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REVIEW ARTICLE

# GROUNDWATER AND EARTHQUAKES: A GENERAL REVIEW

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ABSTRACT

Researchers have for decades investigated Groundwater-level responses to earthquakes and vice versa. Findings have been adequately documented in each case especially when it comes to the rises and fall of water levels, and the impact of the groundwater flow regime on the earthquakes. This paper reviews the concept of earthquake generation, groundwater occurrence, and characteristic properties common to earthquake and groundwater materials, as well as interactions. Also, some case studies are evaluated. The rise and fall in groundwater-level most often occur before, during and after the earthquake's seismic wave train come to a point. It is clear from the discussions that, groundwater flow systems, naturally or induced can trigger earthquakes, whereas naturally occurring earthquakes can impact groundwater flow systems. Finally, responses to the stress-strain relationship generated are site-specific and are dependent on the local geologic conditions.



## INTRODUCTION

Groundwater movement and earthquakes are subsurface occurrences; they interact through the characteristic geologic properties of the local host rock. Earthquake, depending on magnitude, impacts groundwater flow, and transient rise or fall in groundwater levels. On the other hand, occasionally groundwater facilitates the quick release of energy stored in subsurface rocks to generate seismicity and are often propagated to surfaces to cause either minor or severe destructions. Groundwater flow dynamics that triggers earthquake is hypothesized as hydroseismicity (Costain, 2005). Earthquakes facilitated by groundwater occur either naturally or are induced. The natural process may result from a high rate of natural and continuous/seasonal recharge from snow melts, precipitation, which results in pore pressure increases. Pore pressure rise reduces the overlying weight and thus making faults and fracture zones more susceptible to movement. Changes resulting from the subsequent movement in faults and fracture zones cause the associated groundwater reservoirs to contract or expand. The impact leads to a drop or rise in groundwater levels, with the existing and generated faults and joints by movement serving as either conduits or barriers to groundwater flow.

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Nearly all induced earthquakes are generated through artificial or natural recharge of large amounts of water into subsurface aquifers or the withdrawal of large amounts of water from subsurface aquifers. On some order of scale, the induced rocks of the subsurface have similar characteristics as natural earthquake occurrences. In each case, the stress-strain relationships of the subsurface materials are the principal agents of the observable impacts. This paper reviews the concept of earthquake generation, groundwater occurrence, and characteristic properties common to earthquake and groundwater materials, as well as interactions. Also, some case studies are evaluated.

**Groundwater:** The name groundwater describes the subsurface storage of water in permeable rocks. Groundwater is accumulated in subsurface rocks through the process of permeation of surface water, snowmelts, runoff from precipitations through layers of surface soils and fractured rocks. Upon accumulation at subsurface, they generate "pools" of water in layers bounded by impermeable or semi-permeable layers. The water is retained between the pores of the grains or fractures (cracks and joints) of the storage rock layer (Figure 1). The storage unit is defined as an aquifer, with well-defined storage properties such as hydraulic conductivity, specific storage, storability which are impacted by stress-strain relationship during subsurface movement, recharge or withdrawal.

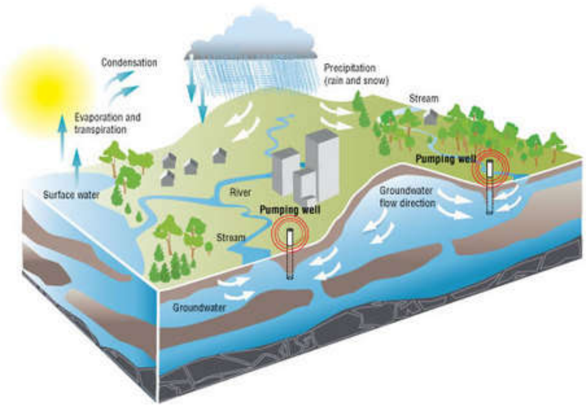



Figure 1. Groundwater and processes of accumulation (blog.mlive.com/.../liquid_assets/)

**Earthquakes:** Earthquakes occur when there is an impulsive release of energy built up in the Earth's crust, or when a sudden movement is registered between boundaries large blocks of rocks within the earth’s crust (Figure 2). The boundaries along which these movements occur are called faults and fracture zones. The energy released propagates in all directions, far, and near, causing vibration on the earth‘s surface that leads to minor and severe damages respectively. In addition, subsurface structures are altered through internal frictions processes. Associated destructions are often measured by how much buildings and bridges have collapsed. Earthquakes, thus, initiate landslides, subsidence, avalanches, flash floods, fires, water level fluctuations in wells, and huge ocean waves (tsunami). Static pressures changes in groundwater are also inevitable (Shunji *et al*., 1999).

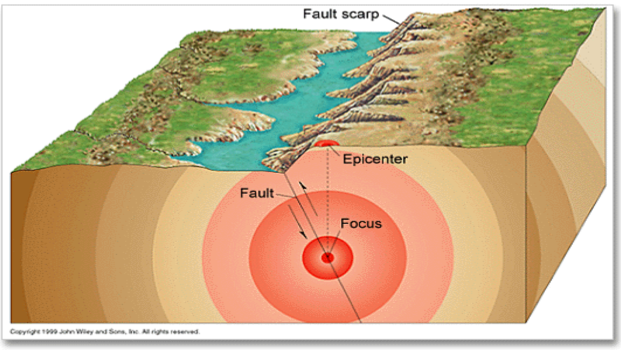



Figure 2. Diagrammatic representation of earthquake (adapted from http://earthquakesandplates.files.wordpress.com/2008/05/eqfocus.gif )

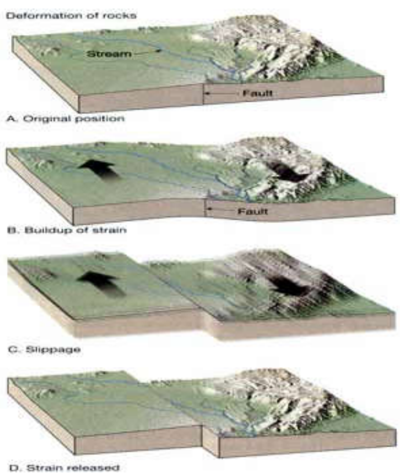



Figure 3a: stress-strain relationship (adapted from http://alancolville.com/quakes/elastic_rebound.jpg)

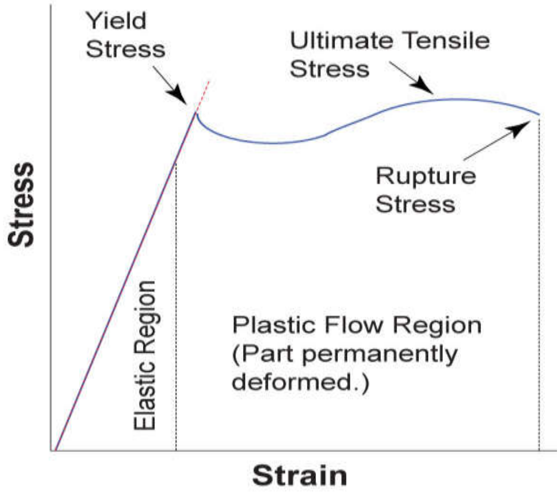



Figure 3b: stress-strain relationship (adapted from www.intuitor.com/student/StressStrainSteel.jpg )

Earthquakes are caused by stress forces or pressures directed at acting on rocks. The resulting effect is rock deformation termed as a stress-strain response. Three types of stress act on rocks; they are tensional, compressional and shear. Depending on the properties of the rocks (materials), the response (deformation) generated is elastic, plastic or rapture. The elastic deformation occurs under conditions where upon removal of the stress applied, the rock (material) regains or returns to its original shape, whereas rapture generates a complete break or fracture of the rock, which results in observed damages (figure 4). The elastic deformation responses from earthquakes stress are attested by Shunji *et al*., 1999, that groundwater pressure changes observed under such conditions recover several weeks after.

Figure 4. Road damaged by an earthquake (www.recentearthquakes.net/resources/Earthquakes )

Plastic deformation on the other hand, upon removal of stress, expresses permanent deformation. Rocks stay bent without breaking. Again, responses are felt at far and near places. Severe damages occur when the focus of the earthquake is at shallow depths. Figures 3a and b diagrammatically explain all three-stage stress-strain relationship.

**Stress-strain principles of groundwater withdrawal or injection:** The groundwater flow systems are divided into a number of parts called aquitards and aquifers.

Aquitards are less permeable and serve as breaks or barriers for vertical flow of groundwater through a system of units. Aquifers exhibit the opposite behavior. An aquifers ability to withstand resulting strain (deformation) from over withdrawal or injection depends on its elasticity or inelasticity and, the hydraulic properties that may cause a reduction in permeability of the materials that form the aquifer and the weight of the overlying materials. These parameters may help in either generating a permanent or temporal deformation. In practice, most observed deformation is permanent (Galloway *et al.*, 1999). Aquifer compaction due to groundwater withdrawal is largely due to head (hydraulic heads) and aquifer storativity changes.

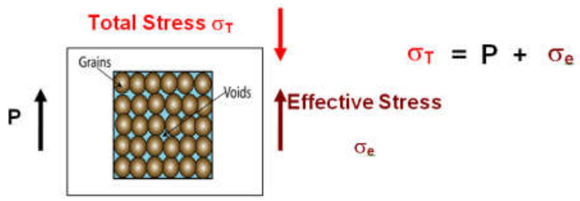



**Figure 5. Explains the principles of effective stress on an aquifer. Where P is fluid pressure, $\sigma_T$ and $\sigma_e$ are total and effective stress respectively**

The theory of aquifer compaction is based on the principle of effective stress described by Karl Von Terzaghi in 1925 (Galloway *et al.*, 1999) and Figure 5 tries to explain these basic conditions in achieving the theory. The principles of effective stress state that all measurable effects that change stress, such as compression, distortion and a change of shearing resistance are entirely due to changes in effective stress (Atkinson, 2000). The effective changes in volume and frictional accumulation or organization of the shear strength is caused by this stress. Changes in water level below ground (water table changes) result in changes in effective stresses below the water table (Atkinson, 2000). Changes in water level above ground (e.g., lakes, rivers, etc.) have no changes in effective stresses at subsurface (Atkinson, 2000). The governing equation of the theory in Figure 5 depends on the hydraulic head, defined by Fetter (2001) as in equation 1;

$$H = Z + \frac{P}{\rho_w g} \quad (1)$$

$\gamma_w = \rho_w g$ $\rho$ is density (kg/m$^3$)and g is gravity (m/s$^2$)

$$P = \gamma_w (H - Z) \quad (2)$$

$$\Delta P = \gamma_w \Delta H \quad (3)$$

***H*** is the hydraulic head (m), ***Z*** is elevation (m), ***P*** is total pressure (N/m$^2$) and $\gamma_w$ is specific gravity of water (N/m$^3$). $\Delta P$ is the changing pressure whereas $\Delta H$ is the change in hydraulic head. Equation 3 combined with the principle of effective stress explains the theory of aquifer system compaction or deformation. The effective stress is related to the total stress and pore pressures as depicted in Figure 5.

$$\sigma_e = \sigma_T - P \quad (4)$$

$\sigma_e$ is the effective stress, and $\sigma_T$ is the total stress (Fetter, 2001).

$$\Delta \sigma_e = \Delta \sigma_T - \Delta P \quad (5)$$

If the weight of overburden material is assumed to be constant, then $\Delta\sigma_T$ reduces to zero. Thus, equation 5 becomes equation 6.

$$\Delta \sigma_e = -\Delta P \quad (6)$$

Substituting equation 6 into equation 3 gives equation 7,

$$\Delta P = \gamma_w \Delta H = -\Delta \sigma_e \quad (7)$$

Equation 7 then simplifies the concept of effective stress. A change in pore pressure, hydraulic head and the effective stress affects the volume of the aquifer (Fetter, 2001). The aquifer either looses or gains water, and the ability of an aquifer to absorb and expel water depends on the type of aquifer and hydraulic properties (Fetter, 2001). These properties are different for confined and an unconfined aquifer. The disparity is mainly due to which of these (specific storage and specific yield) are applied to the aquifer (Fetter, 2001). Confined aquifers are always saturated and release water from the pore fluid expansion and compressed aquifer skeleton (Fetter, 2001). This depends on the aquifer property storativity which cannot be directly measured, however in confined aquifers it is estimated using in equation 8.

$$S = b S_s \quad (8)$$

***S*** is Storativity (dimensionless), ***b*** is the thickness of aquifer (m), and $S_s$ is the specific storage (1/m).
In the case of unconfined aquifers, the storativity depends on the specific yields which indicate the amount of water released due to drainage from lowering the water table. (Fetter, 2001). Thus, storativity of an unconfined aquifer is as expressed in equation 9. $S_y$ is a specific yield.

$$S = S_y + b S_s \quad (9)$$

Volume ($V_w$) of storativity (m$^3$) is estimated by applying the expression in equation 10.

$$V_w = S A \Delta H \quad (10)$$

Where ***A*** is the area (m$^2$) of the aquifer and $\Delta H$ is the average head decline. A change in storativity volumes thus expresses the aquifers elastic properties, which relates to specific storage (Fetter, 2001). Specific storage based on some assumptions is expressed as follows,

$$S_s = \rho_w g (\alpha + n \beta) \quad (11)$$

***g*** is gravity, ***n*** porosity, $\beta$ is compressibility of water, $\rho_w$ is the density of water and $\alpha$ is compressibility of the aquifer skeleton (Fetter, 2001). Assuming water is incompressible, the deformation of an aquifer is considered mainly elastic

(Hoffmann *et al*., 2001). Thus reducing the specific storage expressed in equation 11 to this skeletal storage coefficient in equation 12.

$$S_{sk} = \rho_w g \alpha \quad (12)$$

$S_{sk}$, is the skeletal specific storage due to skeletal compressibility.

$$S_{sk} = \gamma_w \alpha = \gamma_w M_v \quad (13)$$

$$\Delta T = S_{sk} \Delta H T \quad (14)$$

$\Delta T$ is the amount of consolidation (deformation), and $T$ is the thickness of the layer under consideration. Equation 14 is the basic equation used in generating calculated deformation. However, for multiple layers ($N$ number of layers) equation 14 becomes equation 15.

$$\Delta T = \sum_{i}^{n} S_{ski} \Delta H_i T_i \quad (15)$$

**Seismicity:** The shaking and the destructions witnessed during an earthquake event happen as a consequence of three elastic waves. The first two are the P-waves, (Primary - the fastest, expressed within the body of the rock), the S-waves, (Secondary - the slowest, also within the body of the rock). They are a function of the elasticity and the density of the rock. P-waves propagate in compression and dilation (push-pull) motion, whereas, the S-waves are propagated at right angles to the direction of motion through the shearing of the rocks. The motions are as expressed in figures 6 and 7 respectively. The side to side and the up and down motions generated shakes the ground surface vertically and horizontally, consequently destroying surface and subsurface structures. Although P-waves arrivals are associated with dynamic groundwater pressure changes, amplitudes of S-waves of the seismic waves makes the pressure changes more pronounced. Thus the largest dynamic groundwater pressure changes are observed on the arrival of S-waves (Shunji *et al*., 1999). Montgomery *et al*., 2003 suggest that the type earthquake and amplitude of the response are dependent on the local and far subsurface conditions. Shunji *et al*., (1999) verified this concept with observations of waves that generated a positive relationship between the dynamic groundwater pressure changes and the maximum recorded velocity values. Shunji *et al*., (1999), qualitatively explained that the induced earthquakes have uniqueness in dynamic groundwater pressure changes with the procedure through which the occurrence of S-waves are translated to P-waves as they are transmitted along a borehole.

The third of the elastic wave is the surface waves, based on its motion characteristics, have been categorized into two. They are the Love and Rayleigh waves. Love waves have the characteristics S-waves propagation, side to side movement at right angles to the direction of motion but exhibit no vertical displacement (figure 8), while Rayleigh waves move horizontally and vertically in the vertical plane in the direction of the motion (figure 9). Though these waves are much slower than P and S waves, they impact the earth crust significantly. The love waves through the side pushing disposition have the tendency to affect surface water, whereas the characteristics vertical makeup of Rayleigh waves may affect an entire water body (such as lakes), thus, resulting in the dislocation of some sources of recharge to groundwater and vice versa. The faults (fractures) and the subsequent subsurface structures created either inhibit or facilitate the flow of groundwater in the aquifers, and result in an increase or decrease in pore water pressures. The effects are observed in changes in water levels and discharge from or into wells. Interactions between earthquakes and hydrologic/hydrogeologic process are summarized in figure 10.

**Groundwater triggers earthquakes:** Although earthquakes tend to be naturally occurring phenomena, they can be generated by natural groundwater recharge or anthropogenically through human activities, mineral mining, oil extraction, extreme seasonal groundwater recharge through injections and withdrawals. Groundwater flow has long been known to influence subsurface joint (fault, fracture, and shear zones) movements, triggering seismicity. Natural recharge to groundwater aquifers either by seasonal changes or continuous process produces natural changes in amplitude and pore fluid pressures (Saar and Manga, 2003). Normal stress within the aquifer is reduced by pore pressures while shear stress remains the same. Thus, an increase or decrease in pore pressures results more likely in failure. The (Hubbert – Ruby, 1959) hypothesis of fluid pressures suggests that friction between two layers could be considerably reduced when part of the load is carried at elevated pore water pressures. The reverse holds for reduced pore water pressures (Yue and Suppe, 2005). This implies that fractured rocks are able to slide aside with little effort with the rise in pore water pressures. Based on these ideas, it can be deduced that earthquakes can be triggered through natural recharge, injection or extraction of groundwater (Fu-Chun *et al*., 2001). The amount of water extracted or injected determines the magnitude and the number of earthquakes that would be generated (Fu-Chun *et al*., 2001). Since these are locally generated, the epicenters (hypocenters) are close to the point of injection or extraction.

Consequently, water injected or extracted, generate pressures that are related to the number of observed induced earthquakes (Fu-Chun *et al*., 2001). Husen *et al*, (2007), sites a series of locally triggered seismicity in the central Swiss Alps after the large rainfall event of August 2005 (figure 11). Figure 11 illustrates the amount of rainfall recorded during the period after which a series of earthquakes occurred. A large amount of rain led to increased surface fluid pressures and consequently increases in local pore fluid pressures at depth. The pore fluid pressure increases led to a reduction in shear strength of a porous medium by counteracting normal stress, which provoked failures. This triggered the series of earthquakes in central Switzerland (figures 12 and 13). These earthquakes were registered in past seismically active regions, hypocenter locations and comparable magnitudes (figure 10). Thus, the rise in the pore fluid pressures triggered earthquakes along existing faults which were critically stressed (Husen *et al*., 2007).

**Impact of earthquakes on groundwater:** Hsu *et al*. (2006) state that earthquakes occurrence creates hydrological anomalies which intend impact hydrogeological properties such as hydraulic conductivities of aquifers. In addition to the hydrogeological properties, they can cause vertical ground surface displacements.

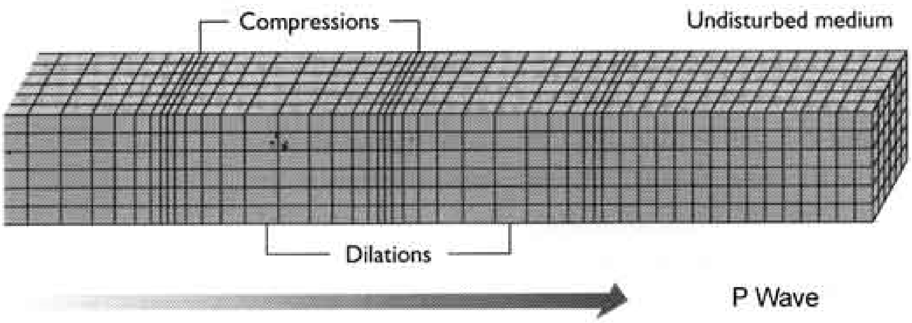



**Figure 6. P-wave motion (http://allshookup.org/quakes/wavetype.htm)**

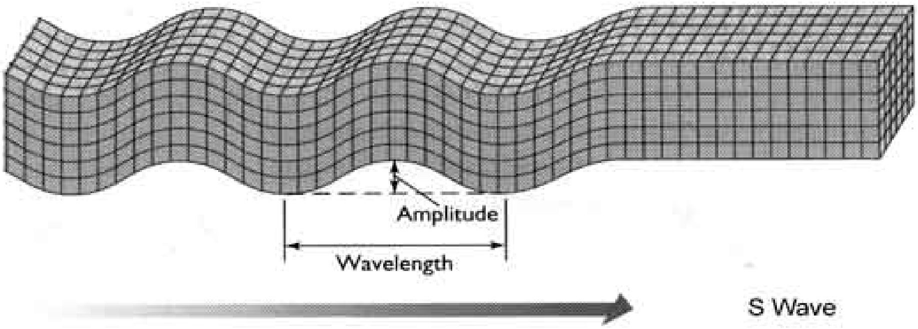



**Figure 7. S-wave motion (http://allshookup.org/quakes/wavetype.htm)**

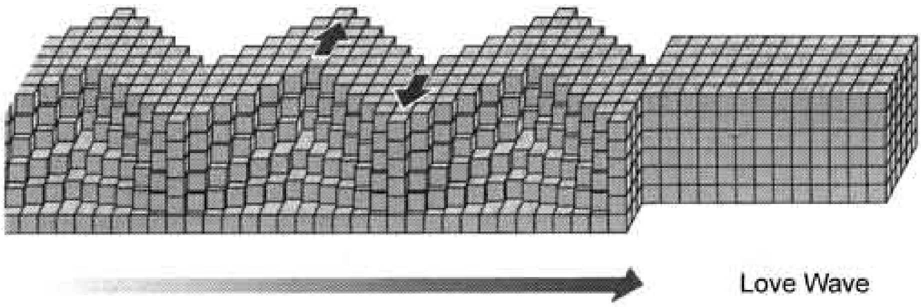



**Figure 8: Love-wave motion (from http://allshookup.org/quakes/wavetype.htm)**

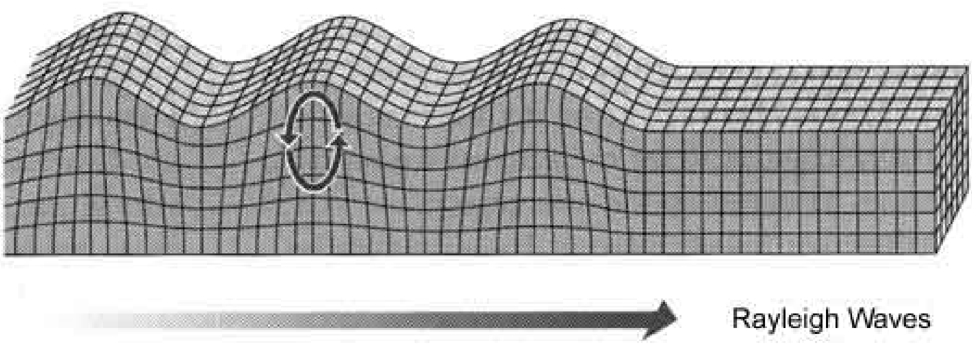



**Figure 9: Rayleigh-wave motion (http://allshookup.org/quakes/wavetype.htm)**

The effects are observed in changes in water levels. Earthquake events may be used as a natural stimulus for aquifer test. The wells involved may well be used as strainmeters in establishing the efficiencies of local-scale static strain and volume strain. Zhang and Zhang (2006), through evaluation of tectonic stress stimulation, confirmed that subsurface fluids anomalies detected in the Minle-Shandan fields were induced by the November 14, 2001 earthquake. Figures 15, 16 and 17 are observations made by Sneed *et al*., (2003) after several earthquake events.

Figure 15 illustrates the response by well 8N/10W-1Q1 in the western Majave desert, California, to 3 southern earthquakes. The first is the Landers earthquake. The data recorded covering some days the months of June and July before and after the earthquake indicated a rise of about 0.5 feet in water level. The Northridge and the Hector mine earthquakes in January 1994 and October 1999 respectively, were also found to have responded to water level oscillations before and after the quakes. Similarly, water levels rose in well number MO-18/02W/29-0017.

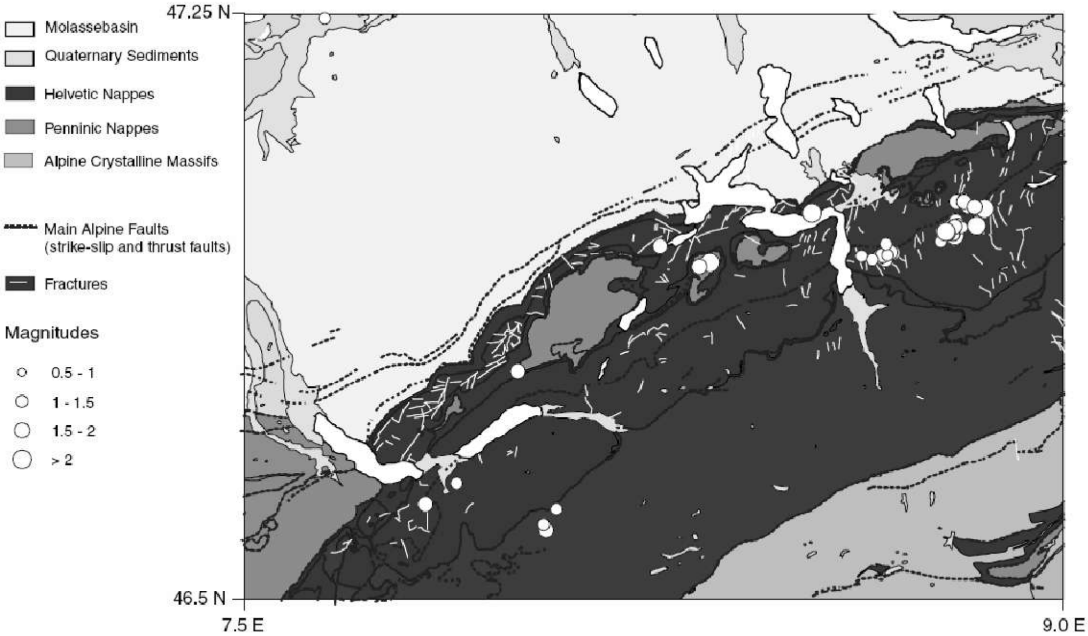



**Figure 10: the geologic setting of the central Swiss Alps (Husen *et al.*, 2007).**

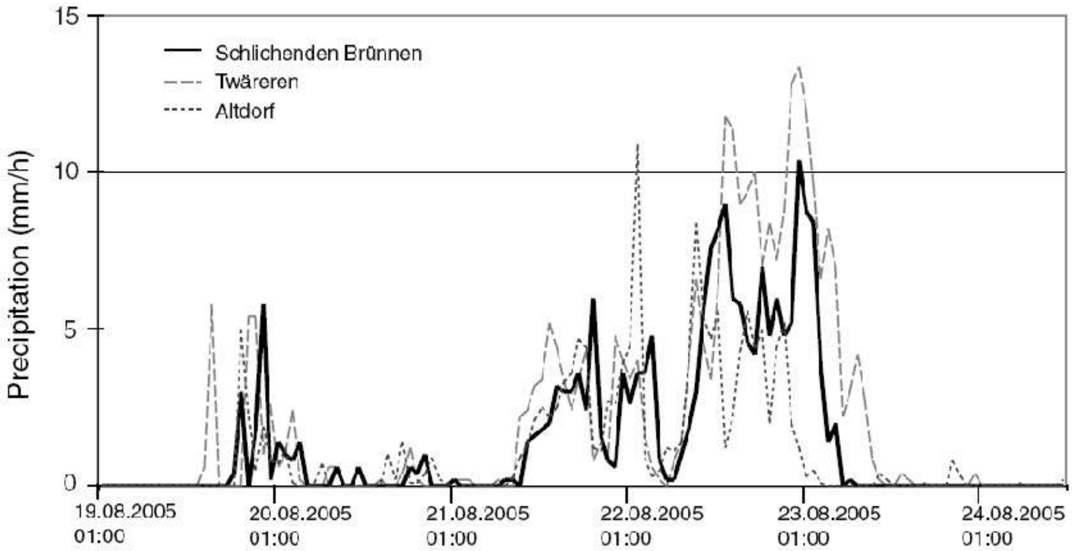
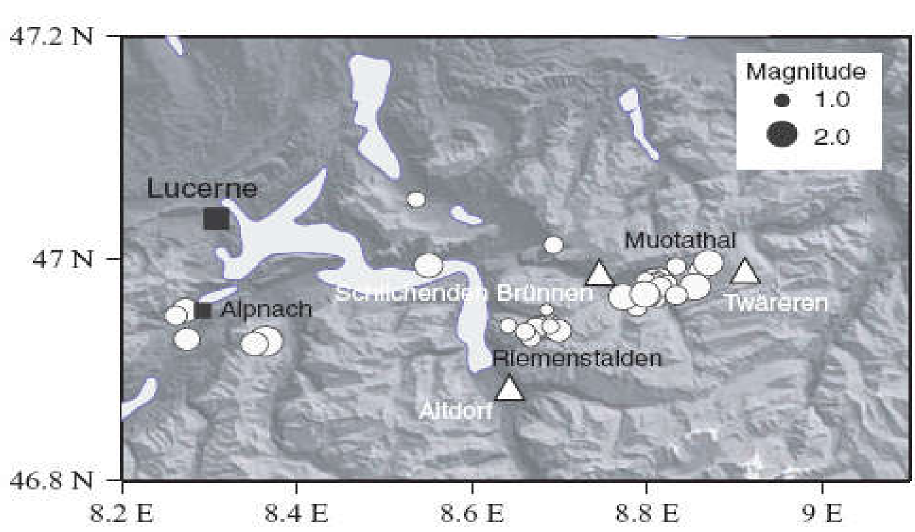



**Figure 11. Amount of rainfall registered at three stations during the period (Husen *et al.*, 2007)**




**Figures 12. Earthquakes magnitudes with respect to rainfall measuring stations (Husen *et al.*, 2007)**

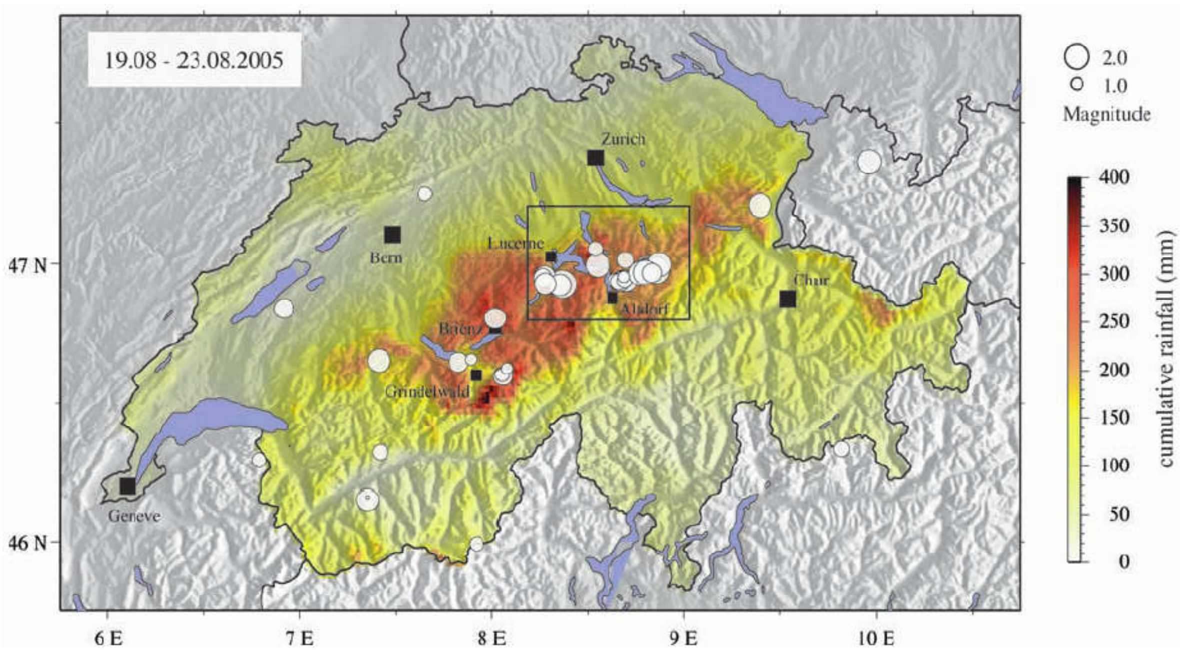



**Figure 13. Cumulative rainfall, number, and magnitude of earthquakes generated (Husen *et al*., 2007)**

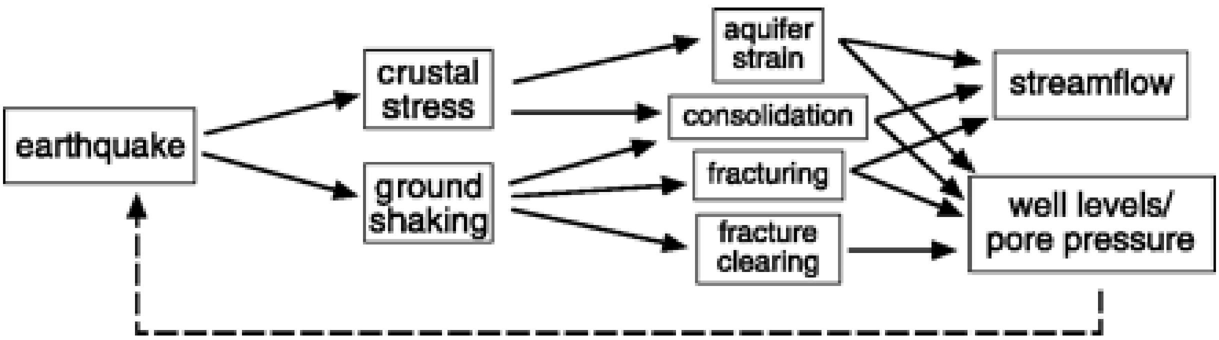



**Figure 14. Interactions between earthquakes and hydrological processes (After Montgomery and Manga, 2003)**

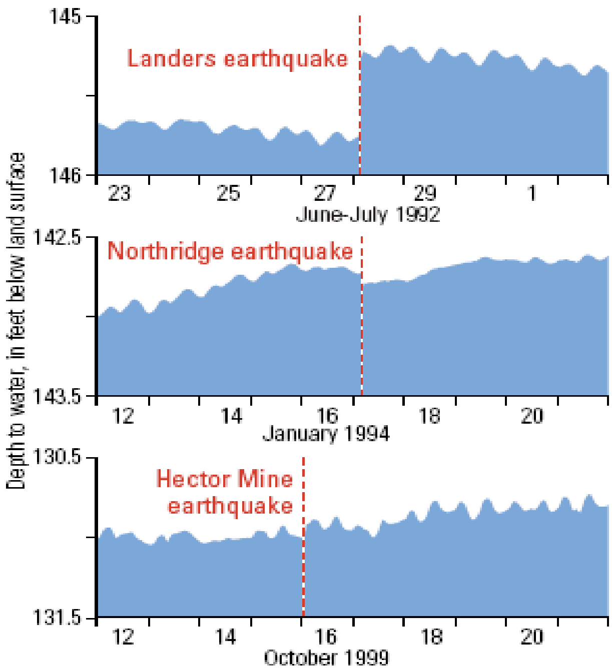



**Figure 15. Response by wells 8N/10W-1Q1 in the western Majave desert, California, to several southern earthquakes (Adopted from Sneed *et al*.,2003, http://pubs.usgs.gov/fs/fs-096-03/)**

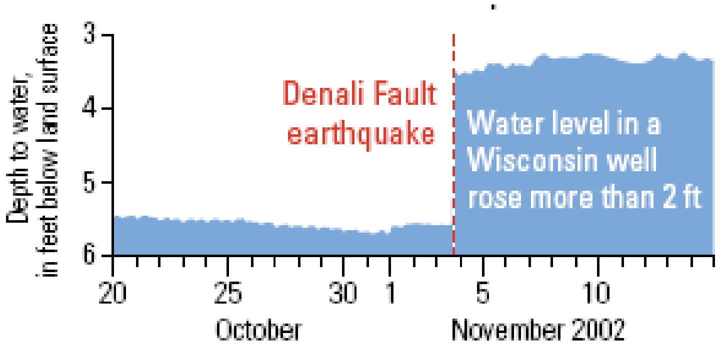



**Figure 16. The response of Well MO-18/02W/29-0017 in Wisconsin to the distant Denali Fault earthquake in Alaska (Adopted from Sneed *et al.*, 2003 http://pubs.usgs.gov/fs/fs-096-03/ )**

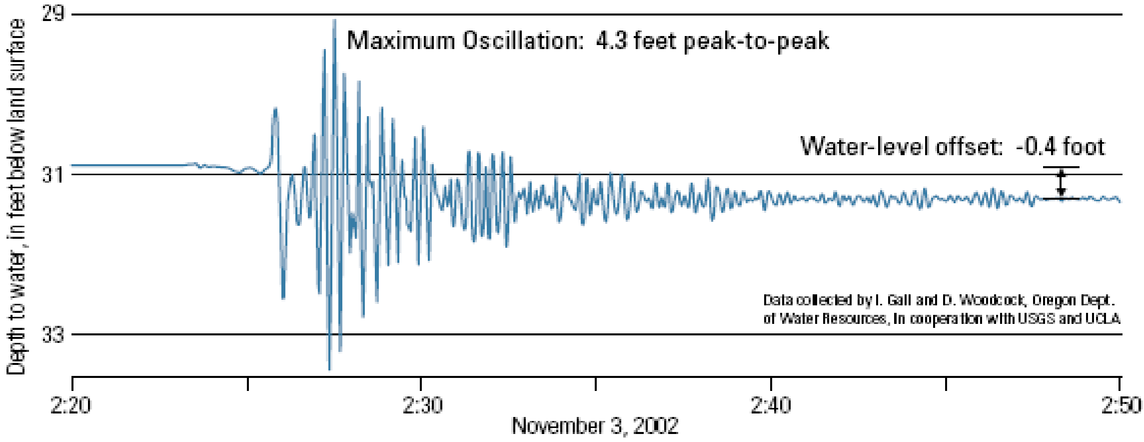



**Figure 17. Hydroseismogram recorded in a well near Grants Pass, Oregon, shows water-level oscillations and a small offset relative to the pre-earthquake water level in response to the Denali Fault earthquake. (Adopted from Sneed *et al.*, 2003 USGS - http://pubs.usgs.gov/fs/fs-096-03/)**

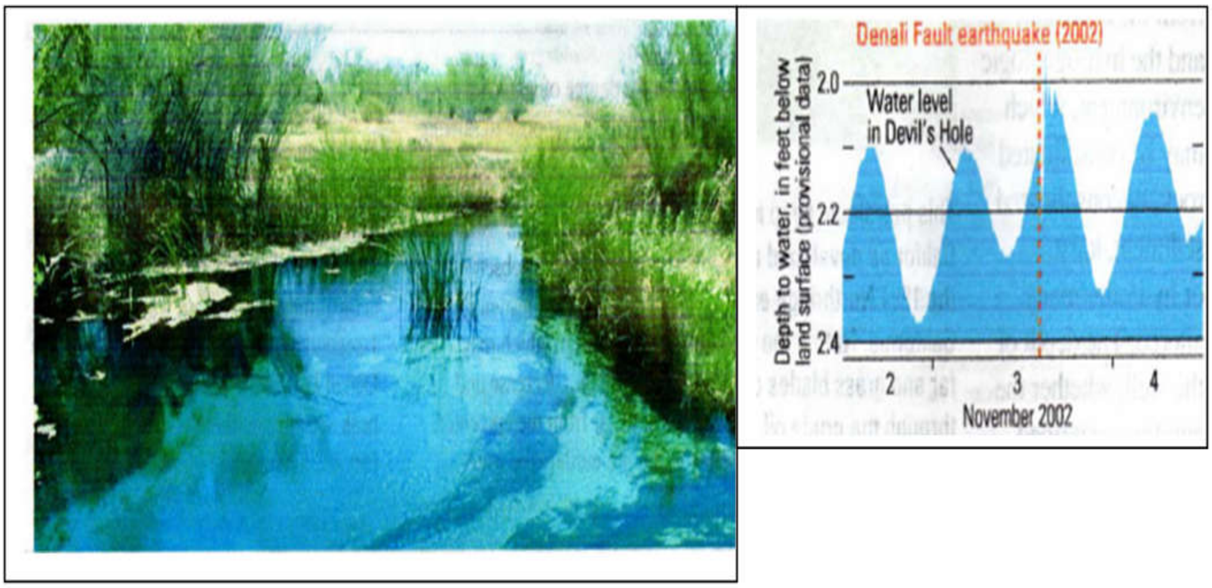



**Figure 18. Water level oscillation in Devils hole, Nevada response to Denali fault earthquake (2002), (Adopted from Sneed *et al.*, 2003 USGS - http://pubs.usgs.gov/fs/fs-096-03/ )**

(Figure 16) in Wisconsin by more than two feet in responses to the distant Denali Fault earthquake in Alaska. Figure 17 demonstrates with a plot from hydroseismogram recorded in a well near Grants Pass, Oregon, water-level oscillations with a peak rise of 4.3 feet, and an offset about 0.4 feet relative to the pre-earthquake water level in response to the Denali Fault earthquake. Figure 18 illustrates an additional observation made in Devils hole, aquifer-fed pool located in a limestone cavern in the Amargosa Desert of Nevada east of Death Valley, in response to the Denali fault earthquake 2002. Also, the response to the earthquake which resulted in oscillations in the

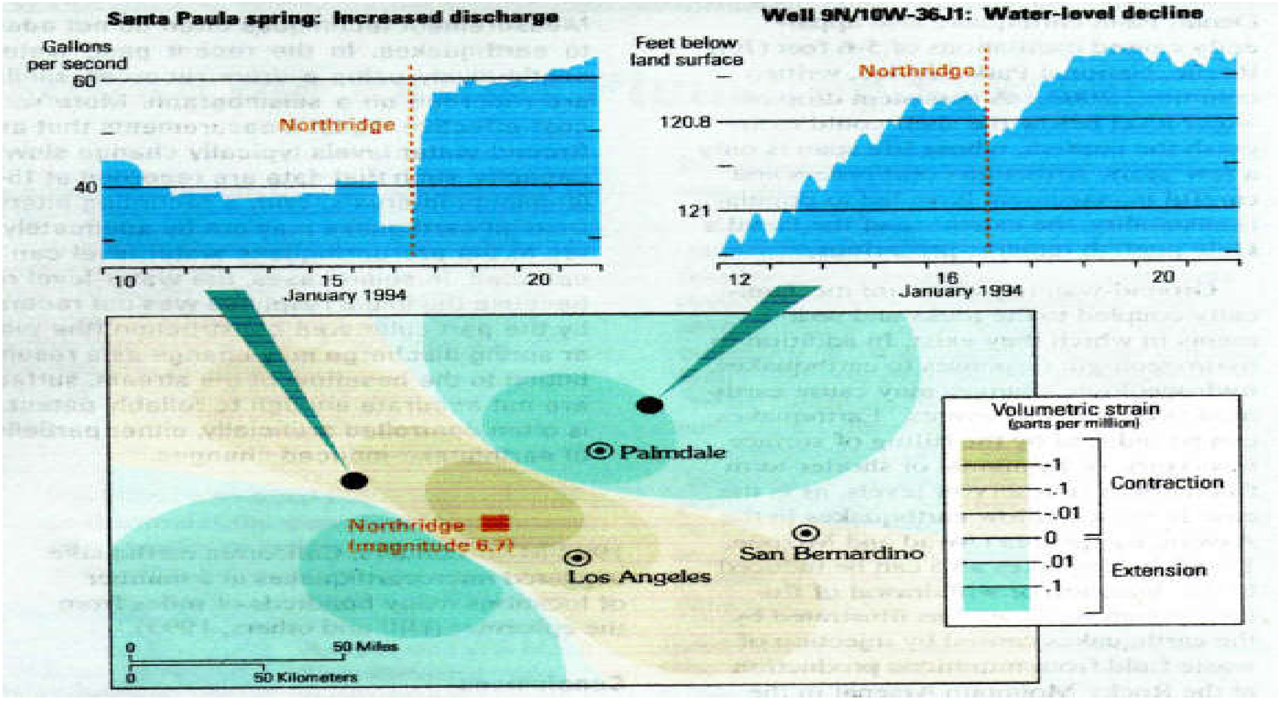



**Figure 19. illustrates the response to compressional and tensional stress. (Adopted from Sneed *et al*., 2003 USGS - http://pubs.usgs.gov/fs/fs-096-03/)**

water levels disrupted the spawning areas of the pupfish at the near surface of the pool. Figure 19 expresses the impact of the Northridge earthquake in 1994. The impact of the earthquakes shows portion in southern California that contracted in response and caused Santa Paula springs, for instance, to increase the amount of discharge. Furthermore, some areas also experienced extensional strain. Observations in well number 9N/10W-36J1 near Palmdale saw a drop in water level. Montgomery and Manga (2003), after some 44 earthquakes, established and outlined the phenomena of earthquake and groundwater interactions. Their conclusions were based on observations from 912 wells. They proposed that groundwater may have been impacted by an earthquake when;

- Fluid is discharged from the seismogenic zones.
- Pore-pressure distribution after the strain occurs in the upper crust.
- Shallow aquifers are compressed due changes structural changes.
- Permeability is decreased as a result of fracture openings in the bedrock.
- Local earthquakes are triggered because of the response of the pore-pressure to earthquakes originating from afar (figure 16).
- There are aquifer compression and dilation (P-wave)
- Water levels are found to oscillate rapidly in wells for weeks. Some may be sustained and therefore may about a month or permanently (figure 17).
- Sustained water level oscillations persist after ground shaking is initiated.
- changes occur in the fault zone; groundwater levels are influenced (figure 15)

## Conclusion

It is clear from the discussions that, groundwater flow systems, naturally or induced can trigger earthquakes, whereas naturally occurring earthquakes can impact groundwater flow systems. The response under each of the conditions has a dependence on the interaction of in and outflow of an aquifer. Additionally, sustained water level changes largely depend on the aquifer characteristics, subsurface structure, magnitude and direction of the natural or induced strain within the locality. Impacts generating water level changes reveals a change in the specific storage of the aquifer, thus, a non-recoverable deformation. Loosen fracture-blocking collusions generates pore pressure changes. Compression zones of a hanging wall of a normal fault are characterized by water level changes, whereas the in unconsolidated sediments, a characteristic rise in water levels is observed due to the compression of the aquifer. Finally, responses to the stress-strain relationship generated are site-specific and are dependent on the local geologic conditions.

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