Summary of Literature
Impacts of Earthquakes on Groundwater Quality

Prepared as part of a Ministry of Health
contract for scientific services

by

Jan Gregor
Bronwyn Dumbleton
Elaine Moriarty

June 2012

Client Report
FW12013

Summary of Literature
Impacts of Earthquakes
on Groundwater Quality

John Wright
Water Programme Manager

Jan Gregor
Project Leader

Chris Nokes
Peer Reviewer

DISCLAIMER

ACKNOWLEDGEMENTS

ESR acknowledges the feedback on the draft report provided by staff of Community and Public Health and Christchurch City Council.

TABLE OF CONTENTS

TABLE OF FIGURES

Executive Summary

Since 4 September 2010, the Christchurch region has experienced eight shallow earthquakes of magnitude 5.8 or greater and ten thousand aftershocks. Many of the drinking-water supplies in the region, including Christchurch city, use groundwater sources. Questions have been raised about possible disruption of aquifers caused by the earthquakes and the resulting effect on drinking water quality. In addition to immediate post-earthquake contamination of compromised drinking-water supply infrastructure from the extensively damaged sewerage system, aquifer disturbance and groundwater contamination, if it occurred, may continue for some time.

Guidance has been sought on confirming the secure status of the Christchurch drinking-water supply with reasonable certainty, and on providing early warning of delayed contamination. The difficulty is not knowing how delayed earthquake impacts will manifest themselves, the possible magnitude of these effects, and how long they will take to become apparent.

This report contributes to the guidance by reporting on a search of the scientific literature for similar international experiences. The majority of papers focussed on the hydrological responses of aquifer systems preceding and following major earthquakes. Where contamination of groundwater was discussed, it was typically in relation to consequences of infrastructure damage and immediate impacts on shallow groundwater and drinking-water quality sourced from this groundwater. Very little was found of direct relevance to the Christchurch context additional to what is already understood about factors that influence delayed impacts on groundwater quality.

The literature provided examples of causes of impacts on water quality, including infiltration of surface sources of contamination (eg, leachate from demolition debris, petroleum products), mixing of waters from different aquifers, saltwater intrusion and dissolution of heavy metals from aquifer material. Water was contaminated with faecal coliforms, heavy metals, petroleum products and saltwater, and significant changes in major ions were commonly noted. The timeframe of water quality changes ranged from immediate to continuing for more than one year.

While water quality changes are described in international accounts of the effects of earthquakes on groundwater, the literature search found no reports of delayed effects. We do not know whether this means that such effects did not occur, or they went unnoticed. However, as it is possible to conceive of ways in which delays might occur, we cannot assume that they will not occur as a result of the Christchurch earthquakes. Observations, inspection, monitoring and estimations of times based on aquifer properties will be necessary for determining when any delayed changes may occur.

1 Introduction

1.1 Earthquakes and Christchurch's drinking-water supply

Since 4 September 2010, the Christchurch region has experienced eight shallow earthquakes of magnitude 5.8 or greater and ten thousand aftershocks (as at end of February 2012). The two main natural hazards resulting from earthquakes are earth deformation and earth shaking. The September 2010 earthquake, initiated at a depth of 11 km, produced a surface rupture approximately 30 km long in a west–east direction, with displacement up to several metres laterally and up to one metre vertically. The earthquake generated ground shaking 1¼ times the acceleration due to gravity, the strongest ever recorded in New Zealand (Geological and Nuclear Sciences 2012a). The February 2011 earthquake was initiated at a depth of 7 km but did not break the surface. The fault rupture, 14 km in length, extended east-north east along the southern edge of the city and extends offshore (Geological and Nuclear Sciences 2012b). In Christchurch, the ground accelerations of this earthquake were 3–4 times greater than during the September 2010 earthquake (Royal Society of New Zealand 2012).

Many of the drinking-water supplies in the region, including Christchurch city, use groundwater sources. Questions were raised about possible disruption of aquifers caused by the earthquakes and the resulting effect on drinking water quality. Earthquakes centred on the Alpine fault and more locally in Canterbury, and the consequential failure of drinking-water and wastewater systems, are identified in the top 10 risks of the Canterbury Civil Defence Emergency Management Group Plan 2005-2010 (Environment Canterbury 2005).

The immediate post-earthquake concern for drinking-water was contamination of the compromised drinking-water supply infrastructure from the extensively damaged sewerage system. However, earthquake-related aquifer disturbance and groundwater contamination from surface sources also posed risks and may continue to do so for some time. The difficulty faced by agencies working to ensure the security and quality of Christchurch's drinking-water supply is not knowing how delayed earthquake impacts will manifest themselves, the possible magnitude of these effects, and how long they will take to become apparent.

1.2 Evidence of immediate impacts (water quality monitoring)

Before the earthquakes, the Christchurch-West Melton aquifer system was a source of secure groundwater for Christchurch city, providing water for the majority of Christchurch residents (Christchurch City Council 2009). However, following the earthquakes the groundwater could not be regarded as secure because of possible aquifer disturbance. In the case of the semi-confined and unconfined aquifers used by the city supply, there was also the possibility of contamination from the surface. Figure 1 shows an overlay of the earthquake epicentres and fault zones, and the urban Christchurch area water supply comprising 8 different pressure zones plus the Lyttleton Harbour Basin supply. Each pressure zone has multiple pump stations, and each of these has a number of wells drilled into different aquifers, totalling approximately 155 wells.

Environment Canterbury has compared water quality data gathered after the recent earthquakes with historical groundwater data (Environment Canterbury 2011)[1,2]. It has concluded that there is no

[1] Parameters determined: field and laboratory pH, water temperature, dissolved oxygen, sodium, potassium, calcium, magnesium, iron, manganese, ammonia-N, alkalinity, nitrate-N, sulphate, chloride, conductivity, reactive silica, dissolved reactive phosphorus, and Ca:Mg, Na:Ca, Na:Cl ratios.

[2] The Environment Canterbury #2 report notes 'Because we generally sample deeper groundwater, we decided not to include indicator bacteria in our investigation of groundwater quality after the February 2011 earthquake.' The

clear evidence of significant changes in the composition of the groundwater and consequently no threat is posed to the city's drinking-water supply.

Levels of turbidity and iron were most often found as outliers[3] from the mean of historical groundwater quality data. Environment Canterbury explains the increased turbidity as most likely arising from disturbance of sediments. Most of the iron outlier results were above the guideline value in the drinking-water standards (Ministry of Health 2008). Elevated iron concentrations will also have contributed to the turbidity, if the iron was in an insoluble form.

1.3 Report context and purpose

Before the earthquakes of 2010 and 2011, all but one[4] of the city's water supply zones was supplied with groundwater having a secure status[5]. The non-secure zone, abstracted from the aquifer on the lower Canterbury plains west of the city, supplies about one-fifth of the Christchurch city population.

The secure status of the wells that serve Christchurch city was established using the hydrogeological model option in the Drinking-water Standards for New Zealand (Ministry of Health 2008), supported by targeted monitoring for residence time of the water. Well water security must be reassessed at least every five years, but should also be reassessed following any event that throws doubt on its security. Post-earthquake groundwater quality monitoring and comparison with historical water quality data have been carried out (see section 1.2). However, this is insufficient for the purposes of re-establishing the secure status of the city's groundwater sources, and a reassessment of the secure status of groundwater by residence time has not yet been completed.

The need to re-establish a secure groundwater status following an earthquake has not arisen previously in New Zealand. Consequently, the water supplier (Christchurch City Council) and the drinking-water assessor (with the authority to approve the status) sought guidance on data and information that might be useful in confirming the status with reasonable certainty, and information that might provide early warning of delayed contamination following a major earthquake. This report contributes to the guidance by reporting on a search of the scientific literature for international experiences of delayed impacts of earthquake-related aquifer disturbance and surface-influenced contamination affecting the quality of groundwater supplying drinking-water systems.

The secure status of a groundwater, as defined in the Drinking-water Standards for New Zealand, describes the level of risk to its microbiological quality. It is not intended to cover threats from chemical hazards. However, new chemical contaminants are possible following the earthquake, and this report also considers steps necessary to guarding against these contaminants.

Environment Canterbury #3 report notes that although Christchurch City Council monitoring detected total coliforms (indicator bacteria) in four wells into aquifer 1 and one well into aquifer 2, *E.coli* was not detected.

[3] Levels more than three standard deviations from the mean of the historical data.

[4] The Northwest Christchurch water zone drew from bores providing water that was not classified as secure.

[5] Bore water is considered secure when it can be demonstrated that contamination by pathogenic organisms is unlikely because the bore water is not directly affected by surface or climate influences, as demonstrated by compliance with bore water security criteria 1 and 3, and abstracted from a bore head that provides satisfactory protection, bore water security criterion 2. (Ministry of Health 2008).

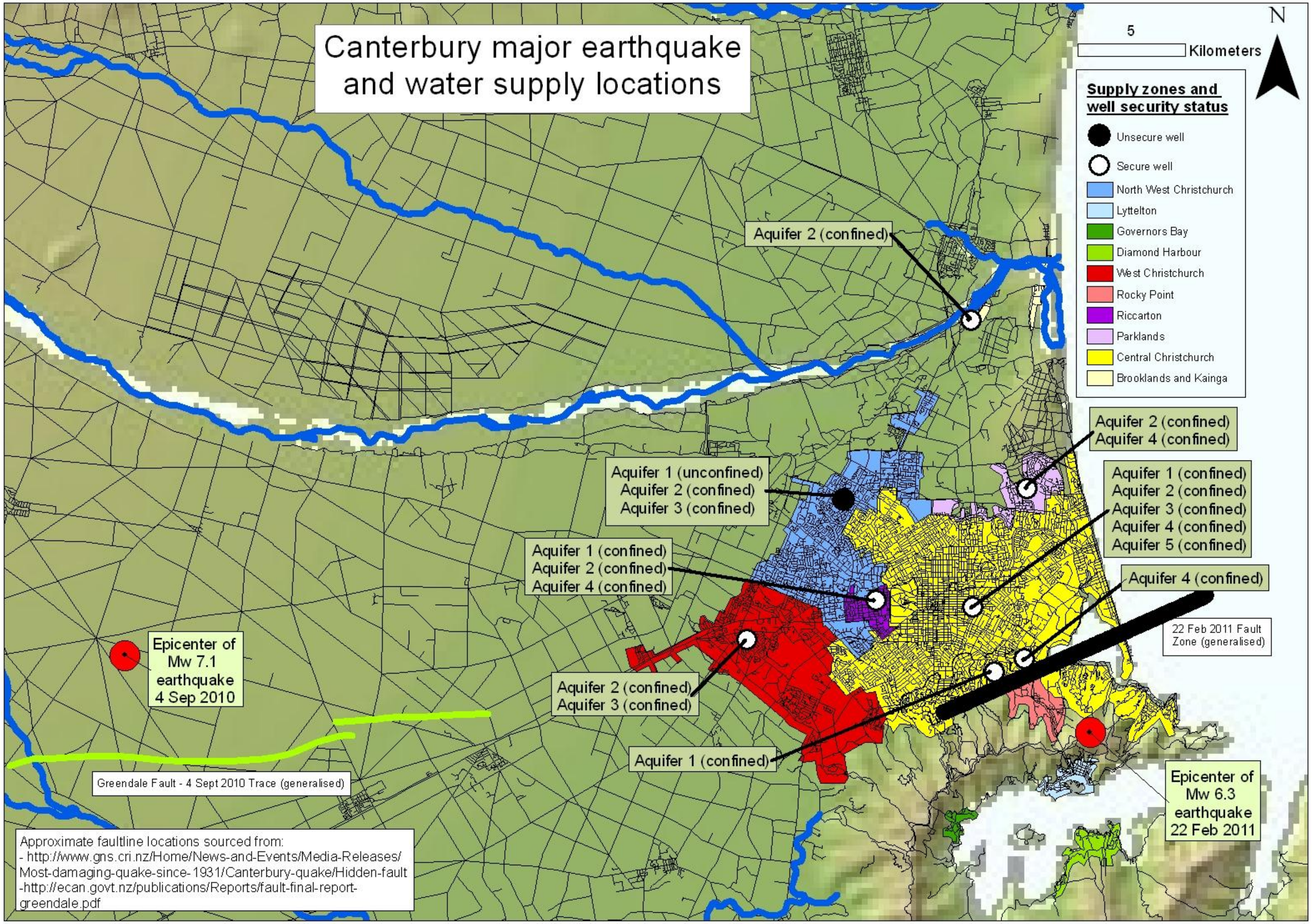

Figure 1 **Overlay of Christchurch city drinking-water sources, earthquake epicentres and faults**

2 Method for selection of papers

Five scientific bibliographic databases, ‘Scopus’, ‘Web of Knowledge’, ‘Science Direct’, ‘Compendex’ and ‘Pubmed’ were searched for academic peer-reviewed papers that might meet the requirements for inclusion in the literature review. Target publications were scientific papers published in the last thirty years (1981–2011), using search keywords:

- earthquake*
- groundwater or ground water or aquifer or confining layer
- quality or water quality or contamination.

Approximately 200 papers were identified, then accepted if the following criteria were met:

- the paper was in English
- the paper was primarily concerned with water quality changes observed either prior to, during or after an earthquake event, noting that papers describing changes in groundwater level may indicate a disturbance of the aquifer and by implication the possibility of quality changes.

This resulted in a list of 61 papers for review, which are listed in the bibliography at the end of this report.

3 Summary of relevant papers

A search of the scientific literature sought international experiences of delayed impacts of earthquake-related aquifer disturbance and surface-influenced contamination affecting the quality of groundwater sources of drinking-water supplies.

The majority of papers focussed on the hydrological responses of aquifer systems preceding and following major earthquakes. Where contamination of groundwater was discussed, it was typically in relation to consequences of infrastructure damage and immediate impacts on shallow groundwater. Very little was found of direct relevance to the Christchurch context additional to what is already understood about factors that influence delayed impacts on groundwater quality. This report provides a summary of the nine most relevant papers and a bibliography of the 61 papers that met selection criteria.

3.1 Impact of earthquake demolition debris on the quality of groundwater (Benmenni and Benrachedi 2010)

This study highlights the potential long-term impacts of buried demolition debris on the quality of groundwater. A landfill was used for the disposal of demolition debris following the May 2003 earthquake in Northern Algeria. Analysis of the leachate coming from the landfill five years after it was established was found to exceed national standards for heavy metal content. The leachate had also reached an aquifer 10 m beneath the soil surface. The leachate from the five year old site contained organic matter with relatively high chemical and five day biological oxygen demands of 1136 mg/L and 200 mg/L O_2 respectively. The pH of the leachate indicated that fermentation of the debris was occurring in a manner similar to an urban waste decomposition scheme. This was an unexpected finding because the demolition debris had been regarded as consisting of reusable and inert materials, having no environmental impact.

3.2 Did arsenic contamination in the Inagawa River occur in geogenic relation to the Great Hanshin (Kobe) earthquake of 1995? (Ogoshi et al 1996)

Three weeks after the 1995 Kobe earthquake in Japan, arsenic levels above the environmental standard (0.01 mg/L) were detected in the Inagawa River, 35 km from the epicentre of the earthquake. Samples from 24 of 54 points along the river contained arsenic at concentrations exceeding environmental standards. Sampling was extended to the tributaries of the river and further along the Inagawa River. The Inagawa River had been part of a regular monitoring programme for several years and had never exceeded environmental standards prior to the Kobe earthquake. Arsenic levels above the standard were found in the tributaries on occasions during sampling, but no baseline data were available to compare pre- and post-earthquake levels.

The groundwater in the area is known to contain arsenic due to its geological characteristics. Several smaller earthquakes occurred in the region surrounding the river prior to the larger earthquake centred 35 km away. It is thought that the seismic activity in the area caused displacement along the active faults and this resulted in groundwater containing arsenic rerouting into the tributary rivers of the Inagawa River. This led to the detection of arsenic in well-waters and groundwater in the area.

3.3 Modeling of earthquake-induced hydrological changes and possible permeability enhancement due to the 17 January 1995 Kobe earthquake, Japan (Tokunaga 1999)

Hydrological changes occurred in response to the 1995 earthquake in Kobe, Japan. These changes included:

- a large drop in the water table in the mountainous area, which continued for four months
- the water table in the central part of the island dropping tens of metres
- a rapid increase in the discharge of water along the active faults, which continued for more than a year
- changes to the chemistry of the discharged water, which continued for more than 10 months.

The drop in the water table, the increased discharge of water and the changes in water chemistry are explained by the increased aquifer permeability due to the earthquake. The increased permeability also allowed saltwater intrusion into the aquifer resulting in the upward movement of deeper water or mixing with other deep water.

3.4 Temporal variation of seepage water chemistry before and after the Hengchun Ms 7.2 earthquake in south Taiwan (Liu et al 2010)

A magnitude 7.2 earthquake struck Taiwan in December 2006. The epicentre was close to a nature reserve where on-going scientific studies were occurring. Over the five years preceding the earthquake, seepage waters from the nature reserve had been sampled and analysed for a range of chemical determinands. This had continued for one year after the earthquake. Temporary and permanent modifications to the water chemistry had occurred because of the earthquake. The concentrations of calcium and bicarbonate showed sharp increases before the earthquake and steadily decreased after. This was due to increased contact between the thermal waters and the limestone rock (a source of bicarbonate/carbonate ions) in the aquifer, because of changes to flow through the aquifer prior to the earthquake in response to the increased tectonic activity. The concentration of chloride in the seepage water also increased two years prior to the earthquake and remained elevated for the 12 months after the earthquake.

3.5 Hydrogeochemical changes before and after a major earthquake (Claesson 2004)

This study investigated the hydrogeochemical changes which occurred in 1500 m deep borehole water before and after the magnitude 5.8 earthquake in Iceland in 2002. Before the earthquake several changes in the geochemistry of the water were noted. The change was attributed to the mixing of the original bore water with other fluids that had been in contact with hot basalt. This mixing caused a change in the copper, zinc manganese, iron and chromium concentrations in the water. Post-earthquake changes were also noted in the water samples. It is thought these were due to seismic stress sealing the original aquifer and switching the source of the bore water to a new distinct aquifer that contained older water reservoirs.

3.6 Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes (Rojstaczer 1995)

Following the October 1989 earthquake in California three major changes were noted in the region surrounding the epicentre.

- Stream flow increased within 15 minutes of the earthquake.
- The ionic concentration of the stream water increased.
- The water table dropped at sites up to 15 km away from the epicentre.

Unlike the other changes, the drop in the water table occurred many months after the earthquake, highlighting the long-term impacts of an earthquake on a water system. The increased permeability of the earth's crust caused an increase in the rate of groundwater flow into the streams. This increased flow of groundwater to the streams without an increased recharge to the groundwater system created a water mass imbalance and forced the water table to drop.

Studies three years after the earthquake found that the increased permeability of the shallow crust remained. The ionic concentrations of the water had also remained elevated confirming the increased permeability.

3.7 Hydrologic changes associated with the October 28, 1983, Idaho earthquake (Whitehead et al 1984)

Following the 1983 magnitude 7.3 earthquake in Idaho, significant hydrologic changes were observed. While most of these changes were observed close to the epicentre, some changes occurred in wells up to 700 km away. Several hydrologic changes were noted from data compiled from well and spring recorder charts, observation and unconfirmed reports, including:

- a change in discharge rate
- surges in discharge rate
- changes in water table levels
- changes in water colour (water going brown) and odour (hydrogen sulphide)
- increased iron levels in water
- drying up of a well.

Groundwater in wells close to the epicentre rose rapidly and sometimes overtopped their casings. Much of the water from these wells was muddy and clogged pumps. In wells where water levels dropped, the water was muddy and smelt of hydrogen sulphide gas. Changes in groundwater levels were noted at wells 210 km from the epicentre and remained significantly different (10 fold increase in discharge rate) for six months after the earthquake.

After the earthquake some surface water flows doubled, and temporary lakes were formed.

3.8 Chemical variations of ground water affected by the earthquake in Bam region (Malakootian and Nouri 2010)

A magnitude 6.3 earthquake struck in the Bam region of Iran in December 2003. A study was carried out to determine the impact the earthquake had on the chemical quality of the groundwater resources in the area surrounding the epicentre. Samples were taken from drinking water wells and agricultural wells one year prior to, and for over two years post-earthquake. Measurements were made of electrical conductivity, total dissolved solids, pH and a range of cations and anions. Post-earthquake, the chemical quality of the water from the wells fluctuated more than it had before the earthquake. Determinand levels fluctuated by 7–83%. All parameters reached their highest level in the first year post-earthquake.

Aftershocks in the region caused an increase in dissolved minerals. As the aftershocks decreased in frequency, the fluctuations in water quality returned to normal. While none of the measured determinands breached the Iranian water quality standards, they did display significant concentration changes from before the earthquake to 12 months afterwards.

Various factors were identified as influencing the chemical composition of the groundwater.

- Contact of the water with rocks nearer the surface because of water level fluctuations caused by the earthquake.
- Water temperature fluctuations increasing the solubility of minerals.
- Mixing of water between aquifers caused by the earthquake.
- Amount of rainfall influencing dilution rates.

3.9 Identifying and managing conjoint threats: earthquake-induced hazardous materials released in the US (Lindell and Perry 1996)

This paper reports a case review of the hazardous materials problems that arose during the 1994 Northridge (California, USA) earthquake. The magnitude 6.8 earthquake resulted in unexpectedly large consequences because of its unprecedented horizontal and vertical accelerations.

Of the more than 2000 hazardous materials assessments made post-earthquake, approximately 7% of the sites/structures inspected had some level of hazardous materials concern. Structural damage was not necessarily the cause of concern for earthquake-initiated hazardous materials release. Spillage of chemicals from containers such as open-top tanks and retail chemical supply stores, and from a derailed train, were of concern.

The standard operating procedure for petroleum pipeline pumping stations following an earthquake is to shut down immediately, but this did not eliminate spillage. Crude oil contaminated soil, rivers and groundwater (see also Young et al 2004).

4 Guidance on delayed contamination

The Drinking-water Standards for New Zealand already provide the possible protocols for determining whether a groundwater source should be regarded as secure. The difficulty faced in making these assessments following the Christchurch earthquakes is knowing when these protocols can be applied. These assessments must wait until any delayed effects from the earthquake have become apparent.

Four questions are pertinent to evaluating when to make the assessment of security status. They also provide guidance in determining what might provide early warning of delayed chemical contamination, should it occur, which is not covered by the compliance criteria for bore water security.

1. What could cause a delayed change in groundwater quality?
2. What contaminants are of concern?
3. How long might the effects take to become apparent?
4. How long might the effects continue?

International experience is one source of information to help answer these questions.

The following sections respond to the four questions, first with an outline of general considerations, followed by any guidance found in the literature from international experiences.

4.1 Causes of change in groundwater quality

Changes in groundwater quality after an earthquake might be expected as a consequence of:

- surface-influenced contamination from, for example:
  - infiltration of contaminants from the surface or near surface from accidental spill, such as fuel storage under service stations
  - infiltration of contaminants from the surface into unconfined aquifers as the result of the unsaturated zone material becoming more permeable
  - direct flow of contaminants into confined or unconfined aquifers through a damaged well-head or well casing
  - a fault zone creating direct connection between the surface and the aquifer
- mixing of waters of different qualities between aquifers caused by, for example:
  - fracturing of confining layers between aquifers
  - short circuiting via damaged well casings passing between aquifers
- mixing of seawater with groundwater, which is of particular concern if the interface moves onshore
- dissolution of contaminants from subsurface material when the groundwater level of a saturated zone rises into an unsaturated zone, or dissolved gas concentrations change, or hydraulic pressure or temperature change.

These events could cause immediate and delayed impacts on groundwater quality. Regular monitoring of the quality of bore water to detect changes in water quality will provide evidence of one or more of the events above having occurred.

What guidance can be gathered from international experiences?

- The disposal of earthquake demolition rubble has the potential to be a long-term source of contaminants that impact on groundwater quality. The contaminants may be from the rubble itself (eg, heavy metals), or released from other material in the landfill because the degrading rubble changes properties such as leachate pH.
- Ruptured petroleum infrastructure has the potential to contaminate groundwater as the petroleum products permeate downwards.
- Seismic activity along active faults has the potential to cause mixing of waters of different qualities between aquifers and to influence surface water quality.
- Increased aquifer permeability has the potential to allow the intrusion of saltwater causing upward movement of deeper water.
- Seismic activity has the potential to seal some aquifers and open others.
- Water level fluctuation has the potential to solubilise minerals through the water coming into contact with aquifer materials with which it had not previously been in contact.
- Water temperature increase has the potential to solubilise minerals.

4.2 Contaminants of concern

For drinking-water, whether sourced from groundwater or surface water, the contaminants of concern to the health of people include pathogenic[6] microorganisms and health significant chemicals. Highest priority is given to microbial contamination because this can lead to rapid and major outbreaks of illness.

Based on New Zealand experience, the health significant chemicals that could be present in groundwater may originate from:

- dissolution of subsurface material, particularly arsenic, manganese, fluoride and boron
- surface contamination, particularly:
    - nitrate and reduced forms of nitrogen (nitrite and ammonia) from septic tanks, sewage outfalls or overflows, intensive grazing, spray irrigation of effluent, and land application of biosolids or nitrogen fertiliser
    - industrial chemicals from fuel storage, timber treatment, landfill, demolition debris, chemical storage, manufacturing and processing.

In addition to health significant chemicals, aesthetic water quality determinands[7] that could be present in groundwater include turbidity and iron, as well as sodium and chloride if seawater intrudes into freshwater.

What guidance can be gathered from international experiences?

- Heavy metals may be present in water from the disposal of earthquake demolition rubble.
- Contact of groundwater with hot basalt may result in the dissolution of heavy metals into the water.

[6] Pathogenic microorganisms are capable of making people ill.
[7] Aesthetic parameters are those that can adversely affect the water's taste, odour, colour or general appearance.

- Changes in the chemistry of waters, such as the appearance of arsenic, because of the mixing of waters between aquifers.
- Iron-enriched, coloured and turbid water from groundwater surges and ground shaking.
- Petroleum products arising in water because of ruptured petroleum infrastructure.
- Changes in the concentrations of cations and anions due to saltwater intrusion.

4.3 Period of delay

Changes in groundwater quality after an earthquake may arise for three reasons:

a) disruption of aquifers, which may result in gradual water quality changes through processes such as the slow mixing of waters from two initially separate aquifers, or the slow dissolution of new determinands into water that is in contact with new materials (both natural and of human origin – such as old landfills)

b) infiltration of surface contaminants as the result of disruption of the layers within the unsaturated zone

c) burial of materials produced from the cleanup after the earthquake, which later undergo chemical changes.

Changes in water quality arising from the causes in a) could happen from the time of the earthquake. However, if the changes are slow, they will appear to have a delay because of the time for them to become apparent at monitoring points. If the concentration of the determinand was previously below the test method's limit of detection, it may also take time for the determinand's concentration to exceed the limit of detection.

Although c) is not a result of the earthquake changing the hydrogeology of the aquifer system, it still arises because of the earthquake. The apparent delay associated with situations such as this, will arise for reasons similar to those associated with a).

In the case of contamination from the surface, b), the time taken for changes in groundwater quality to become apparent will depend on how quickly the contaminant infiltrates into the aquifer, and the speed at which the contaminated plume of groundwater reaches the monitoring point(s).

Groundwater is most vulnerable to contamination from the surface where:

a) the contaminant is soluble, with little tendency to adsorb to soils and aquifer material and is resistant to degradation

b) there are highly permeable coarse textured soils and gravel deposits that allow water and dissolved compounds to infiltrate freely down to the groundwater

c) the water table is close to the surface

d) the area is subject to heavy rainfall.

Once contaminants enter an aquifer, wells down-gradient that are not far from groundwater flow lines passing through the contaminant plume are at risk of contamination. In addition to the factors that influence rates of infiltration, the rate and extent of lateral dispersion of contaminants is influenced by the hydraulic gradient, the nature of the aquifer material, and the distance the contaminants have travelled.

What guidance can be gathered from international experiences?

- The reviewed literature did not provide guidance on the delay period after a major earthquake before an event caused by the earthquake becomes apparent through a change in groundwater quality.

4.4 Duration of impacts

Contamination of groundwater will continue as long as there is a source of the contaminant. Consequently, the most important action to take is removing the source of contamination, if this is possible, for example, repairing a leaking pipe or container, or removal of material from disused landfills. Attention can then shift to reducing the concentration of contaminant in the affected soil and aquifer material.

The attenuation of contaminants in groundwater (reducing their concentration) is achieved through natural processes that reduce the volume, mobility, toxicity or concentration of contaminants, such as ion exchange, chemical precipitation, adsorption, filtration, biodegradation and dispersion. The contribution made by each process depends on the properties of the contaminant and the soil and aquifer material in the particular situation. In addition to natural attenuation of contaminants, active remediation is an option and includes containment and removal of contaminated soil and aquifer material.

Reducing or removing the source of a naturally-derived contaminant is not possible.

What guidance can be gathered from international experiences?

- Landfill leachate contaminated with heavy metals was detected in shallow groundwater five years after disposal of what was considered to be inert demolition debris to the landfill. Without remedial action, it is likely that this type of effect will last for a long period.
- More generally, elevated levels of major ions in groundwater and seepage water continued for typically more than one year post-earthquake. Health significant chemicals are not always routinely monitored in groundwater. However, post-earthquake changes in major ion composition of groundwater should indicate the possible presence of health significant determinands and the need to design a suitable monitoring programme.

5 Conclusions

Section 4 summarised the information to address the four questions posed. This section draws this information together, and assesses what it means for understanding the potential contamination threats to Christchurch's water supply.

While water quality changes are described in international accounts of the effects of earthquakes on groundwater, the literature search found no reports of delayed effects. We do not know whether this means that such effects did not occur, or they went unnoticed. However, as it is possible to conceive of ways in which delays might occur, we cannot assume that they will not occur as a result of the Christchurch earthquakes.

Without guidance from past experience as to how long it may take for delays to become apparent, it appears that observations, inspection, monitoring and estimations of times based on aquifer properties will be necessary for determining when any delayed changes may occur.

The following are suggested actions (or observations) to either reduce the likelihood of contaminants reaching the Christchurch drinking-water supply bores, or provide sentinel monitoring for contaminants. Some of these may already have been done.

a) Identifying possible contamination sources

   i. Check the integrity of all underground and above ground chemical storage systems in the city and in the area up-gradient of the city.

   ii. Geologically-derived contaminants from heated igneous rocks (as reported in some overseas accounts) seem unlikely because of the shallow focus of the earthquakes, and the geological makeup of the strata underlying Canterbury Plains. Contaminants such as heavy metals, and others often associated with geothermal activity are unlikely to be a concern.

b) Assessing pathways potentially carrying contaminants to wells

   i. Inspect and verify the security of the city's wellheads and wellheads of bores up-gradient that draw from the same aquifers as the city.

   ii. Identify locations where there is evidence of faults appearing on the ground surface and determine the nature of potential nearby contamination sources (above and below ground).

   iii. Collate what is known about the properties of the aquifers underlying Christchurch (for example, transmissivity, storativity, water level (in unconfined aquifers) and stratigraphy from bore logs). Substantial changes to the nature of an aquifer may be possible to determine from comparison of these historical data with bore-logs, and with new pump tests on bores. There would be value in re-determining the transmissivity and storativity data of the city's aquifers, as time and resources permit, to provide a baseline against which possible future changes (resulting from future earthquakes) can be compared. The Christchurch City Council has bores that are not used for supply purposes any longer. If they can still be pumped, or sampled, these should not be overlooked as sources of information about possible changes to the aquifers.

   iv. Estimate the velocity of water through the aquifers and use this information with the distance of possible contaminant sources to the west of the city to estimate the time it might take contaminants to reach the city bores. This would probably be the shortest time it would take for contaminants to become evident. Dilution, attenuation and the sensitivity of measurement techniques may extend the time before a contaminant plume is detected.

   v. Determine whether changes to the permeability of the unsaturated strata have occurred, as this could influence how readily surface contaminants can reach unconfined aquifers. This may be the case where liquefaction has occurred.

c) Monitoring of water quality

   Despite the suggestions in a) and b) there may be changes that have occurred to the aquifer system that cannot be detected, but which, in time, may still result in contaminants reaching the city's bores. Consequently monitoring is still necessary to check for water quality changes.

   i. The city council has a large number of bores, but the number of bores that need to be routinely monitored can be minimised by recognising that there are two primary routes of contaminant ingress into the supply aquifers: vertically through the ground over the city area, and horizontally as the result of contaminants entering the aquifers farther west.

The vertical path can be monitored by taking water from the shallowest aquifers at random points over the city area. The horizontal path can be monitored by sampling from bores at a range of depths in the west and northwest of the city.

ii. A high sampling frequency is not required to monitor chemical determinands, because, at their typical concentrations their health effects only become evident after years of exposure. Moreover, the rate which their concentrations change is usually not rapid. As a result, unless there is specific reason to suspect high levels of contamination, quarterly monitoring would be adequate, although monthly monitoring would be preferable. The higher frequency will allow a more reliable measure of the variability of water quality to be assessed more rapidly. This frequency can be revisited after the first year.

iii. The suggested determinands to monitor are: conductivity, turbidity, alkalinity, iron and manganese. All these determinands are cheap and simple to measure. Conductivity provides an overview of changes in the ionic make up of the water. Turbidity shows whether the water's particulate content is changing. Alkalinity has been found to increase in waters affected from landfill leachate. Iron and manganese are ubiquitous metals that frequently arise in Canterbury groundwaters. While heavy metals are not naturally-occurring in Canterbury, changes in an aquifer's water table may affect the dissolution of iron and manganese into water.

iv. If there is reason to suspect contamination by a particular determinand, for example a ruptured fuel storage tank, this should be included in the monitoring list, as should any determinand that historical monitoring has found to be a good indicator contamination or changes in source water quality.

As well as helping to determine whether delayed changes in water quality may occur or are occurring, these suggested actions should also provide checks on water quality until such times as the protocols in the Drinking-Water Standards for New Zealand can be implemented for re-establishing the secure status of the Christchurch groundwaters.

6 References

Christchurch City Council. 2009. *Water Supply Strategy 2009-2039*. Christchurch: Christchurch City Council.

Environment Canterbury. 2005. *Canterbury Civil Defence Emergency Management Group Plan 2005-2010*. Christchurch: Environment Canterbury.

Environment Canterbury. 2011. *Earthquake impacts on groundwater. Updates #1, #2, #3.* Christchurch: Environment Canterbury.

Geological and Nuclear Sciences. 2012a. *2010 Darfield (Canterbury) earthquake.* http://www.gns.cri.nz/Home/News-and-Events/Media-Releases/Most-damaging-quake-since-1931/Canterbury-quake/Darfield-Earthquake. (Accessed March 2012).

Geological and Nuclear Sciences. 2012b. *The hidden fault that caused the February 2011 Christchurch earthquake.* http://www.gns.cri.nz/Home/News-and-Events/Media-Releases/Most-damaging-quake-since-1931/Canterbury-quake/Hidden-fault. (Accessed March 2012).

Ministry of Health. 2008. *Drinking-water Standards for New Zealand 2005 (Revised 2008)*. Wellington: Ministry of Health.

Royal Society of New Zealand. 2012. *The Canterbury earthquakes: Scientific answers to critical questions.* http://www.royalsociety.org.nz/2011/03/16/earthquake-information-paper/. (Accessed March 2012).

7 Bibliography of papers reviewed

Amato RL. 2001. Emergency preparedness guidelines for water treatment systems. *Nephrol Nurs J* 28(5): 500–503.

Andrade AIASS and Stigter TY. 2009. Multi-method assessment of nitrate and pesticide contamination in shallow alluvial groundwater as a function of hydrogeological setting and land use. *Agricultural Water Management* 96(12): 1751–1765.

Bannister SC, Perin BJ, Webb TH. 1989. Normal faulting through subducted oceanic crust: the 19 July 1985 earthquake of Hawke's Bay, New Zealand. *Tectonophysics* 162(3–4): 303–313.

Benmenni MS, Benrachedi K. 2010. Impact of Earthquake demolition debris on the quality of groundwater. *American Journal of Applied Sciences* 7(4): 545–550.

Bhattacharya S, Hyodo M, Goda K, et al. Liquefaction of soil in the Tokyo Bay area from the 2011 Tohoku (Japan) earthquake. *Soil Dynamics and Earthquake Engineering* 31(11): 1618–1628.

Biagi PF, Bella F, Scandone R, et al. 1999. Groundwater argon content on the occasion of strong earthquakes in a seismogenetic area of Kamchatka (Russia). *IL Nuovo Cimento* 22: 503–508.

Biagi PF, Castellana L, Minafra A, et al. 2006. Groundwater chemical anomalies connected with the Kamchatka earthquake (M=7.1) on March 1992. *Natural Hazards and Earth System Sciences* 6(5): 853–859.

Cao ZZ, Youd TL, Yuan XM. 2011. Gravelly soils that liquefied during 2008 Wenchuan, China earthquake, M(s)=8.0. *Soil Dynamics and Earthquake Engineering* 31(8): 1132–1143.

Chabaud S, Andres Y, Lakel A, et al. 2006. Bacteria removal in septic effluent: Influence of biofilm and protozoa. *Water Research* 40(16): 3109–3114.

Chia Y, Chiu JJ, Chung PY, et al. 2009. Spatial distribution of groundwater level changes induced by the 2006 Hengchun earthquake doublet. *Terrestrial, Atmospheric and Oceanic Sciences* 20(2): 315–324.

Claesson L, Skelton A, Graham C, et al. 2004. Hydrogeochemical changes before and after a major earthquake. *Geology* 32(8): 641–644.

Cousins J, Perrin N, Hancox G, et al. 2010. Bulk water supply - impacts of a Wellington fault earthquake. New Zealand Society of Earthquake Engineering conference paper 54.

Davraz A, Karaguzel R, Soyaslan II. 2003. The importance of hydrogeological and hydrological investigations in the residential area: a case study in Burdur, Turkey. *Environmental Geology* 44: 851–861.

Davey F. 2011. Natural hazards - the Christchurch earthquakes. *New Zealand Journal of Geology and Geophysics* 54(2): 149–150.

Esposito E, Pece R, Porfido S, et al. 2001. Hydrological anomalies connected to earthquakes in southern Apennines (Italy). *Natural Hazards and Earth System Sciences* 1: 137–144.

Favara R, Grassa F, Inguaggiato S, et al. 2001. Hydrogeochemistry and stable isotopes of thermal springs: earthquake-related chemical changes along Belice Fault (Western Sicily). *Applied Geochemistry* 16(1): 1–17.

Fawell J, Nieuwenhuijsen MJ. 2003. Contaminants in Drinking Water. *Br Med Bull* 68: 199–208.

Gupta SK, Suantio A, Gray A, et al. 2007. Factors associated with e. coli contamination of household drinking water among tsunami and earthquake survivors, Indonesia. *The American Journal of Tropical Medicine and Hygiene* 76(6): 1158–1162.

Hanna AM, Ural D, Saygili G. 2007. Neural network model for liquefaction potential in soil deposits using Turkey and Taiwan earthquake data. *Soil Dynamics and Earthquake Engineering* 27(6): 521–540.

Holzer TL, Jayko AS, Hauksson E, et al. 2010. Liquefaction caused by the 2009 Olancha, California (USA), M5.2 earthquake. *Engineering Geology* 116(1-2): 184–188.

Igarashi G, Saeki S, Takahata N, et al. 1995. Groundwater radon anomaly before the Kobe earthquake in Japan. *Science* 269(5220): 60–61.

Kaplanides AC, Mimides TM, Papadopoulos NB. 1997. A review of seismic effects on underground structures, groundwater regimes and hydrochemistry effects. *Engineering Geology and the Environment* 1(3): 737–743.

Keskin TE. 2010. Groundwater changes in relation to seismic activity: A case study from Eskipazar (Karabuk, Turkey). *Hydrogeology Journal* 18(5): 1205–1218.

Khan MA, Sharma ML. 2003. Kachchh (India) earthquake 2001 - causes, severity and impact on groundwater resources. *Journal of Environmental Sciences* 15(4): 500–505.

King CY, Basler D, Presser TS, et al. 1994. In search of earthquake-related hydrologic and chemical changes along Hayward Fault. *Applied Geochemistry* 9(1): 83–91.

King CY, Zhang W, Zhang Z. 2006. Earthquake-induced groundwater and gas changes. *Pure and Applied Geophysics* 163(4): 633–645.

Kingsley SP, Biagi PF, Piccolo R, et al. 2001. Hydrogeochemical precursors of strong earthquakes: a realistic possibility in Kamchatka. *Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science* 26(10–12): 769–774.

Koch U, Heinicke J, Voβberg M. 2003. Hydrogeological effects of the latest Vogtland-NW Bohemian swarmquake period (August to December 2000). *Journal of Geodynamics* 35(1–2): 107–123.

Ku C-S, Lee D-H, Wu, J-H. 2004. Evaluation of soil liquefaction in the Chi-Chi, Taiwan earthquake using CPT. *Soil Dynamics and Earthquake Engineering* 24(9–10): 659–673.

Lindell MK, Perry RW. 1996. Identifying and managing conjoint threats: Earthquake-induced hazardous materials releases in the US. *Journal of Hazardous Materials* 50: 31–46.

Liu CP, Wang CH, Hwang LS. 2010. Temporal variation of seepage water chemistry before and after the Hengchun Ms 7.2 earthquake in south Taiwan. *Geoderma* 155(1–2): 107–114.

Magan M, Bile KM, Kazi BM, et al. 2010. Safe water supply in emergencies and the need for an exit strategy to sustain health gains: lessons learned from the 2005 earthquake in Pakistan. *East Mediterr Health J* 16 Suppl: S91–97.

Mahesh P, Kundu B, Catherine JK, et al. 2011. Anatomy of the 2009 Fiordland earthquake (Mw 7.8), South Island, New Zealand. *Geoscience Frontiers* 2(1): 17–22.

Mahmood Q, Baig SA, Nawab B, et al. 2011. Development of low cost household drinking water treatment system for the earthquake affected communities in Northern Pakistan. *Desalination* 273(2–3): 316–320.

Malakootian M, Nouri J. 2010. Chemical variations of ground water affected by the earthquake in bam region. *International Journal of Environmental Research* 4(3): 443–454.

Montgomery DR, Manga M. 2003. Streamflow and water well responses to earthquakes. *Science* 300:2047–2049.

Moss RES, Kayen RE, Tong LY, et al. 2011. Retesting of Liquefaction and Nonliquefaction Case Histories from the 1976 Tangshan Earthquake. *Journal of Geotechnical and Geoenvironmental Engineering* 137(4): 334–343.

Muir Wood R, Steedman RS. 1992. Earthquake induced groundwater changes and liquefaction. *Earthquake Engineering, Tenth World Conference*: 1337–1341.

Ogoshi K, Mori I, Gotoh K, et al. 1996. Did arsenic contamination in the Inagawa River occur in geogenic relation to the Great Hanshin (Kobe) Earthquake of 1995? *Applied Organometallic Chemistry* 10(9): 757–760.

Papastefanou C. 2010. Variation of radon flux along active fault zones in association with earthquake occurrence. *Radiation Measurements* 45(8): 943–951.

Pasvanoglu S, Canik B, Rosen M. 2004. Hydrogeology and possible effects of the Mw 7.4 Marmara earthquake (17 August 1999) on the spring waters in the Orhangazi-Bursa area, Turkey. *Journal Geological Society of India* 63: 313–322.

Prasad Y, Prasad G, Choubey VM, et al. 2009. Geohydrological control on radon availability in groundwater. *Radiation Measurements* 44(1): 122–126.

Quattrocchi F, Pik R, Pizzino L, et al. 2000. Geochemical changes at the Bagni di Triponzo thermal spring during the Umbria-Marche 1997–1998 seismic sequence. *Journal of Seismology* 4(4): 567–587.

Rasheed F, Khan A, Kazmi SU. 2009. Bacteriological analysis, antimicrobial susceptibility and detection of 16S rRNA gene of Helicobacter pylori by PCR in drinking water samples of earthquake affected areas and other parts of Pakistan. *Malaysian Journal of Microbiology* 5(2): 123–127.

Reddy DV, Nagabhushanam P. 2011. Groundwater electrical conductivity and soil radon gas monitoring for earthquake precursory studies in Koyna, India. *Applied Geochemistry* 26(5): 731–737.

Reyners M, Eberhart-Phillips D. 2009. Small earthquakes provide insight into plate coupling and fluid distribution in the Hikurangi subduction zone, New Zealand. *Earth and Planetary Science Letters* 282(1–4): 299–305.

Rojstaczer S, Wolf S. 1994. Hydrologic changes associated with the earthquake in the San Lorenzo and Pescadero drainage basins. *US Geological Survey Professional Paper* 1551 E: 51–64.

Rojstaczer S, Wolf S, Michel R. 1995. Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes. *Nature* 373(6511): 237–239.

Singh VS. 2008. Impact of the Earthquake and Tsunami of December 26, 2004, on the groundwater regime at Neill Island (south Andaman). *Journal of Environmental Management* 89(1): 58–62.

Smith VH, Tilman GD, Nekola JC. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution* 100(1–3): 179–196.

Song SR, Ku WY, Chen YL, et al. 2003. Groundwater chemical anomaly before and after the Chi-Chi earthquake in Taiwan. *Terrestrial Atmospheric and Oceanic Sciences* 14(3): 311–320.

Tokunaga T. 1999. Modeling of earthquake-induced hydrological changes and possible permeability enhancement due to the 17 January 1995 Kobe Earthquake, Japan. *Journal of Hydrology* 223(3–4): 221–229.

Tsunogai U, Wakita H. 1995. Precursory chemical-changes in-ground water - Kobe earthquake, Japan. *Science* 269(5220): 61–63.

Valdespino Gomez JL, Parrilla Cerillo MC, Sepulveda Amor J, et al. 1987. Quality of the drinking water in Mexico City in relation to the earthquakes of September 1985. *Salud Publica Mex* 29(5): 412–420.

Wall K, Pang L, Sinton L, et al. 2008. Transport and attenuation of microbial tracers and effluent microorganisms in saturated pumice sand aquifer material. *Water Air and Soil Pollution* 188(1–4): 213–224.

Wang K, Chen QF, Sun S, et al. 2006. Predicting the 1975 Haicheng earthquake. *Bulletin of the Seismological Society of America* 96(3): 757–795.

Weisman E, Barber J, Ramsey DS, et al. 1994. Disaster preparedness. Ready for earth, air, fire and water (and who knows what else)? *Health Facil Manage* 7(5): 18–25.

Whitehead RL, Harper RW, Sisco HG. 1984. Hydrologic changes associated with the October 28, 1983, Idaho earthquake. *Pure and Applied Geophysics* 122(2–4): 280–293.

Woith H, Milkereit C, Maiwald U, et al. 1999. Physico-chemical behaviour of underground waters after the October 1, 1995 Dinar earthquake, SW Turkey. *IL Nuovo Cimento* 22: 387–391.

Yang H, Otkur M, Zeng J, et al. 2011. Variation of a spring bacterial community from Wuqia Sinter in Xinjiang during the pre- and post-earthquake period. *Shengtai Xuebao/ Acta Ecologica Sinica* 31(10): 2940–2946.

Young S, Balluz L, Malilay J. 2004. Natural and technologic hazardous material releases during and after natural disasters: a review. *Science of The Total Environment* 322(1–3): 3–20.