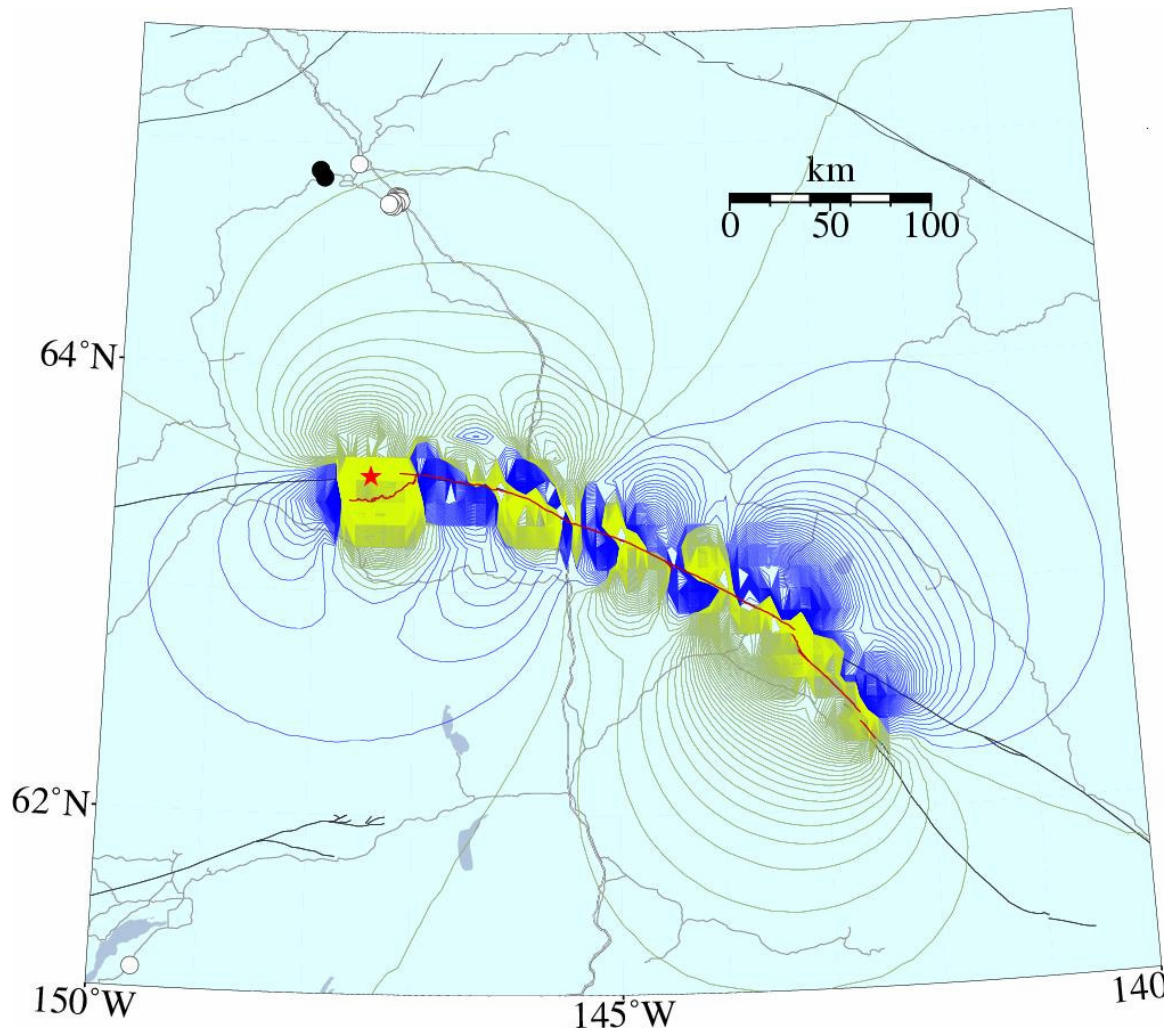
Figure 5.1: Volumetric strain contours based on the Denali earthquake slip model. The blue lines indicate compression and yellow lines indicate dilatation. The black dots are water level falls and white dots are water level rises. The Tanana basin wells and MCGR well showed water level rises even though they are in a dilatation zone.

lies in the zone of compression, and water level increased. These are consistent, at least in sign, with poroelastic theory. The Group I wells of the Tanana basin area fall in the dilatation zone, but we observed a water level rise. The Group II wells of the Tanana basin area, which experienced transient changes, also fall in the dilatation zone. If poroelasticity was the cause of water level changes, we should have observed a step-like fall in water level in those wells. Because we did not observe such changes, we can conclude that poroelasticity is not the main cause of water level changes in the Tanana basin area wells.

From our first order observation we can say poroelasticity can at least explain the polarity of water level changes at the wells EDOP27, EDOP21 and KB6. To make a more quantitative test, we compared the expected water level changes due to the induced volumetric strain using equation 2.5 with our observations (Figure 5.2). The results show excellent agreement between the observations and model predictions. The postseismic decay pattern of the water level in these wells also suggests the gradual diffusion of pore pressure with a characteristic decay constant of 0.5 hours. These two facts lead us to believe that poroelasticity is the cause of water level changes at the EDOP wells and the KB6 well after the Denali earthquake.

The other well where we have observed water level changes is MCGR. MCGR lies in the dilatation zone, but its water level increased for two hours and came back to its original position (Figure 3.6). The B value of the well MCGR is high (0.8), which implies that this well is very confined, so the "Hydroseismogram" phenomenon might be observed in this well. Since no other mechanism can explain the water level changes,
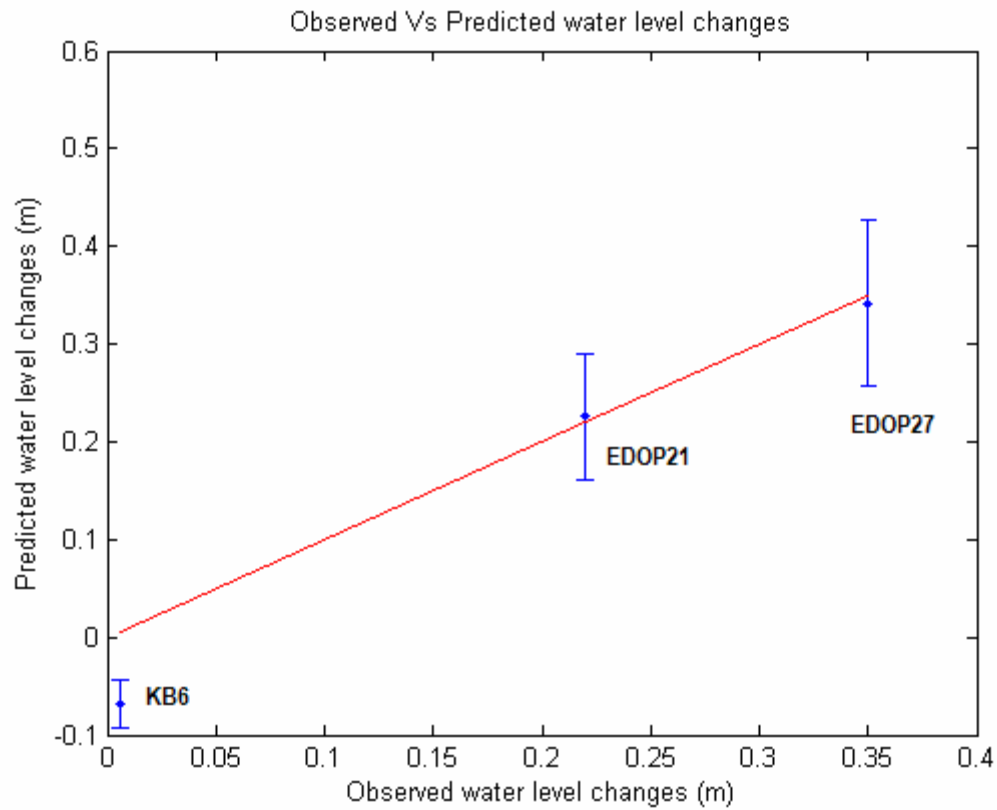
Figure 5.2: Observed versus predicted water level changes using poroelastic theory. The red line shows a 1:1 correspondence. The water level changes in the EDOP wells and the KB6 well are explained well by poroelasticity.

we propose that the water level oscillated as the seismic wave passed the well site. The sudden rise of water level 2 hours after the earthquake may be due to a frequency dependent phenomenon called wellbore storage. We cannot discuss the phenomenon quantitatively as we do not have water level data of sufficient temporal resolution. But qualitatively, in a highly compact aquifer system where tidal effects are negligible a lag in the response of water level can be observed [Roeloffs, 1996]. As MCGR shows the highest B values (0.8) and no response to tidal strain, it has the properties consistent with the requirement for wellbore storage to occur.

5.2. Water level changes in Group-I wells due to all earthquakes

The Group I wells of the Tanana basin area (Figure 1.2) responded to all three earthquakes. The response patterns are similar. After every earthquake we observed a step-like water level increase and a gradual postseismic decrease of water level. These changes are not due to the poroelastic effect, at least for the Denali earthquake. If the changes are due to the poroelastic effect, we should observe an average 12 cm of step like water level drop in this group of wells. For the Nenana earthquake and the Sumatra earthquake these well sites are far field sites (as the distance between source and well site is several times larger than the rupture length of the earthquake) and thus we do not expect any water level changes due to the poroelastic effect [Montgomery and Manga, 2003].

The observed pattern of water level changes in Group I wells from the 3 earthquakes is similar in nature. This leads us to test if there is any statistically significant correlation between water level changes in each well due to all 3 earthquakes. We

summarized the relevant observations of water level spikes in Table 5.1. In this table, each column gives the magnitude of the water level step from each earthquake. So if there is any statistically significant correlation between the rows, then steps due to all 3 earthquakes are correlated for individual wells. If there is any statistically significant correlation between the columns, then changes in all the wells due to an earthquake are correlated. To test this correlation we used the Analysis of Variance (ANOVA) test using the MATLAB software [www.mathworks.com]. The test suggests the correlation across the row is significant. This implies changes in each well due to each earthquake are related to each other. The ANOVA test also suggests that changes in all the wells due to one earthquake are correlated. But the statistical significance of this correlation (correlation between wells) is less than the statistical significance of the correlation between earthquakes.

The Group I wells of the Tanana Basin always showed a step-like water level rise. The occurrence of sudden steps implies a sudden change of pore pressure from an external source of strain. The only reasonable source of this external strain can be the passage of seismic waves. Sil and Freymueller [2006] showed that the occurrence of step-like water level changes in the Group I wells of the Tanana basin area coincide with the arrival time of largest surface waves from Sumatra to Fairbanks (see Appendix). Roeloffs [1998], Matsumoto et al. [2003], and Woodcock and Roeloffs [1996] showed that when a well responds with unidirectional water level changes to several different earthquakes and the cause of water level changes is due to interaction between aquifer and seismic waves, then the relationship between the maximum water level changes (w), the distance

Table 5.1 Water level spikes for each well for each earthquake used in the ANOVA test.

Well	Denali (m)	Nenana (m)	Sumatra (m)
DSAP3	0.002	0.0013	0.002
DSAP4	0.0027	0.0011	0.0016
DSAP6	0.0025	0.0007	0.0008
DSAP7	0.0056	0.0014	0.0003
DSAP8D	0.0078	0.0029	0.001
DSAP8S	0.0065	0.0022	0.0013
USAP3	0.0026	0.0007	0.0019
USAP5	0.0026	0.0018	0.0027

between source of the earthquakes and the well (d), and the magnitude of the earthquake (M in general Mw) may be written as

$$\log_{10}(w) = -X \log_{10}(d) + YM + Z \qquad (5.1)$$

where X, Y and Z are constants. They also showed that the value of X is nearly 2 and the value of Y is always less than X when w is in meters and d is in km.

To test if the group I wells of the Tanana basin follow this empirical relation we took the average water level steps from the Denali, Nenana and Sumatra earthquakes (0.0038, 0.0015 and 0.00145 m respectively, averaged over all wells). Because the wells are so close together, we use only a single average w and d for the group. For the values of source distances (d) we used the distance between the epicenter of the Nenana Mountain earthquake and center of the group I wells, the distance between maximum slip point of the Denali earthquake (near the eastern end of the rupture zone on the Denali fault) and the center of the wells, and the epicentral distance of the Sumatra earthquake from the center of the wells. We fixed the value of X to 1.84 based on Roeloffs [1998] and inverted for the values of Y and Z of equation 5.1. The least squares inversion obtained the following equation (Figure 5.3):

$$\log_{10}(w) = -1.84\log_{10}(d) + 1.21M - 6.8 \qquad (5.2)$$

Roeloffs [1998] and Matsumoto et al. [2003] used data from several earthquakes to determine equation 5.1 and their inversion (without fixing the value of X) returned X=1.84. Though the two studies were made in different parts of the word, the value of X was almost the same for both.
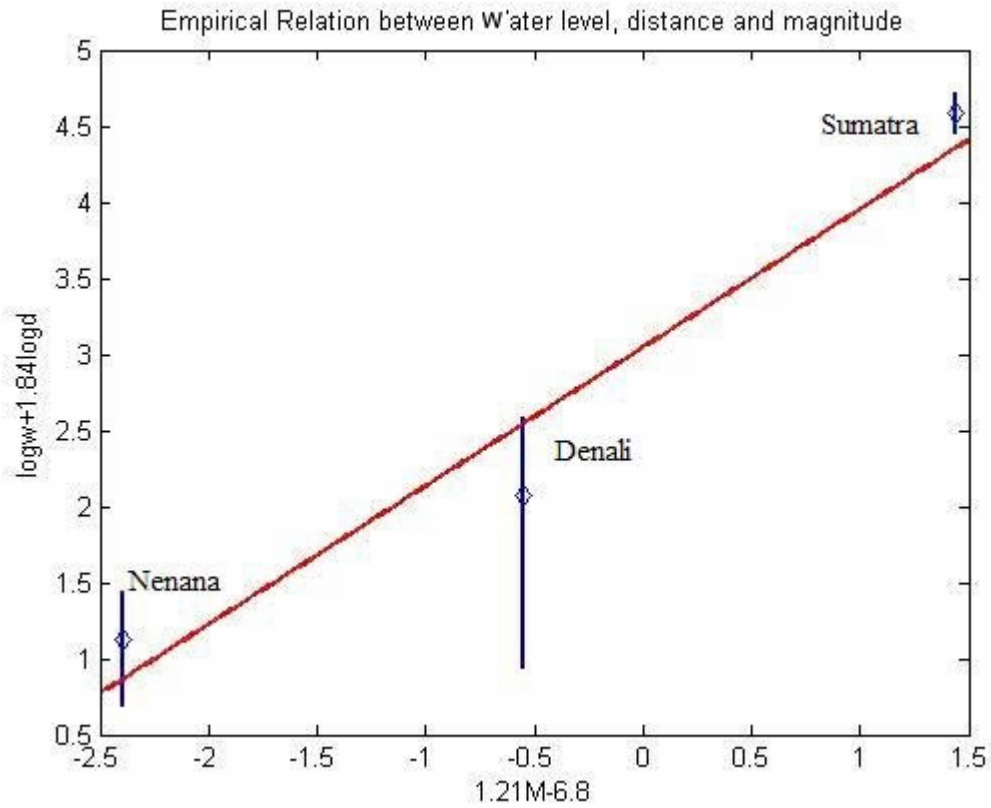
Figure 5.3: Relation between water level steps and the source distance and magnitude of the earthquake for the Group I wells. This relation indicates the water level changes are inversely proportional to the source distance and directly proportional to the magnitude of the earthquake. The relationship gives more weight to the distance than to the magnitude. The uncertainties are combined uncertainties of w and d. The uneven error-bar for the Denali earthquake indicates the westward variation of maximum slip point on the rupture length.

We have data from 3 earthquakes only, so the inversion problem is not over-determined and might return physically non realistic values of X. By fixing the value of X to 1.84, we overcome that problem. We also performed the inversion without fixing the value of X. According to the F test, the improvement in the fit to the data by estimating the additional parameter is significant only at the 50% confidence level. Thus we prefer to use the value obtained by Roeloffs [1998] as the value of X for developing the empirical relation for the Group I wells.

Equation 5.2 suggests that the water level changes in Group I wells follow similar empirical relationships to that observed in different parts of the world, where unidirectional water level changes were seismic-wave induced. This equation can also help us to find a threshold criterion for when water level changes due to earthquakes at different distances from Fairbanks will be observable. The resolution of the water level measurement system is 0.0003 m. So we can assume that if there is a change of water level of 0.0006 m (twice the magnitude of the resolution of the system) due to any earthquake, the instrument might record it. Putting the value of w=0.0006 m in equation 5.3 we obtain the threshold criterion of response of this group of wells as

$$1.84 \log_{10}(d) = 1.21M - 3.58 \tag{5.3}$$

which suggests that if there is a magnitude 6 earthquake within a radius of 100 km from the center of the wells, then it will generate a detectable step-like water level increase in this group of wells.

Equation 5.3 is empirical and determined by fixing the value of X to a standard value. The slightest variation in the value of d can lead to different results which are still

within the acceptable range of mismatch. For the validation of equation 5.3, we have to wait for at least one magnitude 6 earthquake within 100 km radius of the Group I wells. However our work suggests that it is possible to fit the observed data with equation 5.1 and thus it verifies the wave induced source of water level changes.

Once we verified the cause of water level changes (wave induced), we tried to understand the mechanism. Dynamic strain generated by ground shaking from an earthquake can consolidate an unconsolidated aquifer (a phenomenon just like liquefaction) by loading the unpacked matrix material of the aquifer [Manga et al., 2003]. This shaking-induced consolidation will increase the relative pore pressure at the well sites by reducing the pore volume. The Group I wells are drilled into unconsolidated sediments of Chena alluvium, so a dynamic strain induced pore pressure increment (and thus water level rise) is a plausible mechanism to explain the water level changes in this group of wells. Since dynamic strain reduces the pore volume no pore pressure decrement is expected from poroelastic effect. Thus we do not observe a 10 cm spike-like water level rises in this group of wells as poroelastic theory would predict. Dynamic strain is proportional to the horizontal ground velocity [Terzaghi et al. 1996].

To test whether the changes are due to dynamic strain or not, we calculated the peak horizontal ground velocities for the Denali, Nenana and Sumatra earthquakes from the seismogram from the broadband station COLA situated in Fairbanks. We use the digital data from the IRIS website (in SAC format) and calculate the peak horizontal velocities by using a MATLAB code [http://gcc.asu.edu/mthorne/saclab]. The frequencies of peak ground velocities for the Denali and the Nenana earthquakes were

almost the same (nearly 6 Hz) but the frequency for the Sumatra earthquake was much lower (~0.05 Hz). Our calculation obtained peak ground horizontal velocities of 7.27, 2.45 and 1.27 cm/sec for the Denali, Nenana and Sumatra earthquake respectively. There is another strong motion station (CIGO) situated in Fairbanks and almost in the same location as COLA. USGS has published peak horizontal velocities of the Denali and the Nenana earthquake using the data from this station [http://nsmp.wr.usgs.gov/events. html#2002]. To check the performance of our velocity calculation, we compare our calculated velocities from COLA with the velocities calculated by USGS at CIGO which are 9.49 cm/sec and 3.77 cm/sec for the Denali and Nenana earthquakes respectively. We plot the horizontal peak ground velocities (v) from COLA with the mean water level changes (w) for all 3 earthquakes (Figure 5.4). The plot shows an excellent linear relationship between w and v. This helps us to conclude that dynamic strain is the cause of water level changes in Group I wells [Wang et al. 2001; Manga et al. 2003].

5.3. The Denali earthquake and the Nenana earthquake water level changes

The Group II wells of the Tanana basin area responded only to the Nenana Mountain and Denali earthquakes. A gradual water level change (increases in some wells and decreases in others) was observed over duration of several days. The long duration of the changes rules out induced strain (static or dynamic) as the direct cause of water level changes. However, the changes could be caused by opening or closing nearby fractures [Brodsky et al., 2003], which triggered the flow of water to reach equilibrium given the new flow paths. To test this mechanism, we fit the changing water level data using equation 2.10 and obtain the value of τ (Table 4.2). The relatively large values of τ for
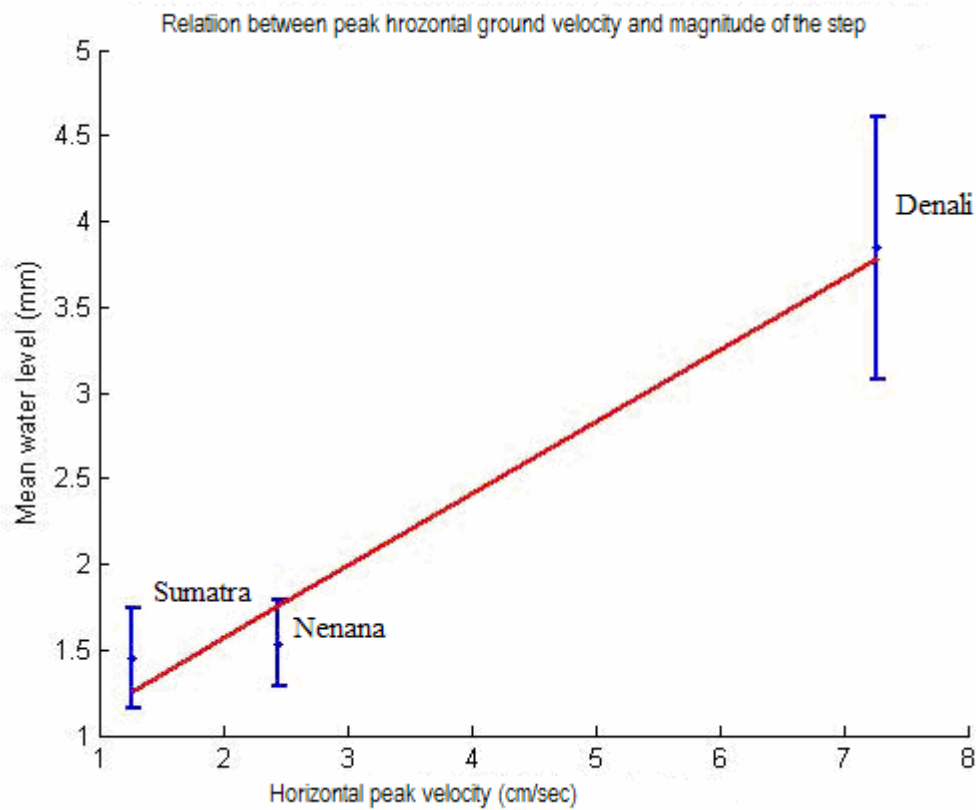
Figure 5.4: Relation between peak horizontal ground velocity and water level rise for the Group I wells. The linear trend (red line) indicates shaking induced dynamic strain is responsible for the changes in water level in Group I wells. We plot the mean values of the steps. Error bars are the standard deviations of the data.

this group of wells (average 2325 hours for the Nenana earthquake and 3073 hours for the Denali earthquake) indicate that the fracture (at depth z of equation 2.11) is outside of the wells. We cannot calculate an exact value of z because the value of the hydraulic diffusivity (c) is unknown. We fit the postseismic responses of the water levels of the Group I wells using the same technique and the value of τ is much lower (141 and 43 hours respectively for the Nenana and the Denali earthquakes, respectively) for Group I wells compared to Group II wells. The high value of τ for Group II wells indicates a high value of z (equation 2.11) which is only possible for a shallow well (average depth of this group of wells is 5 m) if it is connected with fractures [Brodsky et al. 2003].

The Skempton's coefficient (B) for this group of wells is extremely low (0.015), which indicates that the aquifer is very poorly confined by the underlying permafrost layers. Ground shaking due to large earthquakes can very easily create multiple fractures in the permafrost layers. King et al. [1999] and Brodsky et al. [2003] suggested that fracture cleaning can cause transient water level changes after a large earthquake. We propose that the same mechanism was responsible for the water level changes in the Group II wells. We assume for this group of wells that the disrupted matrix of the aquifer was not good enough to show any poroelastic effect.

6. Conclusions

We observed water level changes in several ground water wells in Alaska after the Nenana Mountain, Denali fault and Sumatra earthquakes. The mechanisms of water level changes were different in different wells, and we can group the studied wells based on their mechanisms of water level changes.

One group consisting of the EDOP wells and the KB6 well responded according to poroelastic theory after the Denali earthquake. These wells are drilled into moderately confined to confined aquifer systems (as the average B value is 0.13). Water level data were not available from these wells after the Nenana Mountain and the Sumatra earthquake. But considering the source distances, we do not expect that poroelastic effects could change the water level of this group after these earthquakes. The well EDOP27 showed the highest change in water level (0.35 m).

The second group of wells is part of the Tanana basin wells (Group I wells of Figure 1.2, consisting of 10 wells) situated southwest of the Chena river. This group of wells showed a step-like water level increase after all three studied earthquakes, which cannot be explained by poroelastic theory. Water level changes are nearly proportional to the inverse square of the distance to the source (precisely $d^{-1.84}$), and are directly proportional to the magnitude of the earthquake. Wells of this group are moderately to poorly confined (as the average B value is 0.07) and are drilled into unconsolidated sediments. The water level rises from the 3 earthquakes in this group are proportional to the horizontal ground velocities of the earthquakes. So we propose that ground shaking

induced loading consolidated the sediment and created a localized compression that caused water level to rise after every earthquake.

The Group II wells (consisting of 8 wells in the Tanana basin area) showed a transient water level rise or fall after the Nenana Mountain and the Denali earthquakes. The changes were gradual and lasted for several days. We determined the decay constant by fitting the transient part of the changing water level. The relatively high value (2325 hours for the Nenana and 3073 hours for the Denali earthquake) of the decay constants for this group of wells suggests that fractures located some distance from the wells were opened or closed by the ground shaking. These wells are drilled into a poorly confined aquifer system (lowest average B value of 0.015), and ground shaking by the earthquakes can easily create fractures in the confining permafrost layers. We propose that the ground shaking due to the earthquakes either created fractures or cleaned up some clogged fractures to generate new water flow pathways, which altered the pore pressure gradients. The locations of the fractures could be varied from earthquake to earthquake and well to well. Water levels may rise or fall depending on the direction of increased water flow.

Finally, the well MCGR is drilled into a confined aquifer system (B value 0.8) and showed spike like water level changes. Since the aquifer is very well confined, the "Hydroseismogram" phenomenon might be observed in this well along with wellbore storage. The temporal resolution of the data was not good enough to observe the entire seismogram on the water level or to determine the wellbore storage effect.

We observed 4 different types of water level changes, in 4 different locations in Alaska. Though wells in the Tanana basin area are close together, based on our study we

can classify them into two groups. Similarly, though the EDOP wells and the MCGR well are situated in same terrane, their characteristic responses are different. We observed poroelastic effects in the EDOP wells and the KB6 well, which are comparatively far from the source of the Denali earthquake. This implies that the poroelastic response of the Denali earthquake had a large area of impact. In any geophysical study, generalizations often are made to simplify the problem. This study shows that even in a small area (near Fairbanks) several processes were responsible for water level changes, rather than a single process that is easily generalized.

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Appendix

Well water level changes in Fairbanks, Alaska, due to the great Sumatra-Andaman earthquake.

ABSTRACT

The Mw 9.3 great Sumatra-Andaman earthquake of December 26, 2004 induced water level changes in Fairbanks, Alaska, at an epicentral distance of 10,800 km. Spike like water level changes followed by a step of water level rise were observed in at least four wells. We modeled the timing and magnitude of the water level rise using a combination of a linear trend and a step function. We calculated the misfit between the observed water level rises and our model by systematically shifting the timing of occurrence of step in water level. The minimum value of cumulative misfit suggested the timing of occurrence of steps.

A previous study showed persistent water level rises in all these wells from the 2002 Denali fault earthquake and it's major aftershocks. From those observations, we developed an empirical relationship between water level changes, epicentral distances and earthquake magnitude. This relationship attributed water level changes in the wells to ground shaking by seismic waves. The estimated average water level changes due to the Sumatra earthquake using that relationship was in agreement with the observed water level changes. Thus we concluded that ground shaking in Fairbanks, induced by surface waves from the Sumatra earthquake was sufficient to change water levels.

Introduction

Seismic waves from a distant earthquake can produce water level changes in groundwater wells. Several models have been postulated to describe the processes of water level changes (Roeloffs, 1998, King et al., 1999, Brodsky et al, 2003, Montgomery et al., 2003). During the November 2002, Denali fault earthquake (Mw 7.9) and its aftershock sequence, we observed water level changes in 23 groundwater monitoring wells in Fairbanks, Alaska (Sil and Freymueller, manuscript in preparation). Among those 23 wells, 10 wells showed step like water level rises which persisted for a few weeks. A combination of poroelastic theory and aquifer property changes induced by ground shaking (Roeloffs, 1998) explained the observed step like water level rise. The empirical equation for water level changes due to ground shaking in those ten wells, obtained from the sequence of Denali earthquakes, suggested that the seismic waves from the December 2004, Mw 9.3 (Ms 8.9) Sumatra-Andaman earthquake (Stein et al, 2005) might also have measurably changed the water levels. West et al, (2005) showed that seismicity was triggered at Mount Wrangell volcano, Alaska, at the onset of the arrival of surface waves from Sumatra. These two facts led us to investigate the changes in groundwater level in Fairbanks after the Sumatra-Andaman earthquake.

Well settings, instrument

The 10 ground water wells we studied were all drilled into Quaternary Chena alluvial deposits. The aquifer system is unconsolidated and is considered as confined because of the presence of a permafrost layer and seasonal frost layer during winter [Personal communication with Edward Plumb, Hydrologist, National Weather Service].

The area of investigation falls in the Tanana Valley area of Alaska, which is covered by thick deposits of alluvium and loess. The whole valley is surrounded by an upland consisting of fractured bedrock metamorphic schist (Anderson, 1970) of the Yukon-Tanana terrane. The well locations are plotted in figure 1. The wells were monitored by the USGS water Resource Division office in Fairbanks. Water level data are collected at an interval of fifteen minutes in all the wells. Submersible pressure transducers were used to measure the water level data with an accuracy of 0.3 mm.

Background Work and Present Observations:

While investigating the water level changes in those same 10 USGS wells due to the 2002 Denali fault earthquake, we obtained an empirical relationship between water level rise due to ground shaking and distance from the point of maximum slip on the Denali fault (figure 2):

$$\log (w) = -1.8032 * \log (d) + k \tag{1}$$

Where (w) is the water level rise, (d) is the distance of the well from the point of maximum slip on the fault and (k) is a constant. The constant (k) can be written as a function of the magnitude of the earthquake (Roeloffs, 1998). We studied the water level rises from several local earthquakes and got the empirical relation:

$$k = M - 4.45 \tag{2}$$

Where (M) is the magnitude of the earthquake (Ms, where the data are available). Substituting equation 2 into equation 1, we obtained an empirical relationship between (w), (d) and (M):
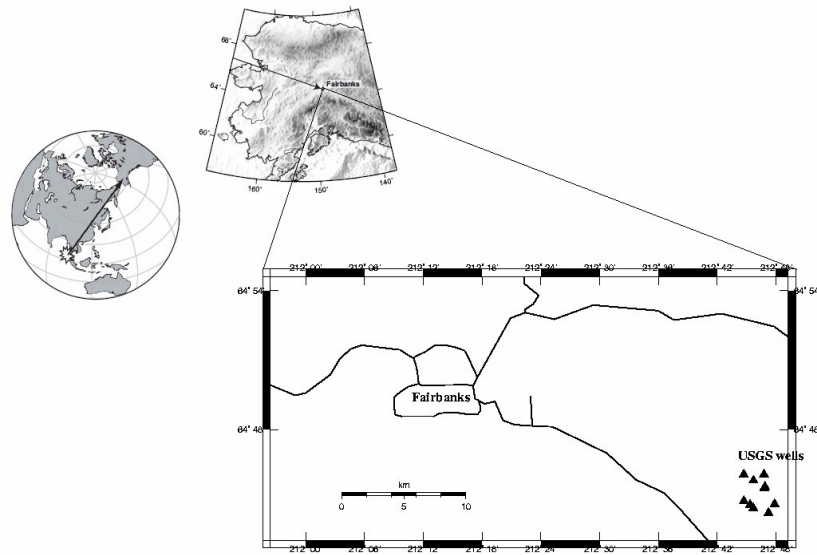
$$\log (w) + 1.8032 * \log (d) = M - 4.45 \tag{3}$$

Figure 1: Location of the studied USGS wells and wave path from Sumatra to Fairbanks, Alaska, after the earthquake. The wave path was mostly continental (West et al., 2005).
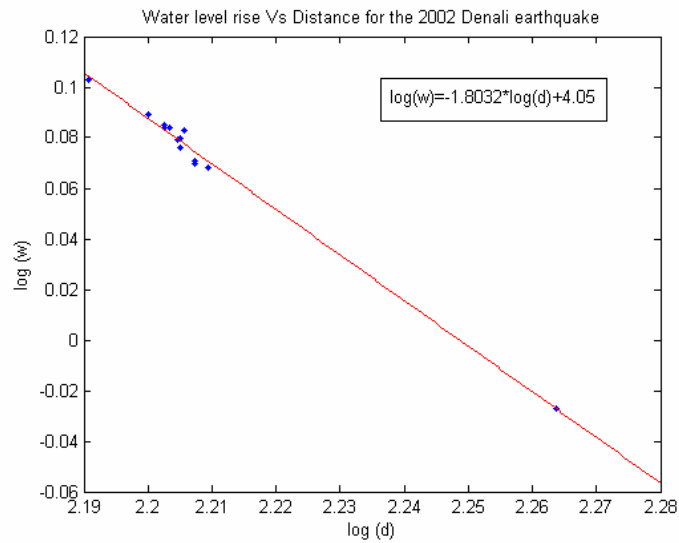

Figure 2: Log water level rise in the same wells as a function of log distance from the maximum slip point on the Denali fault, after the 2002 Denali earthquake. Some of the wells were omitted in the present study, because of the very low temporal resolution of the data. The relationship suggests that water level rise is inversely proportional to the square root of the distance.

Similar empirical relations were obtained for the wells in Japan and California after local and distant earthquakes (Roeloffs, 1998, Matsumoto et al., 2003).

Equation (3) suggests an expected average water level rise of ~1.5 mm in the studied wells due to the Sumatra-Andaman earthquake. Though the resolution of water level measuring system is high enough to determine a water level change of this magnitude, the inherent noise in the data make it difficult to visualize the changes from raw water level data. We corrected the water level data for atmospheric and tidal effects. No correlation with precipitation was found, probably because precipitation in winter remains frozen at the surface. Figure 3 shows the uncorrected and corrected water level data for more than one month for the DSAP 6 well. During correction, we obtained an average Skempton's coefficient (B) value of 0.02. The low B value may indicate that the wells were not perfectly confined during the winter of 2004.

Among the 10 wells, coseismic water level changes were distinctly identified in all of the wells. In most wells, we observed a distinct spike like water level changes followed by a step like water level rise (figure 3). The water level rise persisted for more than 2-3 days in all 10 wells. Since the spike like water level changes were distinct, the timing of the occurrence of the spike was determined easily; it coincided with the arrival of first seismic waves from Sumatra. But because of the presence of inherent noises in the water level, the timing of the step was more difficult to identify.

To identify the timing of steps, we assumed that over a over a short period including the earthquake, the water level could be modeled using a combination of a linear and Heaviside (step) function of the form:
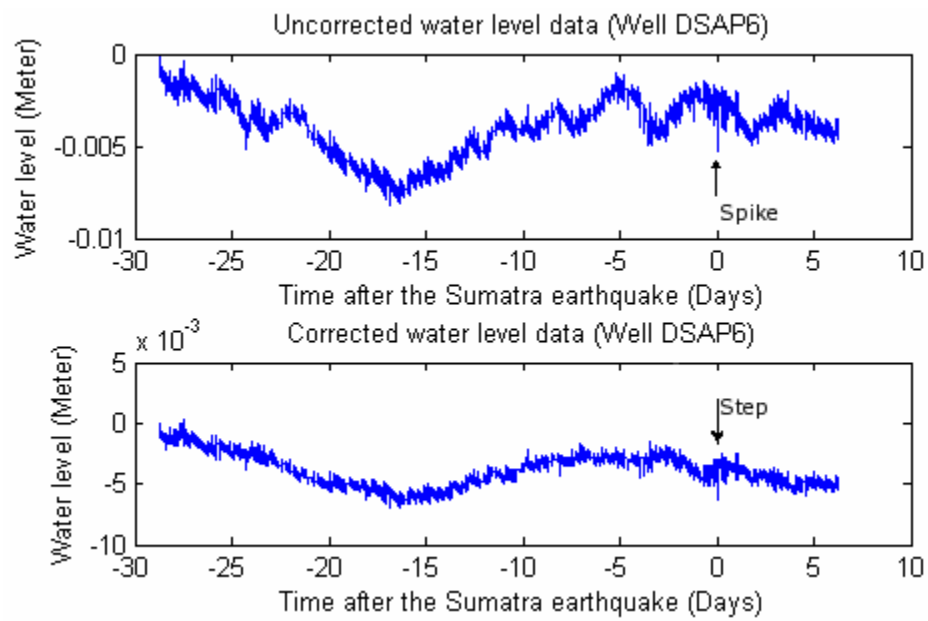
Figure 3: More than one month of water level data from the well DSAP6 (December 2004). Uncorrected water levels are shown in the top panel. A spike like change during the earthquake is visible even in the uncorrected data. In the bottom panel atmospheric and tidal force corrected water level data are shown. Though small in magnitude, a step is quite clear in the corrected data.

$$w(t) = A + B*t + C*H(t- t_0) \tag{4}$$

Where $w(t)$ is the observed water level at any time t, A and B are constants, t_0 is the time of occurrence of the step in the water level, C is the magnitude of water level rise and H is the Heaviside function. Four of the wells showed strong variability in water level or high noise levels both before and after the earthquake, and were not useful in constraining the timing of the steps. For each of the 6 remaining wells we selected 5 days of water level data (2.5 days before and 2.5 days after the earthquake). We fit the data from each well using equation (4), and calculated the misfit by gradually changing t_0 from $t(1^{st}$ day,1st data point) to $t(5^{th}$ day, last data point). The misfit was then normalized by the misfit to a model with no step (linear trend only). This makes the fractional improvement in misfit relative to a model with no step obvious. Misfit in models with a step was generally 25-40% lower than its models with no step. The total cumulative error (E) is:

$$E= (1/i)*\sum s(t)_i/max(s(t)_i) \tag{5}$$

Where $s(t)_i$ was the misfit of ith well (i=1 to6, for 6 wells). Because of the normalization, misfit from each well had equal weight. We assumed the minimum E corresponded to the timing of the offset in the water level. In Figure 4, we plot E as a function of time. We also plot the cumulative misfit for the well DSAP4 and USP5 where the water level changes were largest. In the same figure, the vertical component seismogram from GSN station COLA is shown. A step like increase in water level occurred in between UTC time 02:00 to 02:30 of December 26th, 2004, during the passage of largest surface waves from Sumatra. In figure 5 we plot the 5 days of water level data along with the best fit
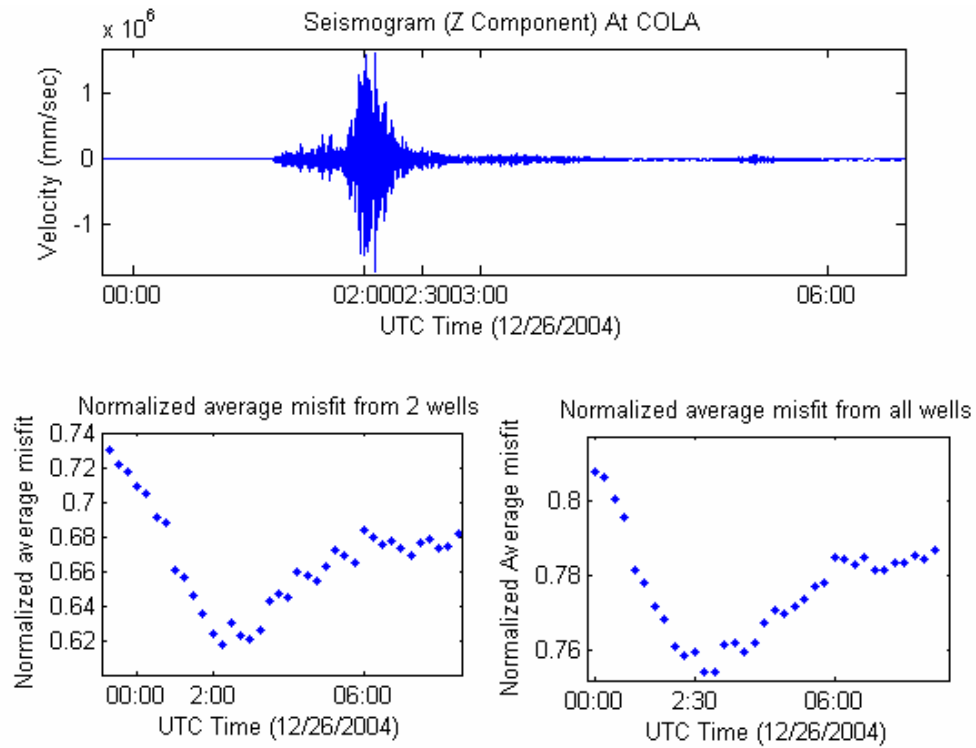
Figure 4: Misfit between observed data and our model, estimated by varying the timing of step function change in each well. Bottom left is the combined misfit from well DSAP4 and USP5 (where magnitude of the steps are maximum), which suggests step occurred at 02:00 UTC time of 12/26/2004 (minimum error). Bottom right is the cumulative normalized misfit from all the wells, suggesting in most of the wells, step occurred at 02:30 UTC time of the same day. In the top, seismogram (vertical) from GSN station COLA. In between time 2:00 and 2:30 the largest surface wave from Sumatra was passing through Alaska.
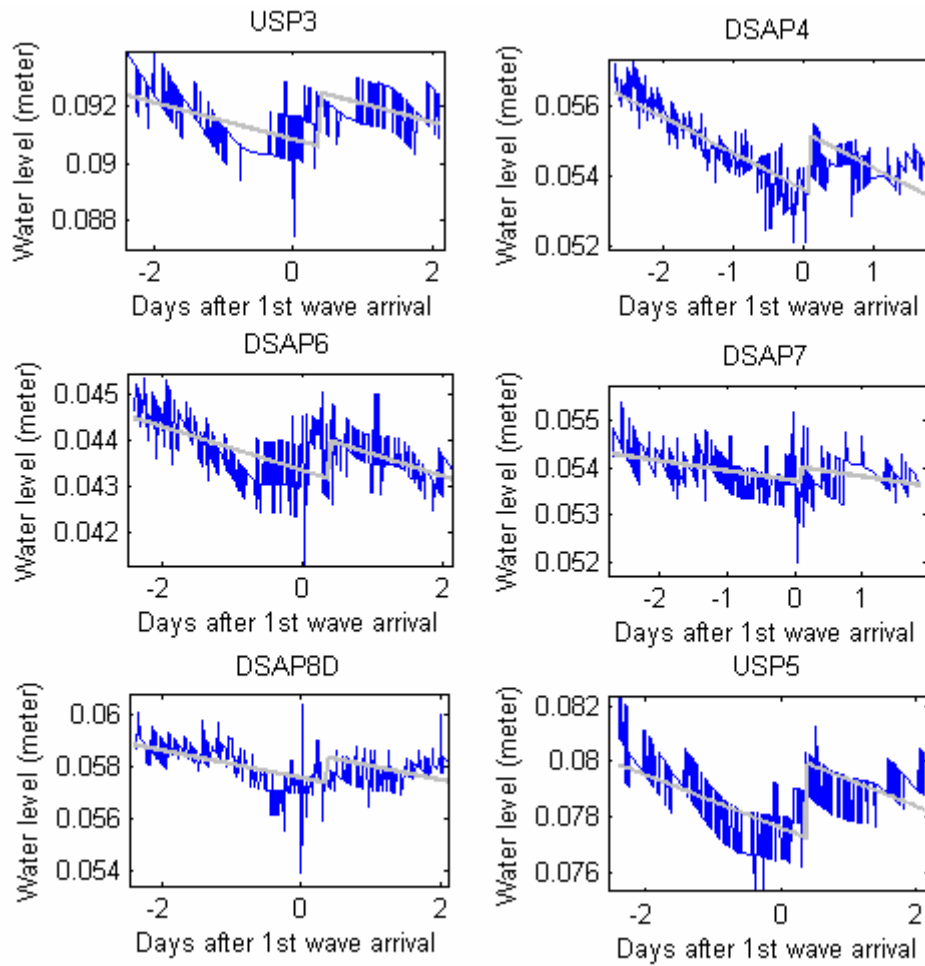
Figure 5: 5 days of water level data from 6 wells. The best fit model is also shown in the same plot (smooth gray line). Offsets are visible in all the 10 wells. We showed those wells, where pre and post earthquake water levels can be fitted with straight lines.

step model from least squares analysis, using equation 4. The water level rise obtained

from the 6 wells varied between 0.3 and 2.7 mm, with an average of 1.4 mm.

Discussions and Conclusions

We observed spike like changes in water level in several wells (Figure 3 and

figure 5). Since the magnitudes of the spikes were several times larger than the normal

fluctuations of water level and they occurred around the time of first P and S wave arrival

from Sumatra, we suspect that the spikes were induced by seismic waves. Because of the

low temporal resolution of the data, further analysis of the spike could not be made. Step

like water level changes occurred in 10 wells during the passage of largest surface waves

(in between UTC time 02:00 to 02:30). More precise estimation of the timing of the step

could not be made because of the low temporal resolution of the data. The magnitude of

steps varied between <1 to 2.7 mm with an average of 1.4 mm, which is compatible with

the predicted water level rise using empirical equation 3. The step-like changes might be

explained by one of several existing models of far-field coseismic pore pressure changes

including mobilization of gas bubble, (Roeloffs, 1998), shaking induced dilatancy

(Bower et. al.,1978), fracture of an impermeable fault (King et al. 1999) and fracture

clearing (Brodsky et. al., 2003). The water level in the Fairbanks wells roughly followed

empirical equation 3, (inverse square relation between w and d), which suggests that

dynamic strain due to surface waves might be the cause of water level changes.

West et al. (2005) showed that dynamic strains due to surface waves from the Sumatra

earthquake triggered seismicity at Mount Wrangell, Alaska. They suggested that a

pressure increment induced by the surface waves could squeeze fluid from interconnected

pore space into the nearby fault system and reduced the effective fault friction. Persistent steam emission of Mount Wrangell helped to establish this fluid pumping model. Our observation of water level increase in the wells provides additional support for this phenomenon.

Acknowledgement:

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