Review of the impact of the February 22nd earthquake on the Canterbury health care system

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Abstract

The magnitude 6.2 Christchurch earthquake struck the city of Christchurch at 12:51pm on February 22, 2011. The earthquake caused 186 fatalities, a large number of injuries, and resulted in widespread damage to the built environment, including significant disruption to lifeline networks and health care facilities. Critical facilities, such as public and private hospitals, government, non-government and private emergency services, physicians' offices, clinics and others were severely impacted by this seismic event. Despite these challenges many systems were able to adapt and cope.

This thesis presents the physical and functional impact of the Christchurch earthquake on the regional public healthcare system by analysing how it adapted to respond to the emergency and continued to provide health services. Firstly, it assesses the seismic performance of the facilities, mechanical and medical equipment, building contents, internal services and back-up resources. Secondly, it investigates the reduction of functionality for clinical and non-clinical services, induced by the structural and non-structural damage. Thirdly it assesses the impact on single facilities and the redundancy of the health system as a whole following damage to the road, power, water, and wastewater networks. Finally, it assesses the healthcare network's ability to operate under reduced and surged conditions. The effectiveness of a variety of seismic vulnerability preparedness and reduction methods are critically reviewed by comparing the observed performances with the predicted outcomes of the seismic vulnerability and disaster preparedness models.

Original methodology is proposed in the thesis which was generated by adapting and building on existing methods. The methodology can be used to predict the geographical distribution of functional loss, the residual capacity and the patient transfer travel time for hospital networks following earthquakes. The methodology is used to define the factors which contributed to the overall resilence of the Canterbury hospital network and the areas which decreased the resilence.

The results show that the factors which contributed to the resilence, as well as the factors which caused damage and functionality loss were difficult to foresee and plan for. The non-structural damage to utilities and suspended ceilings was far more disruptive to the provision of healthcare than the minor structural damage to buildings. The physical damage to the healthcare network reduced the capacity, which has further strained a health care system already under pressure. Providing the already high rate of occupancy prior to the Christchurch earthquake the Canterbury healthcare network has still provided adequate healthcare to the community.

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IV. Acronyms

ALOS	Average Length Of Stay
ALV	Average Length of Visit
AMAU	Adult Medical Assessment Unit
CBD	Central Business District
CDEM	Civil Defence Emergency Management
CDHB	Canterbury District Health Board
CREST	Community Rehabilitation Enablement Support Teams
CTV	Canterbury Television
CWH	Christchurch Women's Hospital
DHB	District Health Board
ECC	Emergency Control Centre
ECLAC	Economic Commission for Latin America and the Caribbean
EMS	European Macro seismic Scale
EOC	Emergency Operations Centre
FEMA	Federal Emergency Management Agency
GMPEs	Empirical ground Motion Prediction Equations
IC	Incident Controller
LRI	Liquefaction Resistance Index
LOS	Length of Stay
MMI	Modified Mercalli Index
MMS	Medication Management Service
MOH	Ministry Of Health
NCMC	National Crisis Management Centre
NHCC	National Health Coordination Centre
NHRP	Natural Hazards Research Management Platform
OSHPD	Office of Statewide Health Planning and Development
OVMC	Olive View Medical Centre
PAHO	Pan American Health Organization
PDNA	Post Disaster Needs Assessment
PGA	Peak Ground Acceleration
PMH	Princess Margaret Hospital
Rhise	Research re the Health Implications of Seismic Events
SARA	Surgical Assessment and Review Area
SLD	Damage Limitation
SLS	Serviceability Limit State
SLV	Life Safety
UHS	Uniform Hazard Spectra
ULS	Ultimate Limit State
WHO	World health organization
WT	Waiting Time.
VSL	Value of Statistical Life

1. Chapter One: Introduction

1.1 Introduction

Earthquakes pose a significant risk to the ability of hospitals and hospital networks to provide continued uninterrupted healthcare to the community. They do so by damaging the vital physical elements which are required to supply, house and treat patients.

A functioning healthcare network is a crucial part of disaster response. Therefore the facilities that make up the healthcare network must be able to not only to treat the victims of any type of likely event, but also to continue the healthcare services necessary to maintain the healthcare for the community (WHO 2006). The United Nations World Health Organization (WHO) made hospital risk and vulnerability reduction a priority by introducing the "Safe Hospitals" Initiative (WHO 2009). Despite these efforts, healthcare facilities have suffered great losses globally due to natural and human-caused disasters, particularly earthquakes and hurricanes.

The Mw=6.2 earthquake that ruptured beneath Christchurch, New Zealand, on the 22nd of February, 2011, at 12:51 pm (NZ local time), also caused significant disruption to the main health care facilities in Christchurch. In total there were 185 fatalities and 7171 injuries (Ardagh et al., 2012). The extensive physical damage caused by the earthquake placed the Canterbury healthcare system under considerable strain. However, despite the physical damage, lifelines outages, and damage to internal services the Canterbury Health Care System continued to provide a high quality of healthcare following the Christchurch earthquake. The cause of the healthcare network resilience presents a valuable learning opportunity.

The approach that is used to determine the how the Christchurch hospital network exhibited a resilient response is outlined in Section 1.4. The methodical approach begins with a review of related literature and seismic vulnerability assessment methodology for hospitals. The assessment methodology is implemented with data collected from the post Christchurch earthquake Christchurch hospital network. The purpose for implementing the methodology is to define the areas that accounted for the resilient response in the Christchurch hospital network. As well to provide recommendations based on the performance of the assessment methodology for future pre earthquake hospital network vulnerability assessment.

1.2 Context

1.2.1 Canterbury Hospital network seismic vulnerability

The 4th of September, 2010 to present day Canterbury earthquake sequence produced ground shaking in several events which was much larger than previously forecast for Christchurch (Stirling et al., 2007). As a result the seismic model only predicted a medium intensity earthquake would strike

Canterbury. Prior to the 4 September 2010 Mw7.1 Darfield earthquake the predicted sources for an earthquake which could damage Christchurch were the Alpine Fault, Foothills Fault (Porters Pass Fault) and a Blind thrust Fault beneath Canterbury (Dorn et al., 2010). The threat of a "direct hit" from a blind thrust fault beneath Canterbury was deemed to be much less likely than an Alpine Fault earthquake or a Porters Pass Fault earthquake (these faults are further defined in Section 2.1.1.1). In a wider sense, attention on seismic hazard generally focused on identified, active, high recurrence interval faults located close to urban centers, such as the Wellington Fault which runs directly beneath New Zealand's capital City Wellington. As a result, Christchurch was deemed to have a comparatively moderate or even low seismic hazard before the Canterbury earthquake sequence (Dorn et al., 2010).

New Zealand's approach for quantifying the seismic hazard is based on the probabilistic seismic analysis model (NZS4203:1992). The model incorporates geological data including; recurrence intervals and locations of 305 active faults, a catalogue of historical seismicity, attenuation relationships for peak ground acceleration and spectral acceleration (geological context further defined in Section 2.1.1.1). The seismic hazard is the highest in Wellington since it is closest to a number of major active faults. In descending order of seismic hazard following Wellington are; Christchurch, Dunedin and Auckland (Davenport 2004) (Section 2.3.2).

In preparation for an earthquake the Canterbury hospital network and the Canterbury District Health Board (CDHB) had planned for the issues that were predicted to arise following an earthquake. The hospital network achieved this by running hazard scenarios at a regional and local level in order to identify areas of weakness (MOH 2010). The structure of the CDHB and the CDHBs approach to hazard management is defined in further Section 2.1.5.1.

1.2.2 Canterbury earthquake's sequence

The Mw 7.1 Darfield earthquake ruptured at 4:36am on the 4th of September, 2010. The rupture was a combination of oblique strike-slip movement on a previously unknown fault (Figure 1.1). Now called the Greendale fault (assigned a slip rate of 0.2 mm/year) (Villamor et al., 2011) it is one of a series of previously unknown seismically active faults in the Canterbury region to have ruptured during the Darfield earthquake aftershock sequence.

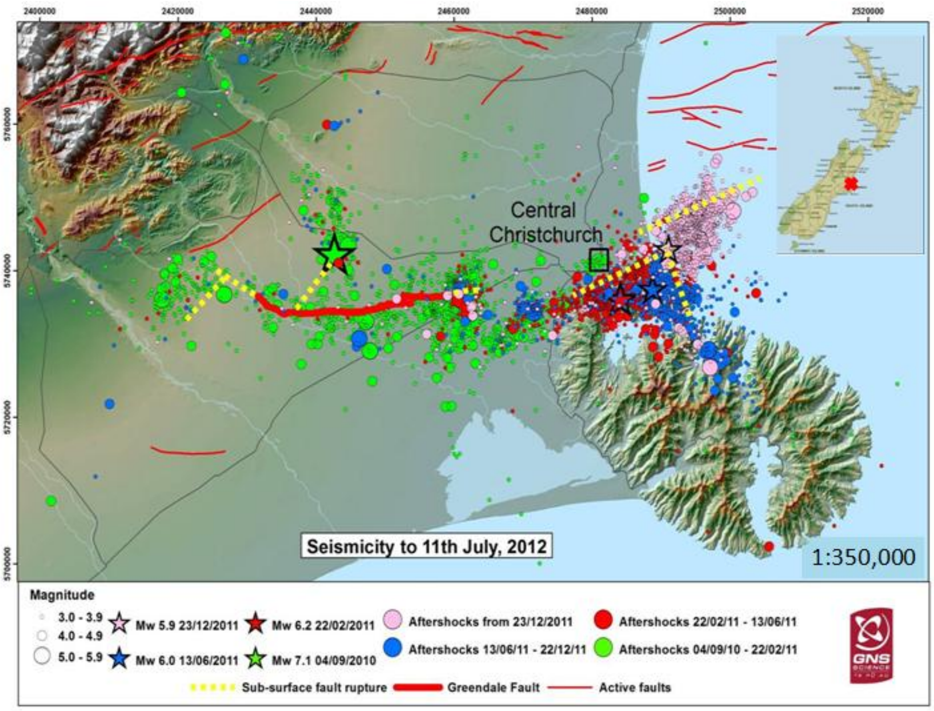

Figure 1.1: The epicenters of Mw 71 Darfield earthquake and the Mw 6.2 (M 6.3) Christchurch earthquake and their aftershocks

The most destructive aftershock thus far was the Mw 6.2, 12:52 PM, 22nd of February, 2011 Christchurch earthquake (Figure 1.1). It ruptured 10 km south of Central Christchurch with a hypocenter depth of 7 km on a previously unknown blind thrust fault located below the Port Hill's of Banks Peninsula (Geonet 2011). The earthquake is characterized as a reverse thrust event with a slight oblique movement (Geonet 2011). The rupture was oriented towards the Christchurch Central Business District (CBD), because of this large energy pulses were directed towards the city. While the magnitude and duration of the Christchurch earthquake were less than the Darfield earthquake, the PGA and the impact of liquefaction in Christchurch City were much larger. The PGA in central Christchurch exceeded 1.8*g* (vertical) the highest recording was 2.2*g* (vertical) at Heathcote Valley (Geonet 2011).

The Christchurch earthquake caused extensive liquefaction which induced permanent ground deformations in the form of land settlement and lateral spreading, the result was lifeline damage, utility damage, road network damage and building damage. There have been 13 earthquakes of Mw 5.0 or greater following the Christchurch earthquake (Figure 1.1) (up to the 31st of March, 2012), in some cases further straining damaged critical infrastructure (Geonet 2013). Just two of the Canterbury earthquakes and aftershocks caused fatalities. 185 casualties were caused by the Christchurch earthquake and one fatality from the 13th of June, 2011 earthquake (New Zealand Police 2011).

1.3 Research objectives

The aim of this research is to determine ways to increase the resilience of hospitals and hospital networks to earthquake induced physical damage and organizational disruption and further define ways to provide continued healthcare following large earthquakes. The main objectives are:

- Prepare a literature review in order to draw common themes from post disaster hospital case studies. As well the review of literature is intended to determine the key components of hospitals and hospital networks that increase resilence and impeded post disaster functionality.
- Define how the Canterbury hospital network was prepared for seismic hazards in the short term and long term leading up to the Christchurch earthquake and how the 4th of September, 2010, M 7.1Darfield earthquake influenced the preparedness of the Canterbury Hospital network (disaster management strategies, seismic zoning, anti-seismic building codes).
- Define how the physical and organizational elements of the Christchurch hospital network performed following the 22nd of February, 2011, Mw 6.3 Christchurch earthquake.
- Assess the merit and apply scenario based, physical and organizational assessment methodology to quantify the damage Christchurch's hospital network sustained.
- Develop a conceptual model in order to predict the location and speed of patient redistribution following functional loss to hospitals.
- Provide recommendations for other hospitals and hospital networks in seismically active cities.

Hospitals can be affected by a range of factors following large earthquakes; this is symptomatic of the complexity of modern hospital networks. The performance of the Canterbury hospital network following the Canterbury earthquakes has provided an opportunity to identify gaps in knowledge regarding modern hospital network disaster preparedness and apply the results to other New Zealand and international seismically active centers such as Wellington. It is of huge importance that hospitals provide continued care following earthquakes in order to avoid further secondary casualties (FEMA 2007).

1.4 Methodology of Thesis

The thesis is the divided into six chapters in order to methodically address the objectives (Section 1.5). Each chapter builds on information presented and or critiqued in the previous chapters. The first and broadest review of information is the Literature review. The literature review of hospitals and hospital networks in the context of past disasters, their components and their design and construction standards defines the scope of the objectives.

The conclusions which were drawn from Chapter Two informed the type of data which was collected and presented in Chapter Three. The specific areas within the hospital network that indicate the loss of functionality and inter-hospital network response were indentified. Princess Margaret's Hospital, Akaroa Hospital, Kaikoura Hospital and Ellesmere hospital are used to represent the Canterbury hospital network. The five Hospitals were chosen because they represent a cross section of the Canterbury hospital network. As well there is limited data available for all the other hospitals in the Canterbury Hospital network.

Different hospital seismic risk assessment methodologies are reviewed in Chapter Four. Applicability to the Christchurch situation is informed by the data available in Chapter Three. Only the methods that are identified as being realistic with the available Christchurch hospital network data are implemented. Implementing the assessment methodology with data from the post Christchurch earthquake Canterbury Hospital network tests the effectiveness of the methodology. A holistic assessment methodology is then used in Chapter Five to define the areas of the Canterbury hospital network that increased resilence and the areas that hindered the response.

Recommendations and conclusions are provided in Chapter Six drawing on common qualitative themes throughout all of the chapters and from processed quantitative data.

1.5 Outline of Thesis

1.5.1 Chapter One: Introduction

Chapter One provides the framework for the thesis, including; the geological background, the context and justification for the research, the aim and scope and finally the breakdown of the chapter content.

1.5.2 Chapter Two: Literature review

The purpose of Chapter Two is to review the literature relevant to the hospital organizational structure and building standards in place prior to the Christchurch earthquake in New Zealand and internationally. Focusing on how the Christchurch hospital network was prepared in light of the perceived seismic hazards in the short term (following the Darfield earthquake) including overseas hospital disaster case studies including the; Maule earthquake (Chile) (2010), Kobe earthquake (Japan) (1995), Northridge earthquake (United States of America) (1995), Hurricane Katrina (United States of America) (2005), Chi-Chi earthquake (China) (1999) and the Kashmir earthquake (Pakistan) (2005).

1.5.3 Chapter Three: Impact of the Christchurch earthquake on the Canterbury healthcare system

The content of Chapter Three exemplifies data collected through surveys and access to hospital operational data via the Rhise network (Research re the Health Implications of Seismic Events). The data is laid out qualitatively and quantitatively, characterizing the effects of the Christchurch earthquake on the physical elements of individual hospitals as well as the organizational response of individual hospitals and the hospital network in its entirety.

1.5.4 Chapter Four: Review and implementation of hospital functionality/fragility assessment methodology

The purpose of Chapter Four is to review the prior fragility and functionality methodology for hospitals and hospital networks, by critiquing their suitability for the analysis of the Christchurch hospital network following the Christchurch earthquake. The elements of the methodology considered are; the type of data required the analysis process, the scope of required inputs and the outputs. The most suitable methods are used to model the individual hospital data from the relevant Christchurch hospitals outlined in Chapter Three to ascertain whether the methods provide the outcomes that were observed post Christchurch earthquake. The data used is specific to the individual facilities structural, nonstructural, ground acceleration and organizational components.

1.5.5 Chapter Five: Holistic analysis of the Canterbury Hospital network post Christchurch earthquake

The purpose of Chapter Five is to apply a methodological approach based on the holistic assessment methodology previously reviewed in Chapter Five in order to define a method to quantify the time taken for inter-hospital patient transfer. In order to quantify the affect of the Christchurch earthquake on the entire Christchurch Hospital network and provide a critical review of what was observed. The holistic assessment incorporates; the capacity redistribution, the seismic hazard, the affect of facilities damage and the organizational performance of the Christchurch hospital network following the Christchurch earthquake.

1.5.6 Chapter Six: Conclusions and recommendations

The purpose of Chapter Six draws conclusions from the content of all the previous chapters. This is achieved by drawing from; the observed common themes in the literature review, trends and gaps in the qualitative/quantitative data collected from the Christchurch hospital network following the Christchurch earthquake and the outcomes of the applied methodology. The chapter concludes with recommendations regarding ways to increase the earthquake resilience of hospitals and hospital networks in other seismically active cities.

2. Chapter Two: Literature review

The purpose of this literature review is to analyse why seismic hazards can affect hospitals' functionality in order to inform the research methodology used in this study. The literature review undertakes this by:

- Analysing risk management approaches for hospital disaster resilience, including organizational planning (individual hospital to national hospital network scale), seismic design standards, critical building characteristics and probabilistic seismic assessments
- Case study analysis of hospitals and hospital networks affected by damaging earthquakes.
- Assessment of research methodologies from previous studies that quantify how the physical performance of hospitals during disasters impacts on the provision of health care.

By integrating current best-practice national and international healthcare risk management and lessons from cases studies, conclusions can be drawn as to the most effective methodology for quantifying risk within hospitals and hospital networks. In order to quantify the risk hospitals are exposed to from a known seismic hazard, firstly, the hospital organization's pre existing disaster management plans must be assessed because the "organization" is the structure tasked with the hospital management. Hospital organizations can be categorised as follows:

- The individual hospital organization.
- The regional hospital network organization (Regional District Heath Board).
- The national hospital network organization (The Ministry of Health).

Organizational hazard management strategies are implemented and managed at all of the three levels mentioned above. The natural disaster/earthquake management plans are designed and implemented at individual hospital and regional network levels based on guidance from the national level. Whereas the seismic design standards are designed at a national level and implemented at an individual hospital level. The importance of the organizational environment is illustrated in international case studies including the Maule earthquake (Chile) (2010), Kobe earthquake (Japan) (1995), Northridge earthquake (United States of America) (1995), Hurricane Katrina (United States of America) (2005), Chi-Chi earthquake (China) (1999) and the Kashmir earthquake (Pakistan) (2005).

Well researched case studies have led to a greater understanding of hospital and hospital network fragility. The organizations' ability to cope with seismic hazards is principally quantified using scenario based risk assessment methodology. The purpose of the methodology is to quantify the degree the geological hazards, building codes, the organizational environment, and individual physical components affect the resilience of the organization. Previous studies of earthquake induced hospital/hospital-network damage indicate that disruption and discontinuity are commonly experienced. "Disruption" is used to describe the decrease in functionality but not loss of the provision of healthcare. “Discontinuity” entails the loss of continuously applied healthcare. The causes of disruptions and discontinuities are varied and complicated, symptomatic of the complexity of modern hospitals and hospital networks.

2.1 Risk assessment within hospitals and hospital networks

Risk = the probability of a disaster x the probable impact of the event upon an entity (FEMA 2007). The ‘outrage’ of the population may also determine how risk is assessed (Sandman 1999). Outrage is the term given to the public perception of a hazard. The public may falsely perceive a hazard to be higher than it really is and influence how it is mitigated. For the purpose of this research “Hazard” is defined as any physical object that is reasonably likely to harm or kill humans (Sperber 2001).

Planning for risk in hospitals and hospital networks with a known hazard is difficult given the complexity of hospitals and hospital networks. Therefore, trying to incorporate the probability of unknown hazards is extremely difficult. The complexity of hospitals and hospital networks makes risk hard to quantify. The Pan-American Health Organization described a hospital as “a hotel, an office building, a laboratory, and a warehouse” owing to the complex nature of the services it provides and its dependence on outside resources (PAHO 2000). Risk can never be entirely avoided within a hospital network, so an “acceptable level of risk” by known hazards must be determined from balancing all the components (CEEP 2009). The components which define the seismic risk to hospitals are covered in a framework consisting of the following five environments:

2.1.1 Natural environment

The global, regional and local characteristics of the natural environment determine the probability of an earthquake. Typically, seismic risk is calculated as a probability of a certain magnitude earthquake which creates a certain ground acceleration at a particular location occurring in a given period of time (ICEF 2011). Probabilistic seismic hazard analysis (PSHA) integrates all possible earthquake source scenarios, the possible magnitudes and distances all of which are weighted by the relative likelihood of occurring. The output is the probability of exceeding given ground motion intensity measures (IM) within a constrained time period. Spectral acceleration (e.g., S_a at 0.2, 0.5, 1 and 2 second period) for return periods of 50, 150, 475 and 1000 years is the principle means of classing the degree to which zones in New Zealand are classified vulnerable to seismicity (Stirling et al., 2007)

The seismic intensity is captured using a number of factors which affect ground motions including; source, path, site response and soil structure interaction effects, travel path effects on seismic waves, site response effects and evaluation of ground motion input ate the structures base (Rutenberg et al., 1980). The sources for earthquakes are defined in terms of magnitude, location, focal mechanisms, and the rate in time which earthquakes of different magnitudes occur (ICEF 2011). The parameters associated with the fault characterization are often uncertain due to limited data; this is considered a source of epistemic uncertainty in the complete computed site hazard (Goulet 2007).

2.1.1.1 Canterbury's natural environment

New Zealand's landmass is situated in the southwest of the Pacific Ocean on the highly geologically active Indian-Australian and Pacific Plate margin. The plate margin in the South Island is the right lateral oblique strike slip fault Alpine Fault (slip rate of 27 mm/year). The Alpine Fault is capable of generating a magnitude 8 earthquake (Dorn et al., 2010). An Alpine fault earthquake was considered to be Christchurch's biggest seismic hazard, due to the size of the predicted magnitude. An array of regional faults including the Porters Pass Fault accommodates the strike slip stress associated with the Alpine Fault (Dorn et al., 2010). The regional faults were also considered a seismic hazard for Christchurch due to their relatively close proximity even though the predicted magnitudes are comparatively smaller than what the Alpine Fault could generate.

Large earthquakes occur regularly in New Zealand, with an average of 363 Mw 4.0 or larger events annually. However in Canterbury alone there were 373 earthquakes of Mw 4.0 and above in the period between the 4th of September, 2010 and the 12th of September, 2011 (Geonet, Canterbury quakes 2011). One rare large earthquake such as the Darfield earthquake event can generate a rich aftershock sequence and skew the annual average and generate even more damaging earthquakes such as the Christchurch earthquake.

The Greendale fault, Port Hills fault and Christchurch Fault were unknown until rupturing between the 4th of September, 2010 and the 22nd of February, 2011. These faults are part of the less active regional and sub regional fault system in Canterbury (Dorn et al., 2010). A "direct hit" under Christchurch from a less active unknown fault was considered to be a small seismic hazard. The Greendale Fault was "hidden" up to when it ruptured on the 4th of September 2010, because of its low recurrence interval. As well the rapid deposition and reworking of the Canterbury plain's sedimentary units destroyed any evidence of historic ruptures and made the faults difficult to identify.

Christchurch is situated on a low energy back barrier environment, in close proximity to an active plate margin (Brown and Weeber 1992). The low energy coastal alluvial deposition created a shallow gradient and low elevation environment where Christchurch was built. The ground water table is generally between 2 to 3 meters below the ground surface in the west, and 0 to 2 meters below the ground surface towards the central and eastern portions of urbanized Christchurch (Shulmeister et al., 1999).

2.1.2 Social environment

The size and health of the population served by the hospital network and the importance of the hospital's function contributes to, the size of the impact. It is beneficial in the long term to build more resilient facilities, but obtaining a high level of resilience takes substantial financial investment. With limited funds, hospitals must balance the need for seismic resilience against coverage of the population. The degree to which risk is mitigated is controlled by its perceived severity, or whether or not the hazard presents an "Acceptable risk". As well as the willingness of society to finance risk mitigation at the expense of other public spending (see Section 2.1.4) (Schmid 2001).

The social environment may influence functionality of the healthcare system in the long term. The epidemiological profile of the population and the way the population is affected by the earthquake influences the demand on the healthcare system. In addition to casualties directly caused by the earthquake, increases in stress, fatigue and domestic violence are common following earthquakes. The degree to which longer term health problems afflict the population depends on the characteristics of the earthquake and the aftershock sequence, as well as the organizational environments ability to deal with the long term health problems (Schmid 2001).

2.1.3 Built and legislative environment

The understanding of the local natural environment and standard of construction of the built environment determines the level of risk to which facilities are subjected to. The knowledge of risk in the natural environment and the standard of construction vary internationally as they are financially dependent (McVerry et al., 2006). New Zealand's current seismic standards use the Ultimate Limit State (ULS), Serviceability Limit State (SLS) and Uniform Hazard Spectra (UHS) (Davenport 2004) in order to quantify the level of financial investment deemed appropriate (explained in Section 3.2). New Zealand's earthquake standards for structural, nonstructural components and lifelines are further defined in Sections 4.1, 4.2, 4.3 (Davenport 2004). California's current hospital seismic safety laws are; Senate Bill 1958 (SB 1958), Senate Bill 1661 (SB 1661), Senate Bill 499 (SB 499) and Senate Bill (SB 90). The standards included within the Bills ensure all hospitals are designed and built as critical facilities, which are required to not only protect life but also be completely operational following strong seismicity. The current Bills also include requirements for extensive upgrades of existing hospital facilities and services. The laws are generated by the Office of State wide Health Planning & Development (OSHPD) further defined in Section 2.4.4 (OSHPD 2009).

2.1.4 Economic/financial environment

Financial planners must take into account all the other environments to provide the most efficient use of money reducing the level of risk. That is, a plan must offer the best value for money while managing the risk at a publically acceptable level. Perceptions of the level of risk that are acceptable are often highly subjective and require inter-disciplinary collaboration to determine how to weight all the environments when operating on a constrained budget. It is important that facilities managers efficiently mitigate known risks in order to have secure insurance and finance (Oldfield et al., 1997). In order to efficiently use the available finance a quantitative value must be given to the value of life and the influence and probability of all the probable hazards must be known. The Value of Statistical Life (VSL) is the statistical per capita value of an individual life which risk planners utilize to distribute finance equally for risk mitigation. New Zealand's VSL was $3.5 million as of 2009 (NZIER 2010) and varies internationally. However, the VSL cannot be used to define the quantity of funding for an unknown hazard. However it is useful when mitigating known hazards in hospitals, as a tool that can quantify how much seismic mitigation is needed for each individual physical component that makes up hospitals in order to protect the individuals residing in the building.

2.1.5 Organizational environment

The organizational environment's purpose is to define the scope and manage the above mentioned environments. The organizational structure, disaster planning, information systems, communication systems and staff structure/training are integral components that define the organizational environment's ability to mitigate risk. New Zealand's current "bottom up" approach to disaster preparedness and response places the responsibility for action on the individuals and organizations closest to the actual events (Figure 2.1) (MOH 2010). A bottom up approach is quicker and more efficient than a top down approach (MOH 2010).

Organizations must plan for multiple emergencies because the characteristics of events influence the post event functionality. In an earthquake physical capital and social capital are vulnerable, whereas in a pandemic only social capital is vulnerable. Thus emergency planning must be specific to the type of emergency.

The role and structure of the organizational environment in hospitals and hospital networks vary internationally. The OSHPD in California and Ministry of Health in New Zealand (Section 2.4.4) are strict national and regional regulatory organizations that insure that all standards are met in hospitals. The challenge for these organizations is to plan for risks in hospitals that are continually evolving with new technological advances, building/design standard iterations and the alteration and addition of services to existing facilities.

2.1.5.1 Canterbury District Health Board organizational structure

The Canterbury District Health Board organisational structure is presented here as an example. The CDHBs emergency response structure is conceptualised in Figure 2.1, the base levels of the organizational structure consists of; Vulnerable people, Public health, Primary health and Hospital services. All the base levels are independent, during the disaster they are coordinated in unison from "Operations" with support from "Logistics" and "Planning and Intel". "Operations" is supported by the local District Health Board (DHB) and Ministry of Health, the response is structured as so to insure the higher levels provide resources at the request of the lower levels which coordinate the response. The structure is implemented for all health crisis, whether they be sudden onset disasters or slow onset pandemics.

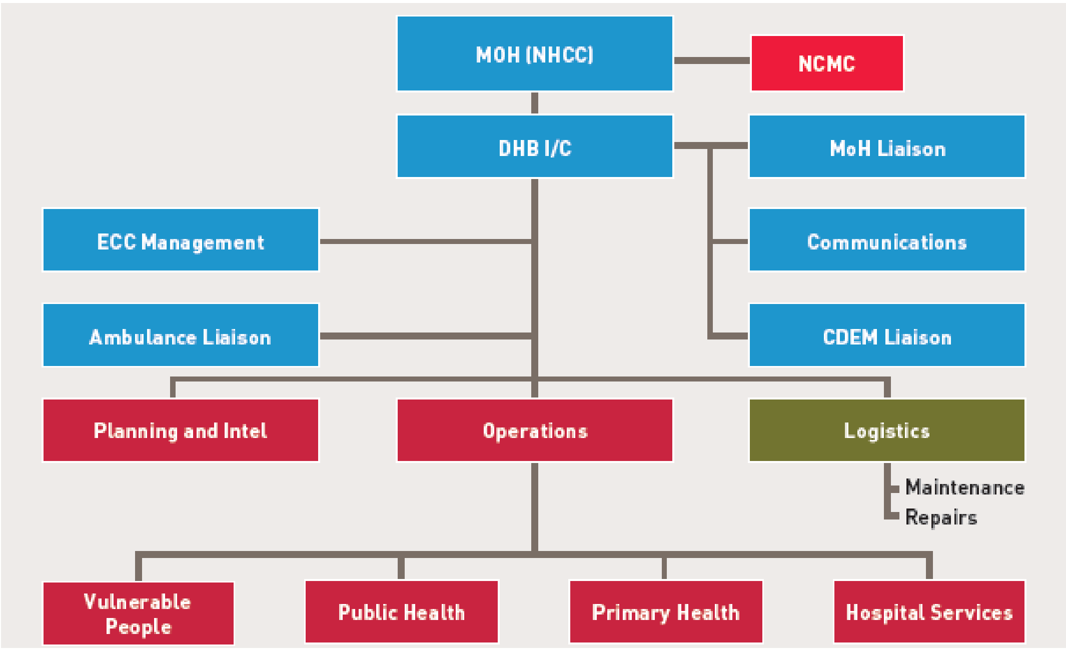

Figure 2.1: The health emergency response organizational structure including; NHCC (National Health Coordination Centre), NCMC (National Crisis Management Centre), DHB I/C (Incident Controller), EOC (Emergency Operations Centre), ECC (Emergency Control Centre) and the CDEM (Civil Defence Emergency Management) (McColl 2012).

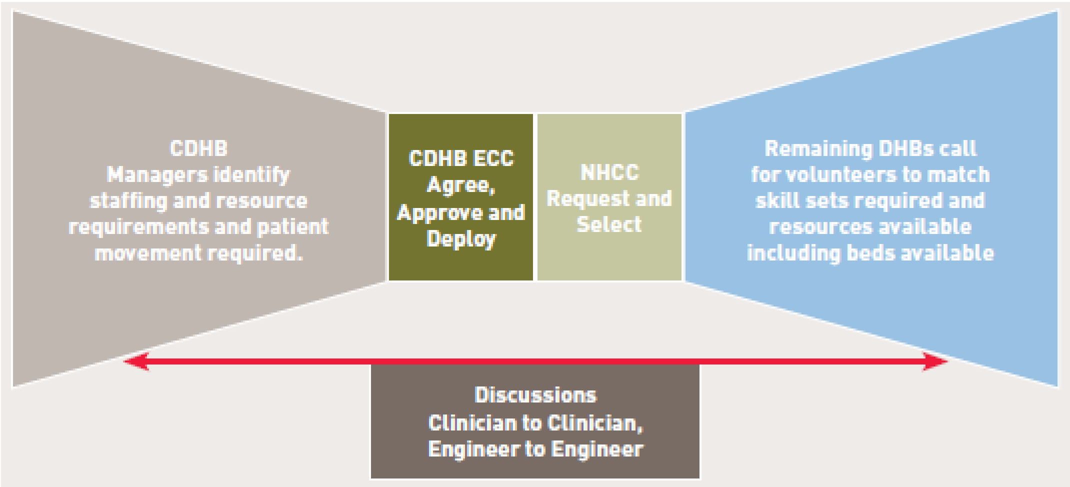

Figure 2.2: The CDHB resource control and co-ordination process (McColl 2012).

The flow chart in Figure 2.2 provides a description of the process for patient transfers following a sudden onset disaster. The process of patient transfers is dependent upon local DHB mangers identifying the required patient transfers and the resources required. The patient transfers are then approved by the local DHB and the ECC, the NHCC request beds and resources from within the afflicted hospital network and the broader hospital network that is not affected by primary earthquake damage at the request of the local CDHB and ECC. The NHCC operates at a national level by providing support for the regional DHB at the DHBs request. The NHCC sources bed space and resources from other DHBs, while clinicians and engineers within the afflicted DHB communicate directly with other DHBs.

Prior to the Darfield earthquake the 2010 pandemic plans provided the newest guide for a healthcare network wide emergency response. The Pandemic plans provided a framework for inter-hospital coordination and integration with the general practice sector (MOH 2010).

2.2 Critical Building Characteristics in Health Care facilities

The most critical elements of seismic design in buildings are; damping, natural period oscillation, linearity and land characteristics. A building's natural period represents the time it takes to oscillate one full cycle. Low rise buildings with short periods have the tendency to oscillate with high accelerations which are more likely to lead to nonstructural damage. High rise buildings have greater flexibility and thus longer oscillatory periods; during earthquakes they deform with lower accelerations but with higher lateral displacements. Larger displacements will be more likely to detach staircases, floors and ceilings (DBH 2011).

Like construction, land conditions also control building resonance during ground motion. In some cases buildings with oscillatory periods around 1.5 seconds situated on young soft sedimentary soils can suffer amplified acceleration because the resonance patterns of the soil match those of the building (FEMA 2007). Damping reduces the size of the building oscillation during earthquake motion; rapid damping is desirable in buildings' in order to reduce the buildings exposure to high accelerations. The level of damping is dependent on the construction materials, the structural layout and the connection of structural components to architectural/nonstructural elements. (Beatty 2006).

It is generally not cost-effective to design buildings to be completely undamaged by strong accelerations. Modern building codes are based on forces that are not as large as the shaking can generate, assuming that the building's structure will deform elastically and absorb a portion of the energy (Wagg et al., 2010). The concept is labelled "nonlinear behaviour"; if severe enough, it can cause structural damage. Nonlinear deformation is incorporated into hospital structures in order to minimize structural damage and the transfer of acceleration to non structural components, ensuring that facilities will remain operational after strong accelerations.

2.3 Seismic Design Standards/organizational planning in hospitals and hospital networks

Building codes have been developed to promote the protection of society from collapse of structures during extreme natural events (Hamburger 2002). They are usually legally enforceable, providing standards and guidelines for engineers and architects. Enforcing building codes is crucial for the resilience of buildings. Code implementation is achieved by compelling designers and architects to follow the law and by spreading awareness of resilient design (Hamburger 2002).

2.3.1 International seismic design

California's current seismic code is regarded as the most comprehensive design standard of all international codes. It has gone through a long history of successive iterations following comprehensively investigated destructive earthquakes (FEMA 2007). California's most modern comprehensive code is the structural resistance code "Senate Bill (SB) 1953 (OSHPD 2009) SB 1953". The code was developed by the California Seismic Safety Commission 2001, after the 1994 Northridge earthquake demonstrated that the pre-existing Act did not encompass nonstructural components as comprehensively as structural components. The pre-existing code was reworked to include nonstructural components. The mechanical and electrical equipment standards are categorised as follows:

1) The critical electrical and mechanical systems required for continued functionality, including; air handling units, air conditioning units, switch gear and emergency power supply systems. All first category systems must be certified by an approved laboratory or agency.
2) The systems that do not play a significant role in operational continuity include motors and motor operators, vacuum pumps and sterilizers. These systems do not require any certified testing (Uma et al., 2010).

The other most advanced seismic codes are found in Japan where, the two-level code used at present was introduced in 1981. The code dictates that a structure should remain elastic in small to moderate earthquakes (Level 1 design), while it can sustain some “yielding and plasticization” in some structural components during large earthquakes (Level 2 design). Level 1 design is defined as “no or very limited damage” ensuring continued occupancy and operational functionality. Level 2 design is defined as “collapse prevention” in order to ensure the safety of life, not operational functionality. The seismic design forces are set with respect to the distance of buildings to known active faults, the local soil characteristics and the height of the structure. The standard base-shear coefficients are set at 0.2 for Level 1 and 1.0 for Level 2. The peak ground acceleration values are 0.3 ~ 0.4g for Level 2 design, and they are reduced to one-fifth for Level 1 design. A force reduction factor is introduced in Level 2 design to allow for the trade-off between the structural rigidity and ductility of the building. The strength required for the most ductile category of buildings is reduced to 0.25 for steel and 0.3 for RC from the unreduced base-shear coefficient of 1.0 (Nakashima et al., 2000).

2.3.2 New Zealand seismic design codes

New Zealand’s performance based earthquake engineering loadings code has been developed continually since the first 1935 seismic code was introduced (NZSS No. 95-1935). The 1976 code introduced strength design (NZS 4203:1976), replacing the 1965 working stress design (NZSS 1900:1965). The NZS 4203:1992 code built on the previous iterations, by increasing the complexity of seismic spectra requirements and advising that buildings be symmetrical structures (King 1999).

The 1992 code introduced the ULS and the SLS requirements to prevent structural damage and limit damage to nonstructural components during moderate earthquakes. To protect life and prevent building collapse during large earthquakes. NZS 4203:1992 also introduced the “uniform hazard spectra”, defined as a 10% probability of occurrence in 50 years, or a return period of 475 years (the ultimate limit state) (Davenport 2004). The foundation soil requirements encompass three categories that determine the foundation: "rock/stiff soil", "intermediate" and "flexible/deep soil" NZS (4203:1992).

NZS 4230:2004 expanded the limit state requirements to match the performance expectations for operational continuity that were also introduced (DHB 2008). The ultimate limit state for earthquake loading further defined the avoidance of collapse. Also recognized as important was the loss of support to elements that represent a hazard to a crowd of more than 100 people inside the building, and hazards to individual life within and without the building (NZS 1170.5:2004). The requirements were further constrained to the components necessary for the continued function of life safety systems in the building and the avoidance of inoperative damage to nonstructural systems for emergency building evacuation. The SLS stated that buildings should not require immediate repair after a SLS1 earthquake and must remain operational after a SLS2 earthquake (Table 2.1) (King et al., 2004).

The latest seismic standard iteration is NZS 4219:2009. The code improves upon the prior requirements for restraining engineering systems that resist seismic damage. Engineering systems include; boilers, ducting, chillers, cooling towers, cable trays, steam pipes, gas pipes, water pipes and lights (NZS 4219:2009). The requirements which were introduced are for the calculation, selection and installation of seismic restraints, anchors and braces (Uma et al., 2010).

New Zealand's current zone factor is a continuously varying value between 1.2 for Wellington, between 0.7 and 0.9 for Christchurch and 0.6 for Auckland and Dunedin. The risk factor reflects the function of the structure; it ranges from 0.6 for temporary buildings to 1.3 for essential buildings (Table 2.1) (NZS 4203:1992) (Davenport 2004). NZS 4219 also includes longitudinal and transverse restraint requirements for suspended components excluding gravity support elements (Uma et al., 2010).

Table 2.1: Annual probability of excedance variance and the building importance level

Annual Prob. of exceedance	Return Period Factor R	Building Importance Levels			
		1 Low hazard structures	2 Normal buildings	3 Important buildings including schools	4 Critical post disaster bldgs
1/2500	1.8				ULS
1/1000	1.3			ULS	
1/500	1.0		ULS		SLS2
1/100	0.5	ULS			
1/25	0.25		SLS1	SLS1	SLS1

Source; (King et al., 2004)

2.4 Vulnerability of hospitals and hospital networks to Seismic Hazards

The four main categories of hospital and hospital network vulnerability are the buildings structural, nonstructural, lifelines and organizational components (FEMA 2007). Failure of anyone of the categories can be responsible for the functional failure of the hospital, or in extreme situations the entire health care system (WHO 2008).

2.4.1 Structural Vulnerabilities

Structural building elements are the necessary components required to physically support the buildings structure (WHO 2006). Structural elements include; foundations, bearing walls, columns, beams, staircases, floors, roof decks, including and other types of structural components that support the building against the force of gravity (MOH et al. 2002). The level of vulnerability of these components depends on the following factors:

- The level the design of the structural system has addressed the known hazard forces.

- The quality of the building materials, construction, and maintenance.
- The architectural and structural configuration of the building.

The aspects of design and construction in areas known to be hazard-prone are regulated by building codes and regulations, which are further explained in Sections 2.3.1 & 2.3.2. In New Zealand seismic building code requirements (Section 2.3.2) for essential buildings such as hospitals are heavily focused on reducing causalities and on maintaining functionality following earthquakes (King 1999). The later is harder to accomplish due to the fragility and interdependence of all the components required for hospital functionality. However, building regulations alone cannot guarantee hospitals remain operational after earthquakes, because many other factors effect hospital functions such as nonstructural elements, lifelines and support agencies (FEMA 2007).

2.4.2 Nonstructural Vulnerabilities

The affects of damage to nonstructural building components and equipment and breakdowns in public services (lifelines), transportation, re-supply, or other organizational aspects of hospital operations, are as disruptive and as dangerous for the safety of patients, as any structural damage. In modern facilities nonstructural damage is often the biggest disruption following large earthquakes (FEMA 2007). In most modern hospitals nonstructural components represent up to 85 to 90 % of the entire buildings worth (WHO 2006). For example, during the moderately sized 2001 Nisqually earthquake most buildings did not sustain major structural damage, but nonstructural damage meant many buildings were un-occupiable (Filiatrault et al., 2001).

The nonstructural complexity of modern hospitals is due to the dependence of facilities on extensive networks of mechanical, electrical, and piping installations for essential services (FEMA 2007). The air conditioning, suction and ventilation systems are highly important in maintaining an appropriate pressure gradient in different areas; malfunction in any one part of the system could create a risk of infection to patients and staff. This system like other services is extremely vulnerable to disruption as a result of large ground accelerations (WHO 2006).

Damage can result from relatively small events. Vulnerabilities that will most likely affect hospital functionality and the safety of occupants are detailed in Table 2.2. If severe enough the damage may require patient evacuation (Section 2.7.1), and if not the required repair work will cause disruption. Patients in critical and acute care units are particularly vulnerable during evacuation because they require medical gas, monitors, lighting, and other essential life support services (FEMA 2007).

Non-load bearing partition walls and ceilings are rarely designed and constructed to the same standards of hazard resistance as the structural elements. Ceiling panels are particularly vulnerable during earthquakes (FEMA 2007). The misinterpretation of nonstructural damage as structural damage following the 8th of October, 2005 M7.6 Kashmir Pakistan earthquake caused the unnecessary evacuation the Ayub Medical College in Abbotabad (Sections 2.5, 2.8.1) (EERI 2006).

Table 2.2: Nonstructural components common in hospitals (PAHO 2007)

Architectural elements	**Installations**	**Equipment and furnishings**
Divisions/wall partitions	Drinking water	Industrial equipment
Facades	Industrial water	Cleaning equipment
False ceilings	Steam pipes	Medical equipment
Cornices	Medical gasses	Office equipment
Chimneys	Fuel	Furnishing
Aesthetic covering elements	Vacuum/pressure network	Supplies
Glass	Air conditioning	Clinical files
Antennas	Piping	Pharmacy shelving
Ceiling panels	Waste disposal	Laboratory shelving

2.4.3 Lifeline vulnerabilities

Lifelines such as electric power, water supply and telecommunications are critical services which hospitals depend upon to function adequately. These services are often supplied by main grids which are susceptible to earthquake damage (Guest 2004). Automatic switch offs are common in power substations and gas lines in order to mitigate damage from the secondary risks of fire following large earthquakes. The unintended effect of automatic switch offs is to cut services to hospitals.

The emergency power generator system along with its fuel supply is the hospital's most critical utility following critical lifeline damage. Backup power enables equipment and installations not directly damaged to function after an earthquake (FEMA 2007). The performance of back up utilities depends on the integrity of the source as well as the components needed for distribution such as battery racks, pipelines and electrical connections (FEMA 2009). The fragility of each system must be reduced to its individual components separately in order to reduce interdependency and insure back up utilities are functional after strong seismicity. For example following the Northridge earthquake the Olive View Medical Center (OVMC) had to switch off its power generators after the cooling systems water supply was lost (Pickett 1997) (Section 2.5.3). As well, the Kobe Central City Hospital had to be evacuated following the Great Hanshin earthquake due to the similar flow on effects of water loss on water cooled generators (further explained in Section 2.5) (Ukai 1996).When Hurricane Katrina cut New Orleans's mains power extreme heat caused a number of hospitals to evacuate, as the backup power did not cover the air-conditioning systems as they were not seen as critical services (FEMA 2007). Following strong ground acceleration sewers and mains water often become inoperable; this is an issue because waste disposal and water for showers and fire sprinklers are essential for hospitals.

When the toilets, sterilizers, and cleaning equipment are nonoperational the hospitals ability to function is immediately affected (FEMA 2007).

Specialized services not supplied by a mains grid but by regular deliveries are also vulnerable to disruption, they include; chemicals, oxygen, pharmaceuticals and other medical gases. The resilience of specialized services following disruption depends upon the level of storage on site and the fragility of the internal network used to supply wards (FEMA 2007).

2.4.4 Organizational Vulnerabilities

In the event of disruption of the normal movement of staff, patients, equipment, and supplies disaster mitigation or emergency operation plans play an important role in providing operational continuity. The hospitals disaster plan must identify the risks of a disaster/emergency, integrate its disaster plan with the community wide disaster plan, assign responsibility for the coordination of the response and provide the capacity to treat mass casualties after a damaging earthquake (Section 2.1) (Henry et al., 2006).

The interdependence and spatial distribution of the inter-relationships of hospital functions make disaster planning difficult. The way in which they are dealt with determines the extent hospital operations are effected when the normal movement and communication of staff, patients, materials and waste products are disrupted (MD 2004). Organizational vulnerability can steam from damage to any of the components mentioned in Sections 2.4.1 - 2.4.3.

It is the task of the organizational environment to mitigate the risk of failure of the physical components which comprise its facilities. California's OSHPD operates a review program for hospital organizational plans and nonstructural installations, in order to ensure all buildings comply with the current seismic building codes and ensure the organization exhibits "operational continuity"(OSHPD 2009). New Zealand's regulatory organizations are the Ministry of Health (MOH), local District Health Boards (DHB) and the Department of Building and Housing (DBH). The Department of Building and Housing defines the code requirements for; facilities, contents and lifelines the MOH and DHB's are responsible for organizational requirements such as pandemic planning and the organizational structure of facilities. Each major hospital has an emergency planner tasked with identifying the risks in facilities, contents and services. The MOH's current pandemic plan provides guidance for necessary actions following a pandemic, by defining the likely weakness in hospital network organizational structures, the agencies and individuals required to act, and the authoritative limits for organizations and individuals undertaking actions.

The operational characteristics and connectivity of a hospital or hospital networks organizational structure govern the severity of an earthquakes effect on the hospitals ability to operate. In order to mitigate disruption it is important that hospital organizations coordinate during emergencies, good communication is also vital to achieve continued operation during the response phase. The inter-corporate and inter-personal relationships are highly valuable during earthquake responses phase (EQC 2012). New Zealand's current "bottom up" approach to disaster preparedness and response places the responsibility for action on the organizations and individuals closest to the actual events (MOH 2010).

2.5 Prior hospital performance following earthquakes

In order for a hospital to operate without disruption it must depend on the components mentioned in Section 2.4 working without interruption 24 hours a day even after a large earthquake. Hospitals continually evolve as older facilities are extended and upgraded; as a result, hospitals have to adapt new technology to be integrated into older facilities. The rarity of large earthquakes in developed cities makes it difficult for designers to predict how certain elements of hospitals will perform given hospitals are continually evolving, changing the way components interact following damage to part of the system (Achour 2011).

2.5.1 Great Hanshin earthquake

The M7.2 1995 Great Hanshin earthquake (Kobe, Japan) ruptured at a depth of 16km and 20 kilometres from Kobe. It was considered a "shallow inland earthquake" on a fault that had not been active for roughly 400 years, sixty one percent of hospitals in disaster area were severely damaged (Ukai 1996). Out of 180 hospitals in the disaster area, four were destroyed and 110 suffered serious structural damage. Most of the complex medical equipment, such as computed tomography (CT), magnetic resonance (MR), X-ray angiography and chemical auto analysers were damaged and unusable in the hospitals that sustained severe damage.

In Kobe Central City Hospital, wards were evacuated after water flowed from damaged roof top water tanks. As the water in the tanks drained, water was automatically pumped up from water tanks in the basement, all stored water was lost (Section 2.4.3) (Ukai 1996). The water loss caused the breakdown of the backup water-cooled power plant, shutting down the hospitals electricity supply for 30 minutes. The medical instruments that weren't physically damaged were un-operational without power. The depleted staff pool also decreased the hospitals functionality (The City of Kobe 1999). The body of research following the Kobe earthquake has been influential in the formation of Japans current building code for critical buildings (section 2.3.1).

2.5.2 Kashmir earthquake

The 2005 M7.6 Kashmir (Pakistan) earthquake ruptured at a depth of 10 km and 100km north-northeast of Islamabad, it destroyed most major hospitals near the epicentre. The financial cost to the health sector was equivalent to about 60% of the national health budget. The damage to the hospital network is characteristic of a strong shallow earthquake on facilities comprised in most cases of insufficiently earthquake proofed buildings, services and non structural building elements (EERI

2006). One of the biggest Hospitals lost was the Ayub Medical College (AMC) in Abbotabad. The AMC was one of the few critical care facilities designed to withstand high seismic loads, it was lost due to the lack of a proper post-earthquake assessment. The hospital was evacuated due to the mistaken categorization of non structural damage as severe structural damage (Sections 2.4.2& 2.8.1). (WHO EMRO 2009). Quickly and effectively assessing hospitals is very important, unthreatening nonstructural damage can often appear initially dangerous and cause unnecessary evacuations.

2.5.3 Northridge earthquake

One of the biggest hospitals to sustain damage after the 1994 M 6.9 Northridge earthquake (California, United States of America) was the Olive view Medical Centre (OVMC). The current OVMC was built as a replacement to the original OVMC building which sustained severe structural damage during the M6.4 San Fernando, California earthquake of the 9th of February, 1971 (Celebi 1997). It was subsequently demolished along with the Veteran's Administration Hospital complex which partially collapsed (Rutenberg et al., 1980). Engineering research following the 1971 San Fernando Earthquake found that the seismic forces experienced at the Veteran's Administration (VA) Hospital were underestimated by the current seismic codes (Holmes 1976). The positive and negative effects of nonlinear soil structure interaction and PGA amplification caused by soil resonance helped some structures to withstand damage, while nearby structures collapsed (Rutenberg et al., 1980).

The replacement OVCM building was designed before 1976 with an increased level of seismic resistance, similar to most other hospitals built in the last 40 years in seismically active, economically developed nations. The new OVMC building was designed to survive two levels of zero period acceleration (ZPA) of 0.52g and 0.69g. The peak ground accelerations experienced by the Northridge earthquake far exceeded that of the design limits, due to the epicentres proximity (16km) and the large spectral characteristics of the recorded motions. The observed accelerations were 0.91g (free field) and 2.31g (roof) (Celebi 1997).

Even when building sustain minimal structural damage, structural components can still impact nonstructural components by transferring forces through the structure itself and damage utility or architectural elements connected to the structure (Section 2.2)(WHO SEARO 2002).The new OVMC buildings rigidity and linear behaviour (Section 2.2) contributed to the transfer of strong accelerations through the building during the 1994 M 6.9 Northridge earthquake, in some cases overwhelming the seismic anchorage and bracing provided for the building's nonstructural systems. Some of the damaged components and systems were not considered sufficiently vulnerable to require special bracing, the failure to recognize the transfer of forces through different components is indicative of how complex fragility assessments are in hospitals (defined in Section 2.6) (FEMA 2007). Similarly, the failure of nonstructural walls at St. John's Hospital following the 1994 M 6.9 Northridge earthquake caused the rupture of water lines and as a result the hospital lost water services (Pickett 1997).

2.5.4 Chi-Chi earthquake

During the Mw 7.6 22nd of September, 1999 Chi-Chi Earthquake (China) the 400-bed reinforced concrete (RC) Christian Hospital suffered only slight structural damage (NCREE1999). However the newest section sustained considerable nonstructural damage from the main 20th of September, 1999 event and was evacuated to the hospital grounds. The damage to backup power, water, communications, piping, HVAC anchorage, medical equipment, gas storage tanks and mechanical equipment and the lack of an emergency management plan added to the crisis. The result was to reduce the capacity by 10% at a time when the demand was the highest (Lee 1999). The building sustained significant nonstructural damage again during the M6.8 26th of September, 1999 aftershock (NCREEa 1999). Patients were again evacuated and housed in temporary trailers with 50 fewer beds than the hospital had prior to the aftershock. The excess patients were transferred to other hospitals in the area. The first floor of the building remained open and was used for emergency care, patient registration and as a command post (Soong et al., 2000).

2.5.5 Hurricane Katrina

Hurricane Katrina made landfall on the coast of Louisiana on the 29th August, 2005 (New Orleans, United States of America) causing 1,836 deaths. Similar to the Chi-Chi earthquake (Section 2.5.4) and Kashmir earthquake (Section 2.5.2) case studies, New Orleans's Charity Hospital was evacuated following Hurricane Katrina (Berggren 2005) (Section 2.4.3). The exhausted food and water supply was also responsible for the hospitals evacuation. The observations are symptomatic of the trend towards reducing onsite storage of linen, food, and other essential materials by out sourcing the services in order to maximize efficiency (FEMA 2007).

2.5.6 L'Aquila earthquake

The three-story San Salvatore Hospital located in western L'Aquila was constructed in 2000 and sustained damage during the M6.3 6th of April, 2009 L'Aquila earthquake, even though the facility was thought to be able to resist strong accelerations. It was concluded that irregularities in plan and elevation, poor detailing (steel bars were exposed) and design (beams larger than columns) lead to structural damage (EEFIT 2009). These factors caused the inadequately anchored third level unreinforced masonry infill walls of the hospital to collapse onto the emergency entrance and the disintegration of the exterior wall panelling. Widespread nonstructural failures of insufficiently braced and anchored suspended ceilings, brick infill walls and equipment also ceased clinical services. In response to the damage all patients were evacuated and treated outdoors immediately after the earthquake (L'AQUILA 2009).

2.5.7 Maule earthquake

The Mw 8.8 Maule earthquake in Chile ruptured off the coast of central Chile on the 27th of Saturday, 2010 at 03:34am. The earthquake resulted in 484 fatalities Chile's hospital functions were widely disrupted by the earthquake. The loss of communications impeded the response efforts at all levels. All of the 7 hospitals in the Bio-Bio region lost their municipal electrical power, water and communications for days after the earthquake. 23 of the 117 hospitals in the Bio-Bio and Maule regions lost some functional capacity. As well, many of the hospitals sustained physical damage to varying degrees however, only one hospital sustained severe structural damage (Kirsch et al., 2010).

Chiles strong adherence to good seismic standards prevented any of the hospitals from completely collapsing, however Structural and nonstructural damage did negatively influence their functional capacity. It was identified that the loss of lifelines and water forced some hospitals to evacuate. There were also issues with the decision making process, because the major decisions had to be made in Santiago where the national healthcare service is centralized (Kirsch et al., 2010).

2.6 Risk assessment for hospitals and hospital networks

Modelling fragility and functionality is the principle means of risk assessment; it enables the disaster response to be planned for and for increased building resilience within individual hospitals and hospital networks. Risk assessment is not just used to increase health care facility resilience, but also to define specific areas of vulnerability in facilities and the organizational structure for post earthquake hospital emergency response procedures (Berler et al., 2009).

Risk assessment aims to quantify the probability of failure of; physical elements, services and lifelines within a hospital or healthcare network, and the affect the damage has on the capacity of the facilities or the hospital network (Cimellaro et al., 2007). Functional and fragility evaluation methods are important means to assess individual components (structural, nonstructural, equipment and lifelines), or hospital networks. Hospital evacuation, surge capacity and residual capacity can be used as affective measures that quantify the holistic affect of physical damage on society. The elements needed for the holistic assessment of hospital networks are the:

- Operational characteristics of the network and individual facilities.
- Geographical distribution of the facilities.
- Physical characteristics of the facilities.
- Degree to which the system is able to meet the health care needs of the population.
- Epidemiological and demographic profile of the population.
- Natural hazards and land conditions that threaten the hospital network.
  (Cimellaro 2010)

2.6.1 Fragility assessment for physical components

Fragility is defined in seismic engineering as the probability that a structural, nonstructural and/or geotechnical component or system violates a limit state when exposed to a seismic force of a specific intensity (Kafali et al., 2004).Fragility can be calculated for an entire hospital network, single hospital, or a particular physical component or function of a hospital. The assessment methodology requires a certain level of generalisation and assumption in order to calculate either qualitative or quantitative outputs. The methods covered in this section are critiqued for their suitability in Chapter Four.

2.6.1.1 Assessment methodology for physical components

Structural Damage fragility curves have been used to model building damage from prior earthquakes globally (Wenzel 2008). The world health organization (WHO); Health facility seismic vulnerability evaluation – a handbook – (WHO 2006), outlined a structural vulnerability function (Section 4.2.3). The assessments purpose to provide a numerical output that can be used to estimate the vulnerability of facilities for a given MMI value. The assessment is implemented and critiqued in Chapter Three using data from Christchurch Hospital following the Christchurch earthquake.

The WHO (2006) Nonstructural vulnerability assessment is similar to the WHO (2006) structural assessment; however the nonstructural assessment has 21 indicators whereas the structural assessment has 14. The indicators for the WHO (2006) structural and nonstructural assessments are both qualitative and quantitative (WHO 2006). Kafali (2003) defines fragility Analysis methodology for nonstructural and structural systems in critical facilities. The method includes calculations for; site specific ground motion, structural response at attachment points, motion of the structural system, second moment properties and fragility surfaces by Monte Carlo simulation (Kafali et al., 2003).

2.6.1.2 Capability assessment methodology

WHO's "Health facility seismic vulnerability evaluation: a handbook" outlines a capability assessment methodology considering the allocation of resources and personnel to the various medical services. Assigned personnel, emergency supplies, medical equipment and backup systems define the capability of each of the medical services (WHO 2006). The parameters define the ability of the service to function under both normal and emergency conditions. The four parameters are labelled as following:

1. *Optimal*: "efficient allocation of resources and personnel".
2. *Adequate*: "acceptable allocation of resources and personnel; operation can proceed normally".
3. *Minimal*: "barely acceptable allocation of resources or personnel; operation can proceed with certain restrictions".
4. *Inadequate*: "unacceptable assignment of resources or personnel; severe limits on the service in question or impossibility of carrying out the service in question".

The medical services with an importance index of 5, 4 or 3 are considered the most important to maintaining a functional hospital during an emergency. All medical services with an importance index of 5 or 4 must have all parameters rated 1 (optimal) or 2 (adequate) in order to attain a net "high" capability rating. Services with an importance index of 3 may have a parameter with a rating of 3 (minimal). Services with an importance index of 5 or 4 with parameters rated 3 (minimal) or 4 (inadequate) have an overall healthcare capability rating of "moderate" or "low" (WHO 2006).

2.6.1.3 Functionality assessment methodology

Cimellaro. *et al.*, (2010) defines a method for calculating the functionality of individual hospitals by using Waiting Time (WT) in an Emergency Department (ED) as a key parameter in the quantification of the Quality of Service (QS). The WT is defined by the time taken between the request for care by the patient and the provision of the care by the hospital, it is determined by the number of; staff on duty, labs, Beds (B) and Operating Rooms (OR). The outcome of the model is the Qualitative functionality (Qqs), which is calculated using the outcomes of the Quality of Service (QS). And the Quantitative functionality (Qls) related to the losses in the healthy population calculated with the variables mentioned above (Cimellaro. *et al.,* 2010).

The required data is as follows:

- (Wt) waiting time in emergency department (saturated or unsaturated)
  - i) (B) Number of spare beds
  - ii) (OR) Operating rooms
- (WT0) Waiting time during normal unsaturated conditions
- (WT(t)) Waiting time during saturated conditions
- (NTR) Number of patients treated under saturated conditions (indicator of functionality)
- (Ntot) Total number of patients requiring treatment
- (NNTR) Total number of patients not treated

The above variables are used to calculate the qualitative functionality output using equations 1 to 6, which are further defined in chapter three (Section 4.3.1) (Cimellar et al., 2010). Simularily Hossain (2012) defines methodology for modelling coordination in emergency departments through social network analysis following disasters (Section 4.2.5) (Hossain et al., 2012). Cimellaro (2010) also contains methodology that aims to capture the influence of the hospital networks interconnecting road network.

2.6.1.4 Holistic assessment methodology

Fawcet et al., (2000) provided a regional model in "Casualty Treatment after Earthquake Disasters: Development of a Regional Simulation Model; Disasters 2000", the models output estimates the number of causalities under different scenarios in "Casualty Treatment after Earthquake Disasters: Development of a Regional Simulation Model". The models inputs are; the quantity and localities of casualties rescued alive, the pre-earthquake hospital capacity, the post-earthquake hospital capacity, and the transport network (Fawcet. et al., 2000). The method outlined by De Boer *et al.,* (1989) uses the number and severity of casualties as the model input to define a "numerical Medical Severity Index" (MSI) (De Boer. *et al.*, 1989). Masi (2012) proposes vulnerability assessment methodology, the results of which help define seismic risk reduction strategies (Masi 2012) (defined in Section 4.3.2). The Post Disaster Needs Assessment (PDNA) (defined in Section 4.3.3) is similar to (Masi et al., 2012) in that it is a holistic assessment that includes the financial environment (PDNA 2010),

2.7 Patient capacity redistribution

2.7.1 Facilities evacuation and patient transfer

Hospital evacuations are relatively common following large scale natural disasters. Examples include; the evacuations of the Ayub Medical College in Abbotabad following the Kashmir earthquake (EERI 2006) (Section 2.4.2), the Tulane and Charity hospitals in New Orleans following hurricane Katrina (Section 2.5) (Berggren 2005), the Christian Hospital During the Mw 7.6 20th of September, 1999 Chi-Chi Earthquake and the M 6.8 26th of September, 1999 aftershock (Section 2.5) (Lee 1999) and the San Salvatore Hospital following the M6.3 L'Aquila 6th of April, 2009 earthquake (Section 2.5) (EEFIT 2009). However, there are relatively few detailed accounts of hospital evacuations in the literature that consider the motives for evacuation, the decision process and the resulting capacity redistribution. Any of the factors mentioned in Sections 2.3, 2.4 and 2.5 can cause facilities to be evacuated, although evacuation is considered a measure of last resort (FEMA 2007) following critical damage it is unavoidable. The process of evacuation itself is also vulnerable to disruption that can seriously aggravate the health and safety of patients and is a financially costly process (FEMA 2007).

A study by the OSHPD (OSHPD 2009) suggested that even after moderate earthquakes, Californian hospitals may need to evacuate patients immediately because of nonstructural damage. The study found that delayed identification of structural damage may result in permanent closure of facilities even if they remained occupied immediately after the earthquake. Wards can be safely evacuated if the hospital has an effective emergency management plan and the damage is limited to elements not required for horizontal movement and vertical egress such as corridors, elevators and stairwells. The same study found nonstructural damage caused the greatest initial concern for patient safety (CHSSL 2005). After the Northridge earthquake, six hospitals evacuated patients because nonstructural damage made the provision of healthcare unpractical and unsafe. The most disruptive of the nonstructural damage was caused by water leakage from ruptured, pipes, sprinklers, rooftop tanks, and other plumbing fixtures. Similar findings were reported in hospitals damaged during the Hanshin–Awaji earthquake in 1995 (Ukai 1996).

Ukai also identified traffic congestion as a problem for patient transfers following hospital evacuations. Both the wide spread destruction of transport infrastructure and increased traffic are common after large earthquakes (Ukai 1996). Damage to transport infrastructure caused severe traffic congestion following the Hanshin–Awaji earthquake. Within an hour of the earthquake every main road in the disaster zone was jammed (Ukai 1996). The congestion delayed the arrival of relief teams from outside the city and complicated the transportation of casualties. The traffic congestion was compounded by the lack of adequate communication between hospitals. The combination of the aforementioned factors meant the transfer of severely injured patients from damaged hospitals was delayed. Miss-communication and transport issues meant that when the severity of the damage in Kobe was reported on TV news most of the hospitals in nearby Osaka freed up beds to receive large numbers of casualties. But in the first twelve hours only three patients were transferred to Osaka's emergency centres (Ukai 1996).

2.7.1.1 Factors influencing patient transfer

The key factors that influence evacuation time include (HHS 2011):

- Available exit routes within the hospital.
- Available staff.
- Available transportation resources.
- Entry and egress points at the hospital.
- Location of receiving care sites.
- Number of patients and mix of patient acuity.
- Patient transportation requirements.
- Road and traffic conditions.

The amount of assistance patients require during evacuation and/or transfer is dependent on their condition and location within the hospital. The patients in the following hospital units require the most assistance during transfer (HHS 2011):

- Adult medical/surgical wards.
- Adult ICU.
- Bariatric patients.
- Burn Unit or Burn ICU.
- Dialysis patients.
- Neonatal ICU.
- Pediatric medical/surgical ("floor") wards.
- Pediatric ICU.

- Psychiatric unit.
- Patients restricted to negative pressure/isolation rooms.
- Patients in prisons.
- Other specialty care units.

The availability of transport resources, staff, equipment, and supplies determine the extent and speed of patient transfers. The mode of transfer is critical in determining how long patient transfers take. In order to be effective the means of transfer must be properly equipped and staffed (HHS 2011).

The location of the receiving facilities is determined by whether or not the hospitals in the entire region or city must be evacuated or just an individual hospital. If one hospital has to be evacuated patients can be more easily transferred to undamaged hospitals which are close by. In urban centers the distance of transfers is likely to be a distance of less than 15 kilometers. In this case ambulances can transfer patients easily with little need for helicopter and fixed wing transfers. If there is little residual capacity in the surrounding city or region patients will have to be transferred by fixed wing or helicopter to other regions (HHS 2011).

Estimating transfer time is dependent on the variability of all the factors mentioned above. There are a wide variety of possible hospital evacuation times which are determined by different sets of assumptions based on the characteristics of the disaster and the Hospital network characteristics (HHS 2011).

2.7.2 Surge Capacity and Capacity Redistribution

"Surge capacity" is the term used to describe the ability of a hospital or hospital network to surge the capacity to treat patients immediately after a disaster. Surge capacity is achieved by quickly freeing up the resources needed to treat and accommodate casualties following a mass casualty sudden onset disaster. The number of available beds in a facility is the principle means of defining "surge capacity", however other resources must be made available including; staff, supplies and equipment. Hick et al., (2004) categorizes ''surge'' response into three areas (Hick et al., 2004).

1. ''Public health surge capacity'' is the ability of the entire health system to increase capacity for patient care and other health services and cope with disruption.
2. ''Health care facility–based'' and ''community-based patient care surge capacity'' refers to the ability of individual facilities to provide resources in order to deliver adequate acute medical care to the community.
3. 'Surge capability,'' refers to the specialized healthcare resources required for specific groups of patients (Hick et al., 2004).

The capacity terminology includes both the physical resources and the organizational structure of individual facilities and the network as a whole. (Hick et al., 2004). Cimellaro et al., (2010) outlines an effective method for quantifying the capacity response of individual facilities by measuring the waiting time in the emergency department (Section 4.3) (Cimellaro et al., 2010).

2.8 Conclusions

The post disaster and risk assessment literature on hospital/ hospital network suggests that in areas with modern building codes, large earthquakes, and other disasters such as hurricanes, will cause damage to services and nonstructural components which are far more disruptive in the long term than structural damage. As nonstructural systems are comprised of more components than the structural system, the additional complexity and interdependency increases exposure, and can increase vulnerability and make restoration more difficult. However, in extreme cases, if structural damage is severe enough can permanently reduce the capacity of facilities, whereas nonstructural damage can usually be remediated with adapted but continued hospital operation – albeit with disruption. In some cases the nonstructural damage caused evacuations in hospitals following damage to pipes, sprinklers, rooftop tanks, and other plumbing. Evacuations are also initiated following damage to elements required for horizontal and vertical egress such as corridors, elevators and stairwells.

The ability of hospitals to withstand seismicity is clearly related to the robustness of the national and regional anti-seismic design standards. The challenge of mitigating nonstructural damage is more difficult than that of structural components due to the number of elements that complete the systems. The inter relationships between the structural system and the nonstructural components is also of great concern, as in some cases undesirable positive feedback from the structural system has resulted in nonstructural damage.

There are many challenges in indentifying a particular seismic hazards probable impact on the physical system and the expected performance of the organizational system. The literature contains a significant body of assessment methodology which is further analysed in Chapter Four. The methods range from the holistic to very specific for all the components that define a hospital/hospital network. Both pre-disaster and post disaster fragility assessments are important in maintaining operational continuity. Because they define areas of fragility prior to a disaster or areas of fragility that have become apparent following a disaster that the existing assessment methodology did not find. In some cases nonstructural damage incorrectly assessed as structural damage triggered evacuations and capacity redistributions (Kashmir earthquake) (Section 2.5.2).

In the literature hospital capacity following earthquakes is not only influenced by the physical damage but also the organizations response to the damage. As well, the national regional or individual hospital organizations' quality and scope of pre disaster mitigation in the form of emergency plans, building codes and inter hospital/hospital network connections defines the impact of a seismic hazards.

Lifelines, supply networks and critical infrastructure although not directly part of hospitals and hospital networks also have the potential to impact hospital functionality. Both the wide spread destruction of transport infrastructure and increased traffic are common after large earthquakes. Traffic congestion is defined in the literature often as a problem for patient transfers following hospital evacuations. The loss of power and water often forces facilities to rely on backup systems that are less reliable and in some cases not big enough to supply noncritical systems such as air conditioning (Hurricane Katrina), fire sprinklers and showers.

3. Chapter Three: Impact of the Christchurch earthquake on the Canterbury healthcare system

3.1 Introduction

The aim of Chapter Three is to define how the Canterbury hospital network was prepared for seismic hazards in the short term and long term leading up to the Christchurch earthquake and define how the physical and organizational elements of the Christchurch hospital network performed following the Christchurch earthquake.

The methodology of Chapter Three is firstly; to present data which for the key areas that make up hospitals and hospital networks which were identified in Chapter Two. Secondly, the raw data relating to the physical damage and capacity redistribution is processed in order to define the areas of the Canterbury hospital network that were resilient and the areas that hindered the response. As well, the data presented in Chapter Three is used for critiquing various seismic hazard vulnerability assessment methodologies in Chapter Four. Quantifying the affect of physical damage and the loss of lifelines on the capacity of Canterbury's hospitals and the individual wards of Christchurch Hospital is used as a methodological approach for determining the affect the Christchurch earthquake had on the Canterbury Hospital network.

3.1.2 Data collection methodology

The data used in Chapter Three was collected during a Joint project between the University of Canterbury and Johns Hopkins University after being awarded a National Hazard Research Platform (NHRP) grant titled "Hospital Functions and Services". Following the University of Canterbury/Johns Hopkins University collaboration, continued data collection was made possible with help from the Rhise network.

The data collected during a University of Canterbury/Johns Hopkins collaboration included photos and surveys of structural, non-structural, equipment and lifeline damage that disrupted essential hospital functional areas and healthcare services. The impacts surveys include questions regarding the consequence for patient-care systems of losing any one or multiple functions in a hospital due to earthquake damage (McIntosh et al., 2012).

The survey tool (Appendix A) was initially developed to assess the impact of the 27th of February 2010, M_w 8.8 Maule earthquake on the hospital network in Maule and Bío-Bío regions of Chile (Kirsch et al., 2010). The "Hospital Functions and Services" project adapted the survey tool to match the needs of the CDHB Health Care System based on feedback from relevant CDHB personnel. The survey tool was administered to several hospitals in the Canterbury region by way of interviews with key maintenance and clinical staff (Kirsch et al., 2010).

Following the initial data collection; media publications originating from CDHB and private hospital staff, CDHB resources and data from the Rhise network were collected. This data includes quantitative and qualitative information for structural, nonstructural, equipment, and lifeline damage and the redistribution of Canterbury hospital network treatment capacity in the two weeks following the Christchurch earthquake.

3.2 The Christchurch Hospital Functional impact

The Christchurch earthquake heavily impacted the Canterbury region's healthcare system (Figure 3.1). The main regional hospital, the Christchurch Hospital, sustained damage following the earthquake that severely strained the hospital's ability to function at regular capacity. Christchurch Hospital is the largest hospital in Canterbury and operates the only Emergency Department (ED) and performs the majority of elective surgeries within Canterbury. The hospital serves a population of 560,000 and the inpatient wards provide services to over 35,600 inpatients each year, of which approximately two-thirds are admitted acutely; a further 13,000 people are day patients. There are 16,000 theatre visits each year and over 197,000 outpatient attendances, excluding those for radiology and laboratory services. The hospital operated 600-650 beds before the earthquake (Table 3.3), including 15 ICU beds, 18 high-dependency beds, and 9 step-down beds. Before the earthquake, the hospital typically operated at around 98% occupancy with a 48% admission rate from the ED to other wards.

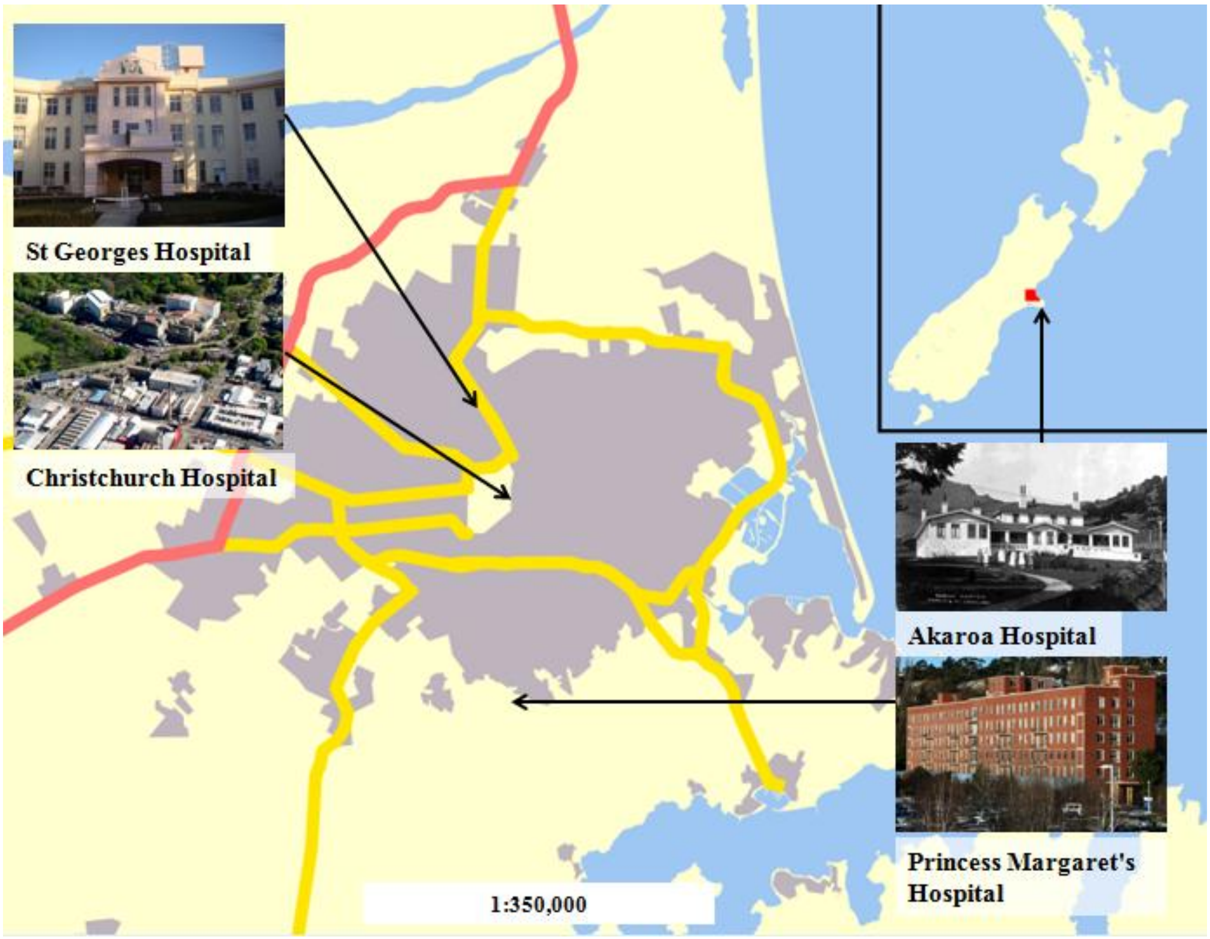

Figure 3.1: Map of hospitals within Christchurch and the surrounding area (Geonet).

Christchurch Hospital is located on the western edge of Christchurch's Central Business District (CBD) and is bordered by the Avon River and Riccarton Avenue. The hospital was built on lenses of liquefaction prone alluvium, during the Christchurch earthquake the site experienced peak ground acceleration of 0.547g (Geonet 2011a). The hospital's proximity to the CBD and ability to provide emergency care meant it was at the centre of the emergency response. However, the area's susceptibility to liquefaction and the exceedingly high ground acceleration caused structural and nonstructural damage in both clinical and non-clinical hospital facilities as well as lifelines and utilities damage (described in Sections 3.1 to 3.4). The resilience of the back-up systems that were operational and the resourcefulness of the clinical and non clinical staff insured the hospital continued to function and provide healthcare during the emergency response phase of this disaster (McIntosh et al., 2012) (Ardagh et al., 2012).

3.2.1 Christchurch Hospital: Structure and Baseline Hospital Information

Christchurch Hospitals buildings (Figure 3.2& 3.3) were constructed during different time periods using a variety of construction methods including concrete-shear-wall or reinforced-masonry which are further defined for each building in Chapter 4 (Table 4.4).The buildings include the Riverside Building (built in the 1970s), Parkside Building (built in late 80s to early 90s), the Diabetes Centre (built in late 1950s and early 1960s), the Christchurch Women's Hospital (built in 2005) and the

Nurses Hostel (built in 1931). The Nurse hostel was vacant during the earthquake and scheduled for demolition (McIntosh et al., 2012). All the medical services contained in the Christchurch Hospital buildings are divided into wards with different specialities (Table 3.1).

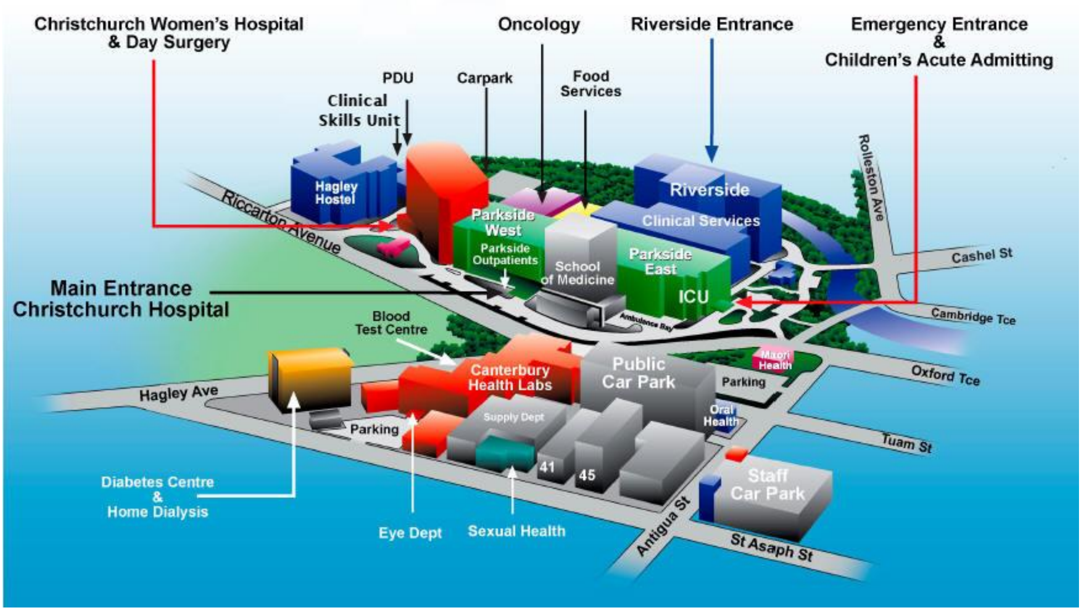

Figure 3.2: Layout of Christchurch Hospital (CDHB 2012b).

Figure 3.3: Christchurch Hospital in the lower right corner adjacent to the CBD and the Avon River, October 2012 (Photo is taken looking SE) (Christchurch City Council).

The Christchurch Women's Hospital building is the most recently constructed facility within the Christchurch Hospital. The structural frame is comprised of reinforced concrete precast beams and columns, cast in situ mid-span joints, and pre-cast flooring units with timber infill and concrete topping to floors. The shear load is accommodated by steel K-braces at the buildings and by the exterior structure. The building is connected to the Parkside west building via three seismically controlled link-ways (CCANZ 2011). The concrete shear wall Parkside and Riverside buildings are older facilities with less modern anti seismic design characteristics, however they were still designed and built with seismic joints and regular plans.

Table 3.1: Christchurch Hospital medical wards (Rhise network).

Ward	**Description**
Ward 12	Part of Christchurch Hospital's Cardiology Department that admits patients directly from the Emergency Department. Specialises in the care of post coronary angioplasty patients, whereas the other Cardiology ward (Ward 26) caters for pacemakers and ablations. The ward consists of 30 beds, of which two are isolation rooms and 15 are telemetry units.
Ward 14	Urology and Nephrology services but also accommodates excess from Cardiology.
Ward 15	Acute/elective general surgical and vascular patients.
Ward 16 (SARA)	One of three surgical wards that take acute/elective patients. It compromises of two surgical wards: Ward 16 is a 16 bed General Surgical unit that specializes in the upper GI. The Surgical Assessment and Review Area (SARA) is a 12 bed unit that is situated in front of ward 16. The SARA is structured to provide an area where patients can be clinically assessed by the general surgical team.
Ward 17	Deals with elective/ Colorectal and acute patient admissions.
Ward 18 & 19	Orthopaedic wards consisting of 55 general ward beds and 5 Trauma unit beds. The ward exclusively provides services for acute trauma and spinal injury patients.
Ward 20	The Plastic Surgery and Reconstructive Unit (PSU) is comprised of a 30 bed ward and adjoining Plastic Surgery Outpatients department. The PSU is also the Regional Burn Unit (RBU) for the whole South Island with the exception of the Nelson / Marlborough DHB. The ward specialises in Plastic Surgery, Reconstruction, Maxillofacial, Burns and all acute hand injuries. All Adult patients are admitted to ward 20, whereas Paediatric patients are admitted to wards 21 and 22. However, the PSU outpatients department deals with both paediatric and adult outpatients. Ward 20 operates with a high turnover although the numbers of short stay patients have decreased after the 23 hour unit was introduced on the May 9, 2011 which has a capacity of 6-8 patients and is currently located in the Preoperative Suite. Ward 32 (ENT) is co located within ward 20 following the Canterbury earthquakes. The current redevelopment program aims to replace the ENT / 23 hour unit and the plastics OPD by early 2013.
Ward 23	Acute General Medicine, Rheumatology and immunology Ward.
Ward 25	27 bed Respiratory that caters to patients with exacerbations of Asthma as well as Pneumothoracies and Pleural Effusions which require chest drainage. Patients are admitted either to Ward 25 acutely or as pre arranged admissions.
Ward 26	25 bed cardiology ward that specialises on Electrophysiology studies, Pacemaker/AICD insertions. The ward also provides facilities to monitor cardiology patients, patients are either admitted directly from the ED or via the catheterization Laboratory.
Ward 27	Oncology has 25 beds, it provides specialized facilities for Oncology services.
Ward 28	Neurology & Neurosurgery has 28 beds and specializes in Neurology and Neurosurgery. The ward includes 4 Progressive Care beds for post-operative craniotomy and spinal surgery, head injury, neurological patients who must be invasively monitored.
Ward 29	Acute medical and gastroenterology ward situated on the 4th floor of the Riverside building. The ALOS in ward 29 is approximately four days.

Ward	Description
Ward 30	An acute medical ward that provides facilities for the treatment of Infectious Diseases. The ward has 29 beds, with a layout of 5 multi bed rooms and 6 single rooms.
Ward 31	Acute 27 bed general, medical ward which includes a 15 bed acute stroke unit.
Ward 32	ENT and EYES but also caters for a variety of other specialties.
CCU	The Coronary Care Unit is an 8 bed special unit with an emergency procedures room that can cater to patients suffering from life-threatening cardiac events and require close observation.
MDU	The Medical Day Unit accommodates pre and post procedure patients and other patients which require full treatment such as IV infusion.
BMTU	The South Island Bone Marrow Transplant Unit specialises in haematological disorder treatment.
ODU	The Oncology Day Unit is associated with the Oncology, Haematology and Palliative departments that reside within the medical/surgical division of the CDHB.
CTW	Cardiothoracic Ward specialises in cardiac and thoracic surgery.
OOD	The Orthopaedic Outpatients Department has approximately 38,000 presentations per year one third of which are acute injuries. Ward admissions also include acute presentations which are triaged from the ED or sent in via GPs, After Hour Surgeries and other centres.
POD	The Parkside Outpatients department consists of clinical rooms, offices, a biopsy theatre and a PUVA treatment area.
ED	Emergency Department
ICU	Intensive care unit
SPCU	The Surgical Progressive Care Unit is responsible for the treatment of un-well surgical patients (CDHB. 2012b).
OTU	Orthopaedic Trauma Unit
EO	Emergency observation
CWH	Christchurch Women’s Hospital incorporates a day surgery unit seven operating theatres, 33 bed gynaecological Unit (GYU) and obstetric services and a 37 bed neo-natal intensive care unit.
GSD	Gastro Day Ward
NED	CWH Labour Ward
NEL	Lincoln Babies
NEM	Maternity Babies
NIC	Neonatal Intensive Care
NSC	Neonatal Special Care
OBD	CWH Labour Ward
OBM	Maternity Ward

3.2.2 Geotechnical and Structural Damage

Geotechnical failures on the Christchurch hospital site caused facilities damage in some areas. Liquefaction induced lateral spreading caused the Avon River retaining walls on the south and eastern boundaries of the hospital to fail. The lateral spreading also caused severe sewage pipe line damage in areas close to the Avon River. Liquefaction caused flooding in all the clinical building basements to varying degrees. The worst flooding was in the Parkside and Riverside buildings basements as well as the lifelines tunnel that connects the clinical facilities to the non-clinical facilities across Riccarton Avenue, which was flooded in up to half a meter of liquefied sediment and water. There was also liquefaction induced land deformation on the banks of the Avon River which the Generator Building is situated adjacent to. Land remediation was required in order to secure the areas of the Avon River bank which threaten the generator buildings (Stylianou 2012).

There were no local or global structural failures of any clinical or non-clinical buildings on the Christchurch Hospital campus. However, structural damage to the underground lifelines tunnel mentioned above caused the tunnel to be unusable for at least 5 months. Two nonclinical administrative buildings on St. Asaph Street also had to be closed; one closure was due to damage to inadequate roof to wall bracing. Spalled concrete beams and columns and cracked steel K-beams caused the closure of the hospital's car parking building (Figure 3.4). The Boiler house on St Asaph street was about to be seismically upgraded prior to the Darfield earthquake. The building was damaged during the Christchurch earthquake however the damage was remediated by reinforcing K walls. The adjoining 55 meter high Boiler stack had to be demolished when structural damage was identified (Stylianou 2012).

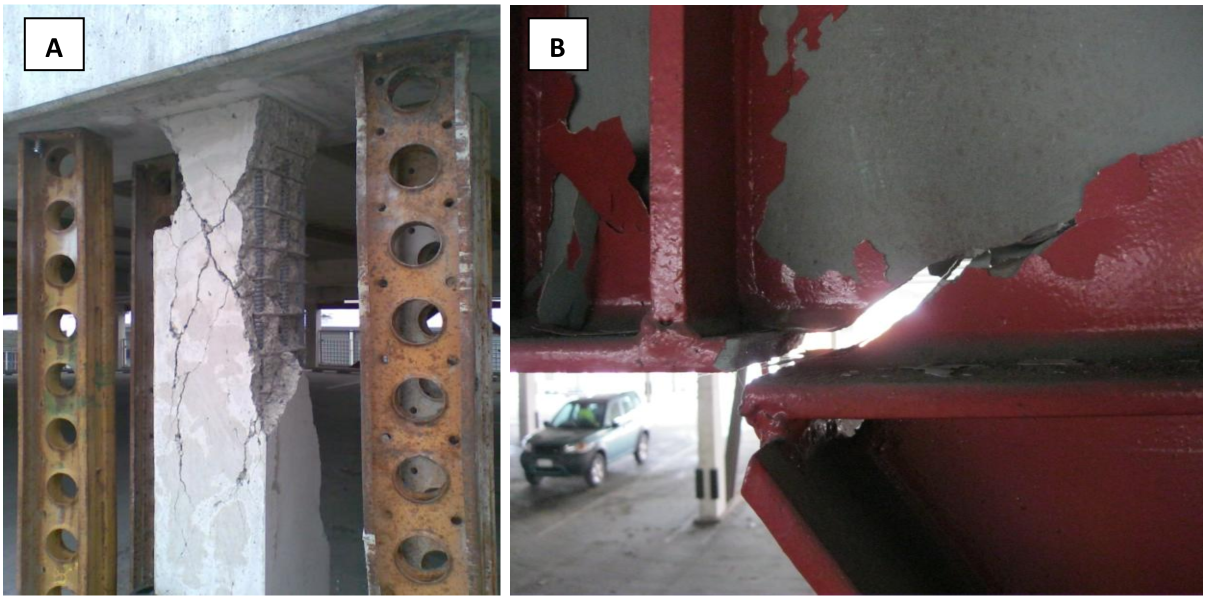

Figure 3.4: (A) A spalled concrete column inside the Christchurch Hospital car parking building. (B) Cracking in car parking building K beam (Bavis 2011).

Minor structural damage was also evident in the Riverside Building when shear wall cracking was discovered some of the cracks went all the way through the wall (Figure 3.5). However, these were fixed relatively easily with epoxy resin. In the Riverside building critical structural weaknesses were indentified in three of the structures that make up the Riverside building. The buildings only met about 40 per cent of the building code, which was introduced May 2012 (Stylianou 2012). All clinical buildings suffered roof damage; however the damage did not warrant closures. In some cases the separation joints of between 100mm and 150 mm were not large enough to accommodate the displacement and were damaged. Each of the seven stairwells in the Parkside building had to be taken out of service for significant repairs, as well some structural walls and floors in the Parkside buildings needed to be injected with resin (Stylianou 2012).

Figure 3.5: Damaged shear wall panels Riverside building, Christchurch Hospital.

In New Zealand hospitals and other critical buildings are categorised in AS/NZ 1170.0 (SNZ 2004) with the "importance Level 4". The code requirements are implemented to insure that critical buildings remain operational under the 500 year serviceability limit state for SLS2 earthquakes (Section 2.3.2) (Uma & Beattie 2010). Christchurch Hospital was most likely mitigated from severe structural damage because the buildings were predominantly rectangular with no abrupt vertical discontinuities; no L- or T- shaped structures and no large overhangs. The separation joints within the structures and the base isolation of the CWH were also mitigating factors. A number of older nonclinical buildings on Antigua Street were seismically upgraded prior to the Christchurch earthquake and thus they were only minimally damaged. The Foundations of the Diabetes Building sank at one end; as well assessments as of the 2nd of March, 2012 identified structural vulnerability in beams, walls and reinforcing steel (CDHB 2012f).

3.2.3 Nonstructural Damage

The effects of nonstructural damage, services damage and transportation network damage along with disruption to supply chains and the organizational structure were far more disruptive to the provision of healthcare at Christchurch Hospital than the minor structural damage. The nonstructural damage affected an array of components that are essential for providing continued healthcare.

The failures of tongue-and-groove jointed, plaster tiled suspended ceilings were one of the most disruptive forms of nonstructural damage to afflict the functionality of Christchurch Hospital (Figure 3.6). The suspended ceiling tiles were designed as thick and heavy fire barriers. The weight of the tiles made them dangerous falling hazards when the ties holding them in place were damaged. The tiles were diagonally braced to the walls when they were first built. However, after they were initially constructed the diagonal ties were replaced with less seismically resistant vertical ties. The damaged tiles' either fell out completely or sagged in place, in some cases the sagging had to be identified by laser level analysis. The weight and damage susceptibility of the old tiles meant they had to be replaced with lightweight less dangerous tiles which were clipped to ceiling grids and diagonally braced. Fuses and light fittings also had to be replaced along with the ceiling tiles. In order to repair the ceilings, parts of Christchurch Hospital had to be closed for periods ranging from hours to days. The majority of the inpatient wards were disrupted for at least two weeks while the tiles were replaced, but in some cases repairs had to be carried out months after the earthquake because the repairs took a lot of planning in order to minimize disruption. Along with the ceiling tiles many light fittings had to be replaced at the same time as the tiles after becoming dislodged from the ceiling tiles during the Christchurch earthquake.

In some areas of the hospital non-load bearing partition walls were also badly damaged. The damage was mostly cosmetic and did not cause the immediate loss of functionality. However, the damaged areas have had to be shut down in order to be repaired in the months after the earthquake. Along with plaster wall damage; concrete wall damage, glazing damage and ceilings damage caused the Diabetes Centre to close for one month for repairs. Broken glazing was also an issue for other areas of Christchurch Hospital.

Most staircases in the clinical buildings had cosmetic cracking along the walls because the connections to the adjacent floors were too rigid. The stairs had to be propped up in order to remain operational during the emergency phase as they are critical for vertical egress. The staircases were later closed one at a time during the recovery phase to be repaired. Power outages described in Table 4.2 meant that emergency lights in some stairwells that were used to evacuate patients failed to work. Most of the hospitals traction elevators were not functional for up to two hours because the seismic switches activated and forced the traction mechanisms to lock the counter weights, they all had to be checked before they could be reactivated (the same situation occurred at Princess Margaret's Hospital). All elevators were traction elevators, except for a hydraulic elevator in the kitchen. The loss of both stairs and elevators complicated the hospitals functions during the emergency phase. However, the disruption failed to impede staff and patients, in some cases staff carried patients with torches through stairwells that lost emergency lighting (Section 3.5).

Most of all the pumps and chillers which were kept in rooftop plant rooms jumped off their mounts following strong shaking; however the snubbers (seismic braces) were not damaged. In the CWH piping for the condenser collapsed because chillers moved. The pumps and chillers were on seismic mounts in accordance with the current NZ seismic standard NZS 4219:2009 (SNZ 2009). NZS 4219:2009 provides the seismic design guidelines and the required performance levels for the engineering systems mentioned above. The code is structured to ensure engineering systems in hospitals are operational under a serviceability level earthquake (Clause 2.4, SNZ 2009).

The River Side Building was extensively disrupted by the effects of nonstructural damage, perhaps more than any other clinical building on the hospital campus. The building is a Level three building designed to protect life but not be functional after 475 year return period earthquake. The nonstructural damage to internal and external roof coverings and roof top water tanks caused water to flow into the 5th and 6th floors of the Riverside building. Precast concrete panels were also damaged throughout the building and have caused disruption during the recovery phase.The water damage caused the evacuation of five adult medical wards in the Riverside building. The wards on the 5th and 6th floors had no horizontal egress so the patients had to be evacuated via the stairwells as explained below in Section 3.5. The loss of clinical space in the Riverside building has been the only permanent loss of capacity at Christchurch Hospital (Section 3.3.1).

Figure 3.6: Damage to nonstructural ceiling tiles in Christchurch Hospital.

3.2.4 Internal and external services damage

During the Christchurch earthquake all of the Christchurch Hospital lifelines were damaged to varying degrees (Table 3.2). The water, wastewater and power networks were all completely un-operational (Giovinazzi et al., 2011). The hospitals internal systems such as suction and back-up power were also partially or completely lost for various periods of time. The loss of power was the most severe internal and external lifeline outage, both the Parkside and Riverside Buildings lost power for one and a half hours. The hospital had back-up generators with a total of 1.5 Megawatts of capacity and one and a half days of fuel stock, the generators were regularly tested roughly every two weeks. However, some of these generators malfunctioned or were damaged (Table 3.2), which affected the immediate functionality of the emergency power supply system. For example, the oil pressure gauge on the Riverside generator broke during the earthquake, which caused that generator to shut down immediately. The 1000 KvA caterpillar Parkside building generator initially ran for a couple of hours, but stopped working because of clogged filters due to sediment in the tanks that had been disturbed by the ground shaking. The filters were replaced and the fuel pumps were re-primed with some trouble by syphoning fuel from a groundskeeper’s car. In addition, shortages to the main low-voltage switchboard caused small fires, damaging the main electrical panel and further complicating the power restoration efforts.

Damage to water and sewage systems, including fire sprinkler systems, also proved a major obstacle. Broken sewage pipes had to be replaced. After the pipes were fixed and re-pressurized new leaks were found and the pipes had to be drained and replaced. Main water was out completely for two days, and full water pressure was not restored for a week. The hospital had back-up water supplies (<1 day's worth), and access to artesian wells, but these did not prove entirely sufficient. Some water could be successfully extracted from the boreholes immediately after the earthquake. However, the silt content in that water was initially too high, which caused issues in moving the water from the ground to the storage tanks as well. Even when this issue was resolved, the water from the borehole could not be used for drinking because it was feared to be contaminated. As well the pressure was too low to pressurize the fire sprinklers because the well was too small. The hospital used bottled water for the first few days after the earthquake.

The lack of water impaired other systems as well, including the fire sprinklers, which could not be pressurized. In order to prevent this situation from occurring in any future disasters, a ½ million-litre capacity tank system was installed after a few days to provide emergency water for crucial systems, including the fire sprinklers. Fortunately, there were no major fires after the event yet the fire alarms were activated because smoke detectors detected dust from damaged nonstructural components. The alarm had to be turned off after the constant sound became an annoyance to clinical staff.

The Riverside building suction network was damaged and un-functional for 30 minutes; the network was quickly restored by connecting the Riverside suction systems to the Parkside suction systems via a bypass in CWH. The Riverside suction network required continued remediation work during the response phase. The medical gases network also continued to be operational however maintenance staff later conducted ultra sonic testing and found some leakage.

Christchurch Hospitals IT system was not lost except for the brief period when it was restarted because of the power outage. Some of the clinical machinery locked up after the strong shaking and had to be recalibrated and restarted, however none were physically damaged. The Sterilizers were all braced and did not cease to operate, however they had to re-circulate the same water for some time. The Steam mains were not damaged but had to be taken out of service while they were fitted with new Gimbals that move with seismicity.

Table 3.2: Summary functional loss by hospital (Y) yes, (N) no (Kirsch et al)

	Hospital											
Function	Christchurch damaged?	Christchurch services backed up?	Princess Margaret's damaged?	Princess Margaret's services backed up?	St George's damaged?	St George's services backed up?	Kaikoura damaged?	Kaikoura services backed up?	Akaroa damaged?	Akaroa services backed up?	Ellesmere damaged?	Ellesmere services backed up?
External												
Electricity	Y(1.5hr)	Y(1.5dy)	Y(4hr)	Y(1wk)	Y	Y	N	Y(4dy)	Y(1dy)	Y	Y	Y
Back up electricity	N	Y(1.5dy)	N	Y(1wk)	N(4dy)	-	N	-	N	-	-	-
Water	Y(1wk)	Y(<1dy)	Y(12hr)	Y(1wk)	Y(14dy)	N	N	Y(5dy)	Y(3dy)	Y	Y	Y
Sewer	N	N	Y(2wk)	N	Y(3dy)	N	N	-	N	-	-	-
Telephone	Y(20min)	Y	Y(6hr)	Y	Y	Y	N	-	Y(1dy)	-	-	-
Internal												
Computers	N	-	N	-	N	-	N	-	N	-	-	
Medical gases	N	-	N	-	Y(4dy)	-	N	-	N	-	Y	Y
Suction	Y(30min)	-	N	-	Y(3dy)	N	N	-	NA	NA	NA	NA
Total services lost	4		4		4		0		3		0	0

3.3 Impact on Hospital Functionality and Residual Capacity of Health Care Delivery Emergency Response and Medical Evacuations at Christchurch Hospital

The day of the Christchurch earthquake (22^{nd} of February, 2011) Christchurch Hospital admitted and dealt with 160 casualties. The triage after the earthquake was set up in the parking lot in front of the Emergency Department. There were no deaths related to the Christchurch earthquake in Christchurch hospital post earthquake patients or staff, though four staff members were injured during the evacuation of some of the hospital wards. Evacuations of sick or injured patients are potentially dangerous events under any circumstances, but are particularly risky when moving a large group of patients with limited personnel, no power, and no elevators.

The darkness of the stairwells and the unavailability of elevators (Section 3.3) made evacuation very difficult. Most patients were able to walk down on their own, but some had to be carried down five to six flights of stairs in the dark. Many patients and some staff self-evacuated after the earthquake to areas perceived as safer locations outside the buildings. The third floor of the Riverside Building was evacuated in a subsequent phase. All evacuations after the initial Riverside evacuation were by horizontal egress routes. These evacuations were triggered by failures of suspended ceilings, the lack of functionality of the fire sprinkler system, and the lack of sufficient pressure in the back up water system (Section 3.2.3). A total of 350 patients were evacuated from the hospital overall. The Oxford Clinic, a general practice located nearby on Oxford terrace evacuated to Christchurch Hospital.

Supplies and non-clinical services were mostly undamaged. The kitchen maintained its functionality, guarantying the provision of food. However, the laundry was shipped out for two days because of short-staffing and lack of water; half of the laundry was handled by Timaru Hospital during this time. Drinking water was provided in bottles brought by a private company. The pharmacy did not run out of pharmaceuticals, blood products, dressings, splints, surgical supplies, or other any other treatment supplies. Similarly, there was no loss or shortage of lab supplies, radiological supplies, or other diagnostic supplies. Two off-site laboratories used by the hospital, one of which was located in the CBD, were shut down, but the onsite laboratory remained functional. All the shelves containing the medical records tipped over.

3.3.1 Short-term Losses of Health Care Capacity at Christchurch Hospital

The hospital never closed completely, the adult wards on the 4th and 5th floors of the Riverside building were the only closures during the quake (wards 29, 30, 31 and 32), making 106 adult medical beds unusable out of a normal 650 beds (CDHB 2012a) (Table 3.3) (or a 17% loss in capacity). The surge capacity of the selected facilities in Christchurch immediately after the Christchurch earthquake is summarised in Table 3.3

One child assessment unit had to be temporarily repurposed to treat adults. Twelve ICU patients were evacuated to other ICUs in Dunedin, Nelson and the North Island. There were 25 ICU patients after the earthquake, but only 16 beds. In order to generate capacity stable patients were evacuated by air to the Wellington Hospital ICU (table 3.3, 3.4 & 3.6). And other patients were steeped down to the Christchurch Hospital recovery wards. The ICU did not have to deal with burns patients because the burns casualties died at the site (CTV) and never had to prioritize the treatment of patients in the ICU and ED. Only two earthquake causalities died within the hospital ICU. Four other patients were deceased upon arrival. The Hospital did not admit many alcohol related patients in the days after the earthquake as the CBD bars were closed.

Table 3.3: Summary of hospital capacity following the Christchurch earthquake (Kirsch et al)

Hospital	Residual capacity	Surge capacity	Patients during EQ	Discharged first 24 hours	Transferred first week	Change in capacity ratio
Christchurch	522	-	-	-	(-) 44	522/650
Princess Margaret's	109	155	109	1	(+)47	109/109
St George's	80	0	52	52	0	80/101
Kaikoura	26	26	15	0	(+) 3	26/ 26
Akaroa	8	8	8	8	(+) 8	8/8
Ellesmere	10	10	8	0	(+) 3	10/10

Following the Christchurch earthquake three wards at Christchurch Hospital were un-operational (ward’s 29, 30 and 31) (Table 3.1). Christchurch Hospital was severely strained during the winter of 2011 as a result of cold weather, earthquake induced deprivation and poor housing. An increase in respiratory and cardiology admissions were also anticipated based on experiences after the Darfield earthquake (CDHB 2012a). Burwood birthing unit staff were deployed to Christchurch Woman’s Hospital while the Burwood birthing unit was closed for two weeks due to earthquake damage.

Christchurch Hospital increased support to the Adult Medical Assessment Unit (AMAU) and the Surgical Assessment Review Area (SARA) ward in order to streamline the assessment and discharge processes. The actions increased the patient flow from the ED to the AMAU. The strain on the ED was relieved by directly referring GP patients to the AMAU and SARA and sending Ambulance and ED patients to primary care providers and after hour’s clinics (CDHB 2012a).

The Orthopaedic Rehabilitation ward was closed for extensive nonstructural repairs and was accommodated in the Surgical Orthopaedic ward (; however this strained both wards capacity (CDHB 2012a). Following the 22nd of February, 2011outpatient appointments increased from an average of around 4% before the earthquake to around 6.5% after. The Lyndhurst day facility and Christchurch Hospitals Oral Health Centre facilities had to be transferred. As well Christchurch Hospitals ENT (Ear, Nose and Throat)/ophthalmology ward was unable to operate for a period of time (CDHB 2012a).

Christchurch hospital stopped all elective surgery and outpatient services immediately after the emergency in order to surge capacity. This decision greatly reduced the number of patients in the clinical buildings. There were approximately 320 inpatients in the hospital after 24 hours, 270 after 72 hours, and 400 after 7 days, Table 3.6 summarises the ward relocations and Table 3.3 summarises the permanent changes in capacity for the Akaroa, St Georges, Princess Margaret's and Christchurch hospitals'.

Table 3.4: Hospital transfers to and from Christchurch's hospitals between 22nd of February, 2011and 8th of March, 2011 (Rhise network).

Hospital	**Transferred out**	**Transferred in**	**Difference**	**location**
Burwood	31	74	43	Christchurch
BWD birthing	0	1	1	
Christchurch	387	35	-352	
Hillmorton	0	4	4	
Parklands hospital	0	1	1	
PMH	0	71	71	
Rosewood rest home	0	1	1	
Parkside Rest home	0	1	1	
St Georges	0	1	1	
Akaroa	1	4	3	Regional Canterbury
Ashburton	14	29	15	
Darfield	1	4	3	
Ellesmere	0	2	2	
Kaikoura	1	0	-1	
Lincoln	0	51	51	
Oxford	1	3	2	
Rangiora	1	57	56	
Timaru	0	22	22	
Waikari	1	4	3	
Dunedin	0	16	16	Rest of South Island
Grey	0	3	3	
Nelson	0	10	10	
Southland	0	2	2	
Wairau	0	1	1	
Buller	0	1	1	
Auckland city	0	5	5	North Island
HAS	0	1	1	
Hawke's Bay	0	1	1	
Middlemore	0	2	2	
Napier	0	1	1	
North Shore	0	2	2	
Tauranga	0	7	7	
Waikato	0	4	4	
Wellington	0	17	17	
Unknown	0	5	5	-
Undocumented	**18**	**18**	**0**	-
Total	**455**	**457**	**2**	**-**

Table 3.5: The number of patients and the number of transfers from Christchurch Hospital in the first two weeks following the Christchurch earthquake (Rhise network)

Date	**22/02/2011**		**23/02/2011**		**24/02/2011**		**25/02/2011**		**26/02/2011**		**27/02/2011**		**28/02/2011**		**1/03/2011**		**2/03/2011**		**3/03/2011**		**4/03/2011**		**5/03/2011**		**6/03/2011**		**7/03/2011**	
Hospital	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**	**Patients**	**Transfers**
Akaroa	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	**1**	**1**	0	0	0	0	**2**	**2**	0	0	0	0	0	0
Ashburton	**3**	**3**	**10**	**6**	**4**	**3**	0	0	**5**	**3**	**2**	**2**	**3**	**3**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Auckland city	0	0	**4**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0
Burwood	**7**	**2**	**10**	**4**	**5**	**3**	**19**	**10**	**9**	**7**	**2**	**1**	**1**	**1**	**3**	**3**	**2**	**2**	**4**	**3**	**1**	**1**	0	0	**1**	**1**	**5**	**3**
BWD birthing	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CWH	**1**	**1**	0	0	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Darfield	0	0	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0
Dunedin	**1**	**1**	**8**	**5**	**1**	**1**	**3**	**2**	**1**	**1**	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0
Ellesmere	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grey	0	0	0	0	**2**	**2**	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAS	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hawke’s Bay	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hillmorton	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	**1**	**1**	0	0	0	0
Kaikoura	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lincoln	0	0	**2**	**2**	**10**	**2**	**2**	**2**	**2**	**2**	**4**	**2**	0	0	**4**	**2**	**4**	**2**	**4**	**2**	**2**	**2**	**10**	**4**	0	0	**4**	**2**
Middlemore	0	0	**1**	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Napier	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nelson	0	0	**2**	**2**	**1**	**1**	**5**	**3**	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North Shore	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**
Oxford	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parklands	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0
PMH	**14**	**3**	**6**	**3**	**2**	**2**	**8**	**5**	**5**	**3**	**1**	**1**	**5**	**3**	**6**	**4**	**5**	**5**	**8**	**6**	**6**	**3**	0	0	**1**	**1**	**2**	**2**
Rangiora	**4**	**2**	**4**	**3**	**6**	**2**	0	0	**11**	**4**	0	0	0	0	**2**	**2**	**5**	**3**	**4**	**2**	**10**	**5**	**6**	**4**	0	0	**4**	**2**
Rosewood	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0
Southland	0	0	0	0	0	0	**2**	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tauranga	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0

Date	22/02/2011		23/02/2011		24/02/2011		25/02/2011		26/02/2011		27/02/2011		28/02/2011		1/03/2011		2/03/2011		3/03/2011		4/03/2011		5/03/2011		6/03/2011		7/03/2011	
Hospital	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers	Patients	Transfers
Timaru	0	0	8	7	7	5	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waikari	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waikato	0	0	3	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Wairau	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wellington	0	0	9	6	3	3	0	0	2	2	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1
St Georges	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Buller	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	1	1	0	0	0	0	1	1	1	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Total	32	14	71	45	46	29	46	30	39	26	13	10	11	9	20	16	18	14	24	17	21	13	17	9	2	2	17	11

Christchurch Hospital's nuclear medicine and clinical engineering operations were undamaged, but the unit had staffing problems. The Dialysis Centre closed for repairs after the earthquake, though it moved and reopened elsewhere. Outpatient services were lost for one day after the earthquake, and reduced for the next two weeks. Rehabilitation and physical therapy were also lost for the first day and partially down for a week.

There were more clinical staff than needed immediately after the earthquake, because off duty staff arrived to help. The Hospital also received staff from the North Island and South Island's West Coast in the weeks after the Christchurch earthquake. Many staff were reluctant to leave the hospital in the hours after the earthquake when compulsory leave was instated. Senior staff identified staff fatigue as a possible future issue when the long term affects of stress caused by the earthquake became apparent. As well the large quantity of volunteers that offered to assist the hospital became disruptive to clinical staff.

The immediate capacity redistribution and there mode of transport for the Canterbury hospital network is quantified in Tables (3.5 & 5.1). Christchurch Hospital's individual ward capacity redistribution for the short term, medium term and long term are quantified in Table 3.6. Analysis of the Christchurch Hospital capacity data shows that the Medical Day Unit (MDU), Christchurch Women's maternity wards (NED, NEM, OBD & OBM) account for a large portion of the immediate transfers (151/387) (Table 3.5 & Table 3.7). The five wards were not severely damaged; therefore the patients were transferred in large numbers to reduce demand on the hospital and were able to be transferred because they were relatively stable. The MDU and certain maternity wards had large numbers of patients that were discharged at the request of the patients and of clinical staff.

The total number of orthopaedic patients 107 orthopaedic patients were admitted over the five days following the February, 22, 2011 earthquake, 65 of which were admitted on the first day. The mass casualty incident response framework and a major external incident plan helped the facilities (ASMS 2012). In Christchurch immediately after the Christchurch earthquake 516 elderly care patients were evacuated and transferred from residential care homes. 298 patients were transferred to other aged care facilities outside of Christchurch, 194 were transferred to other facilities in Christchurch and 18 were accommodated by family (14 within Christchurch and 4 elsewhere). One patient was admitted to Christchurch hospital and died within 24 hours, and 5 patients were lost during the follow up period. Initially elderly care patients from residential care homes were transferred to other areas in the south island, but then they ran short of beds so they had to transfer patients to the north island (CDHB 2012c).

3.3.2 Long-Term Rebalancing of Canterbury Health System

The evacuation of adult wards in the Riverside building top two floors (5^{th} and 6^{th}) (Table 3.5) to date has been the only permanent loss of capacity at Christchurch Hospital. Due to the lack of horizontal egress and the presence of only a single stairwell, the decision was made to permanently change the use of those floors from clinical wards to administrative space. The capacity was accommodated at Princess Margaret's Hospital, also another 10 beds at Ashburton Hospital were created to accommodate long-term care.

Initiatives like the Medication Management Service (MMS), Community Rehabilitation Enablement Support Teams (CREST) and elective surgery outsourcing have reduced the pressure on Christchurch Hospital. Elective surgery at Christchurch Hospital resumed on the 7th of March, 2011. During 2011 approximately 500 elective surgeries such as hip replacements were contracted out to the private hospitals Southern Cross and St Georges under the "Electives Recovery Programme" which will continue up to at least 2013 (CDHB 2012a). The CDHB predicted a shortfall of 740 elective surgery cases during 2011, down 5 per cent on the annual target (The Press 2011). CREST catered to 829 patients in the nine months up to the 31st of March, 2012. MMS had 78 community pharmacists operating as of the 1st of May, 2012 (CDHB 2012). Christchurch Hospital and Princess Margaret Hospital initiated a process that tracks the status of beds within the CDHB on a daily basis (CDHB 2012e).

Christchurch Hospital's capacity over the 18 months following the Christchurch earthquake is quantified in Tables 3.5 and 3.7. The data reveals the quantity of immediate transfers of patients following the earthquakes and the wards the patients were transferred from. The ward capacity data was retrieved from the CDHB on August 21, 2012 which in some cases may not be exactly the same as the ward capacity immediately before the Christchurch earthquake. The 20th of August, 2011 ward location data was retrieved form Bruce Hall the emergency planner for Christchurch Hospital.

Approximately 70% of the transfers for the two weeks following the Christchurch earthquake were in the first week (Table 3.5). However, the data doesn't include discharges, which were significant immediately after the earthquake. The data presented in Table 3.5 shows that the surging of capacity was quick with the largest portion of transfers occurring in the day after the earthquake. The mode of transfer within the Canterbury regional Hospital network was by road and helicopter, the 20 patients from the top two floors of the Riverside building were transferred by truck. Whereas all the transfers between regions where by fixed wing or helicopter.

Table 3.6: Transfers from Christchurch Hospital wards between 22nd of February, 2011and the 8th of March, 2011 for earthquake related injuries and non earthquake related injuries (Rhise network).

Ward	**Pre EQ Building**	**August 20, 2011 building**	**August 20, 2012 Building**	**Non earthquake injury transfers**	**Earthquake injury transfers**	**Post earthquake capacity**
Ward 12	Parkside West 2nd Floor	Parkside West 2nd Floor	Parkside West 2nd Floor	7	0	30
Ward 14	Parkside West 3rd Floor	Parkside West 3rd Floor	Parkside West 3rd Floor	4	0	25
Ward 15	Parkside East 2nd Floor	Parkside East 2nd Floor	Parkside East 2nd Floor	3	0	24
Ward 16	Parkside East 2nd Floor	Parkside East 2nd Floor	Parkside East 2nd Floor	5	0	16
Ward 17	Parkside East 2nd Floor	Parkside East 2nd Floor	Parkside East 2nd Floor	6	3	30
Ward 18	Parkside East 3rd Floor	Parkside East 3rd Floor	Parkside East 3rd Floor	15	15	60
Ward 19	Parkside East 3rd Floor	Parkside East 3rd Floor	Parkside East 3rd Floor	15	7	-
Ward 20	Parkside East 3rd Floor	Parkside East 3rd Floor	Parkside East 3rd Floor	6	3	30
Ward 21	Riverside G Floor	CWH & GYN	Riverside G Floor	0	0	-
Ward 22	Riverside G Floor	CWH & GYN	Riverside G Floor	0	0	-
Ward 23	Riverside 1st Floor	Riverside 1st Floor	Riverside 1st Floor	16	2	-
Ward 24	-	-	Riverside	0	0	-
Ward 25	Riverside 2nd Floor	ICU + PACU	Riverside 2nd Floor	6	1	27
Ward 26	Riverside 2nd Floor	GASTRO	Riverside 2nd Floor	15	1	25
Ward 27	Riverside 3rd Floor	SARA	Riverside 3rd Floor	4	0	25
Ward 28	Riverside 3rd Floor	Parkside East 2nd Floor	Riverside 3rd Floor	17	2	28
Ward 29	Riverside 4th Floor	PMH, Gastroenterology WD26	PMH, Gastroenterology WD26	10	0	27
Ward 30	Riverside 4th Floor	PMH, infectious diseases WD23	PMH, infectious diseases WD23	10	0	29
Ward 31	Riverside 5th Floor	PMH, closed to outpatients	PMH closed to outpatients	2	0	27
Ward 32	Riverside 5th Floor	-	Parkside East 3rd Floor WD20	0	0	22
MDU	Parkside West G Floor	Parkside West G Floor	Parkside West G Floor	21	0	6 (15 chair)
NED	Chch Women’s	Chch Women’s	Chch Women’s	29	0	-

Ward	Pre EQ Building	August 20, 2011 building	August 20, 2012 Building	Non earthquake injury transfers	Earthquake injury transfers	Post earthquake capacity
NEM	Chch Women’s	Chch Women’s	Chch Women’s	29	0	-
OBD	Chch Women’s	Chch Women’s	Chch Women’s	35	0	-
OBM	Chch Women’s	Chch Women’s	Chch Women’s	37	0	-
AMAU	Riverside 1st Floor	Parkside West OPD	Riverside 1st Floor	3	0	-
CICU	Parkside East 1st Floor	Parkside East 1st Floor	Parkside East 1st Floor	1	1	-
ICU	Parkside East 1st Floor	Parkside East 1st Floor	Parkside East 1st Floor	7	7	18
NEL	-	-	Chch Women’s	1	0	-
NIC	Chch Women’s 4th Floor	Chch Women’s 4th Floor	Chch Women’s 4th Floor	9	0	-
SPCU	Parkside East 2nd Floor	Parkside East 2nd Floor	Parkside East 2nd Floor	3	0	6
BMTU	Riverside Lower G Floor	DOSA	Riverside LG Floor	1	0	15
CTW	Parkside East 1st Floor	Parkside East 1st Floor	Parkside East 1st Floor	3	0	10
OTU	Parkside East 3rd Floor	Parkside East 3rd Floor	Parkside East 3rd Floor	1	3	-
SARA	-	-	Parkside East 2nd Floor	1	1	-
EO	Parkside East 1st Floor	Parkside East 1st Floor	Parkside East 1st Floor	2	1	10
GSD	-	-	Riverside 4th Floor	1	0	-
NSC	Chch Women’s 4th Floor	Chch Women’s 4th Floor	Chch Women’s 4th Floor	9	1	-
GYU	Chch Women’s	Chch Women’s	Chch Women’s	1	0	33
CHOC	Riverside G Floor	Chch Women’s	Riverside G Floor	-	-	-
OOD	Parkside East 3rd Floor	-	-	-	-	-
ODU	-	-	-	-	-	-
CCU	Parkside West 2nd Floor	Parkside West 2nd Floor	Parkside West 2nd Floor	1	0	8
UU	Parkside West 2nd Floor	Parkside West 2nd Floor	Parkside West 2nd Floor	1	0	-
DOSA	-	-	Parkside West 1st Floor	0	0	-
OPD	-	-	-	-	-	-
Other	-	-	-	3	0	-
Total				**340**	**48**	**-**

Table 3.7: Patients transferred from Christchurch Hospital wards in the two weeks following the Christchurch earthquake (Rhise network)

Date	22/02/2011	23/02/2011	24/02/2011	25/02/2011	26/02/2011	27/02/2011	28/02/2011	1/03/2011	2/03/2011	3/03/2011	4/03/2011	5/03/2011	6/03/2011	7/03/2011
AMAU	0	1	0	0	1	0	0	1	0	0	0	0	0	0
BMTU	0	0	1	0	0	0	0	0	0	0	0	0	0	0
CCU	0	0	0	0	0	0	0	0	0	0	0	0	0	1
CICU	0	1	0	0	0	0	0	0	0	0	0	0	0	0
CTW	0	0	1	1	0	0	0	1	0	0	0	0	0	0
EO	0	0	0	1	0	0	0	0	0	1	0	1	0	0
GSD	0	0	0	1	0	0	0	0	0	0	0	0	0	0
GYU	0	0	0	0	0	1	0	0	0	0	0	0	0	0
ICU	0	13	0	1	0	0	0	0	0	0	0	0	0	0
MDU	2	14	0	5	0	0	0	0	0	0	0	0	0	0
NED	1	1	5	1	4	3	0	0	4	0	3	3	0	4
NEM	2	0	5	0	5	1	1	3	0	4	3	5	0	0
NEL	0	1	0	0	0	0	0	0	0	0	0	0	0	0
NIC	0	4	1	1	1	1	1	0	1	0	0	0	0	0
NSC	0	2	1	3	0	0	1	0	0	0	1	0	0	0
OBD	2	1	6	2	5	4	0	1	4	0	3	3	0	4
OBM	2	2	5	3	5	2	1	3	0	4	3	5	0	1
OUT	0	0	2	0	1	0	0	0	0	0	0	0	0	1
SARA	0	0	1	0	0	1	0	0	0	0	0	0	0	0
SPCU	0	2	0	1	0	0	0	1	0	0	0	0	0	0
UU	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Wd 12	0	2	0	3	0	0	0	1	1	0	0	0	0	0
Wd 14	0	2	0	0	0	0	0	1	0	1	0	0	0	0
Wd 15	0	1	1	0	0	0	0	0	0	1	0	0	0	0
Wd 16	0	2	1	1	0	1	0	0	0	0	0	0	0	0
Wd 17	0	2	4	0	1	0	0	0	0	0	0	0	1	1
Wd 18	1	7	1	6	7	2	0	1	1	1	1	0	1	1
Wd 19	1	3	2	6	2	0	2	0	2	5	0	0	0	3
Wd 20	0	1	3	2	1	1	0	0	0	0	0	0	0	0
Wd 23	0	0	0	3	4	0	2	3	1	2	2	0	0	1
Wd 25	0	1	1	2	0	0	0	0	0	2	1	0	0	0
Wd 26	0	2	3	0	0	0	3	2	2	1	3	0	0	0
Wd 27	0	2	0	1	0	0	0	0	0	1	0	0	0	0
Wd 28	1	6	1	4	1	0	0	2	2	2	0	0	0	0
Wd 29	10	1	0	0	0	0	0	0	0	0	0	0	0	0
Wd 30	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Wd 31	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total	**33**	**75**	**46**	**48**	**39**	**17**	**11**	**20**	**18**	**25**	**20**	**17**	**2**	**16**
Percentage	**8.5**	**19.3**	**11.9**	**12.4**	**10.1**	**4.4**	**2.8**	**5.2**	**4.6**	**6.4**	**5.2**	**4.4**	**0.5**	**4.4**

3.4 Physical and Functional Impact on the Canterbury hospital network

Canterbury's Hospital network is comprised of 29 publicly and privately operated hospitals (Table 3.8) including public private and elderly care hospitals and seven rural Regional Hospitals which each contain less than 20 beds. The publicly owned hospitals provide the majority of secondary and tertiary medical care. A smaller not-for-profit private hospital sector specializes mainly in elective surgery and long-term care. The private hospitals are operated directly or subsidised by the Canterbury District Health Board (Health, M. O. 2011). The "third sector" providers, made of non-profit non-government organizations (Health, M. O. 2011), offer other services, including general practitioners (GPs), nursing homes, and ambulance service. Following the Canterbury earthquakes, damage to facilities and lifelines placed considerable strain upon the Canterbury health care system, specifically Christchurch's network of private/public hospitals, GPs, and elderly care facilities. To cope with demand, the health system has had to utilize the entire health network's capacity.

Table 3.8: Canterbury Hospital network (Rhise network)

Hospital name	**Location**	**Type**	**Function**
Akaroa Community Hospital	Akaroa	Public/regional	Maternity, rehabilitation & general medical
Ashburton and Rural Hospital	Ashburton	Public	Maternity, medical, gynaecology and surgery
Bethesda Hospital	Christchurch	Private	Elderly
Bidwill Trust Hospital	Timaru	Private	Elderly
Burwood Hospital	Christchurch	Public	Rehabilitation & elective surgery
Canterbury Charity Hospital	Christchurch	Community	Elderly
Cashmere View Hospital	Christchurch	Private	Elderly
Christchurch Hospital	Christchurch	Public	Paediatrics, ED, ICU, Cancer treatment, oncology, maternity, general medical & elective surgery
Christchurch Women's Hospital	Christchurch	Public	Maternity
Darfield Hospital	Darfield	Public/regional	Elderly, surgical rehabilitation, medical & maternity
Ellesmere Hospital	Ellesmere	Public/regional	Elderly, Surgical Rehabilitation and general medical
Hillmorton Hospital	Christchurch	Public	Psychiatric
Kaikoura Hospital	Kaikoura	Public/regional	Elderly, general medical & maternity
Lincoln Maternity Hospital	Lincoln	Public/regional	Maternity
Lyndhurst Hospital	Christchurch	Public	Elderly
Nurse Maude Memorial Hospital	Christchurch	Private	Elderly
Rangiora Hospital	Rangiora	Public/regional	Elderly & maternity
Oxford Clinic Hospital	Christchurch	Private	Elective surgery
Oxford Hospital	Oxford	Public regional	Elderly & general medical
Princess Margaret Hospital	Christchurch	Public	Geriatrics/ Psychiatric
Queen Mary Hospital	Hamner springs	Public	Elderly
Southern Cross Hospital	Christchurch	Private	Elective surgery, Cancer treatment & maternity
St. George's Hospital	Christchurch	Private	Elective surgery, Cancer treatment & maternity

Hospital name	Location	Type	Function
St. John of God Hospital	Christchurch	Private	Elderly
St. Nicolas Medical Hospital	Christchurch	Private	Elderly
Talbot Hospital	Timaru	Public	Elderly
Timaru Hospital	Timaru	Public	Paediatrics, ED, ICU, oncology, rehabilitation, maternity & elective surgery
Tauranga Home	Ashburton	Public/regional	Elderly, dementia
Waikari Hospital	Waikari	Public/regional	Elderly, rehabilitation, general medicine & maternity

The hospitals are structured to provide different specialities and centralise resources such as food and laundry in order to achieve maximum population cover and efficiency. For example, Ashburton Hospital mainly performs lab work, radiology, maternity and physiotherapy services whereas Burwood Hospital (Section 3.4.1.3) specializes in rehabilitation and elective surgery. Princess Margaret Hospital accounts for the majority of the CDHBs geriatric and psychiatric care. Hillmorton Hospital provides most of Christchurch's mental health care and St Georges and Southern Cross hospitals provide private elective surgery and maternity care. Med laboratory, Canterbury laboratory and Christchurch Hospital laboratory complete most of the blood tests from GPs and hospitals within Canterbury (MHO 2010).

Five patients with minor to moderate injuries were driven to the Timaru Hospital Emergency Department by their families on the night of 22nd of February, 2011. Timaru Hospital cancelled elective surgery and freed a total of 76 beds as well as 17 beds at nearby Bidwill Hospital. The first patient to be transferred to Timaru Hospital was recovering from non earthquake related surgery and needed a high level of care (SCDHB 2011).

3.4.1 The Christchurch hospital network excluding Christchurch Hospital

3.4.1.1 Princess Margaret Hospital (PMH)

Princess Margaret Hospital (Figure 3.1 & 3.7) lost main water for 12 hours and full water pressure was not restored for one week (Table 3.2). The small backup water bore could not pressurize the showers or be used for drinking because of E coli contamination; it took one week till the water system was back to normal. The sewage systems were also damaged and were inoperable for up to two weeks due to pipeline damage. Most plastered walls and separation joints were damaged albeit to a non life threatening degree. The Princess Margaret Hospital buildings were constructed with concrete frame, the outside walls were clad with brick veneer, the veneer had vertical, diagonal and horizontal cracking ranging from 1-4 mm and some areas of the Princess Margaret Hospital were yellow stickered (limited access and needs further evaluation) as a result of the damage. However, the concrete structure sustained no damage. The power was lost for 4 hours (Table 3.2) immediately after the earthquake because diffusers popped out. The acceleration within the building also caused nonstructural damage to contents on shelves and in the supply rooms and drugs rooms.

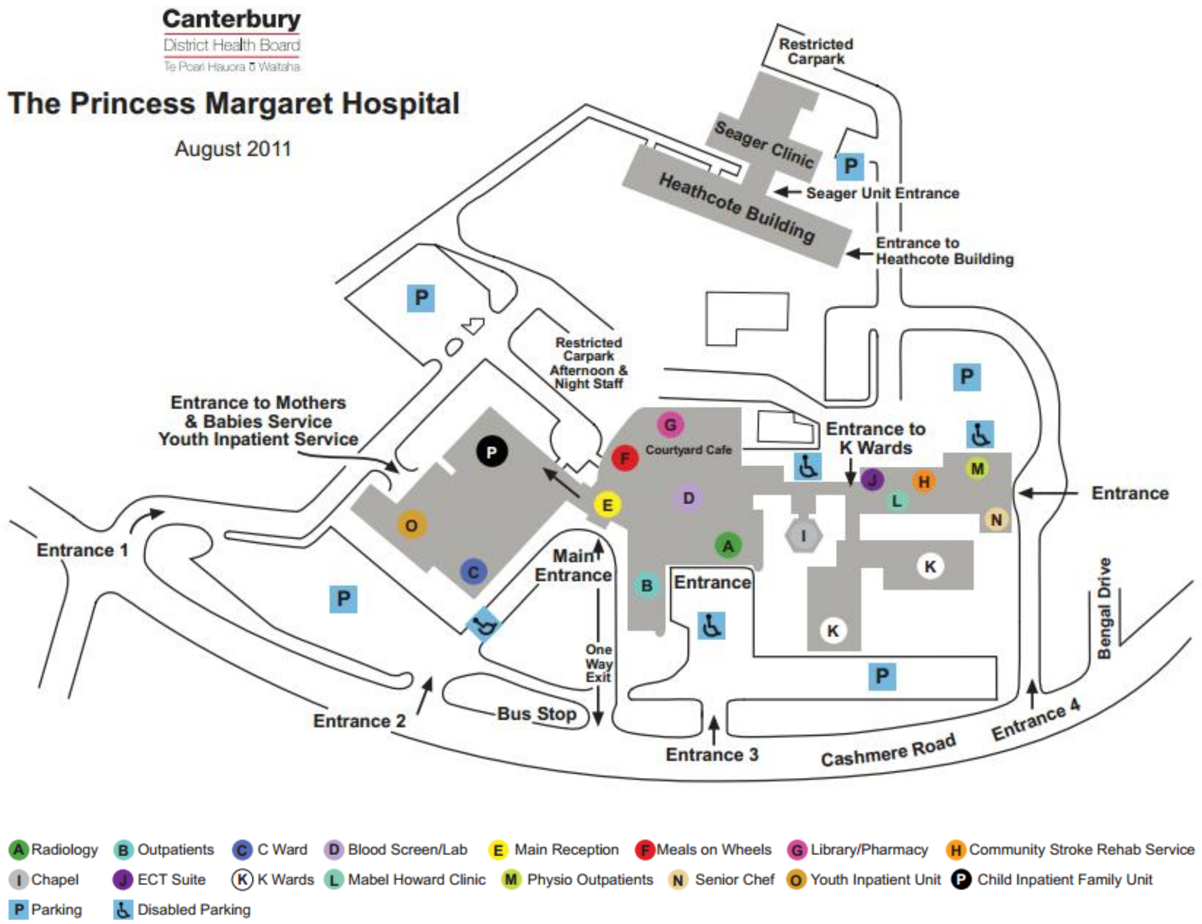

Figure 3.7: Map of Princess Margaret Hospital (CDHB 2012g).

The ALOS for patients at Princess Margaret Hospital is 26 to 30 days, the average age of patients is 83.6 years and the average occupancy is 97%. Immediately after the earthquake the hospital was operating at 100% occupancy with 109 patients in the general wards. In order to free up capacity they cancelled outpatient services for 2 weeks and operated a triage area in front of the hospital for 72 hours. Patients from Christchurch Hospital were transferred to Princess Margaret Hospital on the night after the earthquake via furniture trucks (Section 3.3.1); the ambulance bay was too low to fit trucks so staff used milk trays to create a bridge in order to off load the patients. Thirty three patients were transferred from a closed rest home at 9pm on the 22nd of February, 2011. The patients were kept in lounges for 48 hours before being redistributed by buses and fixed wing military flights.

One patient had a heart attack and one staff member twisted their ankle otherwise there were no injuries or fatalities related to the earthquake. However, the hospital received a lot of crush injuries, fractures and broken wrists from the community. Immediately after the earthquake a crush victim came to Princess Margaret Hospital in a van followed by an MI patient, they also had to treat some patients in the car park.

The loss of water meant staff could not wash patients for two days or shower patients for a week, however patients were hand washed. The toilets where inoperable immediately after the earthquake, instead kimonos were used for patients and staff shared three portable toilets. The Princess Margaret Hospital laundry service was lost for one week because of the loss of mains water. Ashburton Hospital helped source clean linen. Hillmorton hospital supplied Princess Margaret Hospital with food prior to the earthquake but was disrupted during the emergency response. However, there was a couple of day's worth of food on site which was enough to last until the food services were restored.

3.4.1.2 St George's Hospital

St. Georges Hospital (Figure 3.1& 3.13) dominantly performs elective surgery, Cancer treatment and maternity care. The hospital was closed completely from the 22nd of February, 2011 till the 7th of March, 2011 due to structural damage to the reinforced masonry maternity ward, nonstructural damage to the surgical wards and the loss of services. The Maternity building which has subsequently been demolished (Figure 3.10) also housed all the hospitals administrative functions. The medical records kept in the administrative area of the maternity building were damaged when air conditioning units dislodged and fell through the roof. Water from earthquake damaged pipes came in through the holes made by the dislodged air conditioning units.

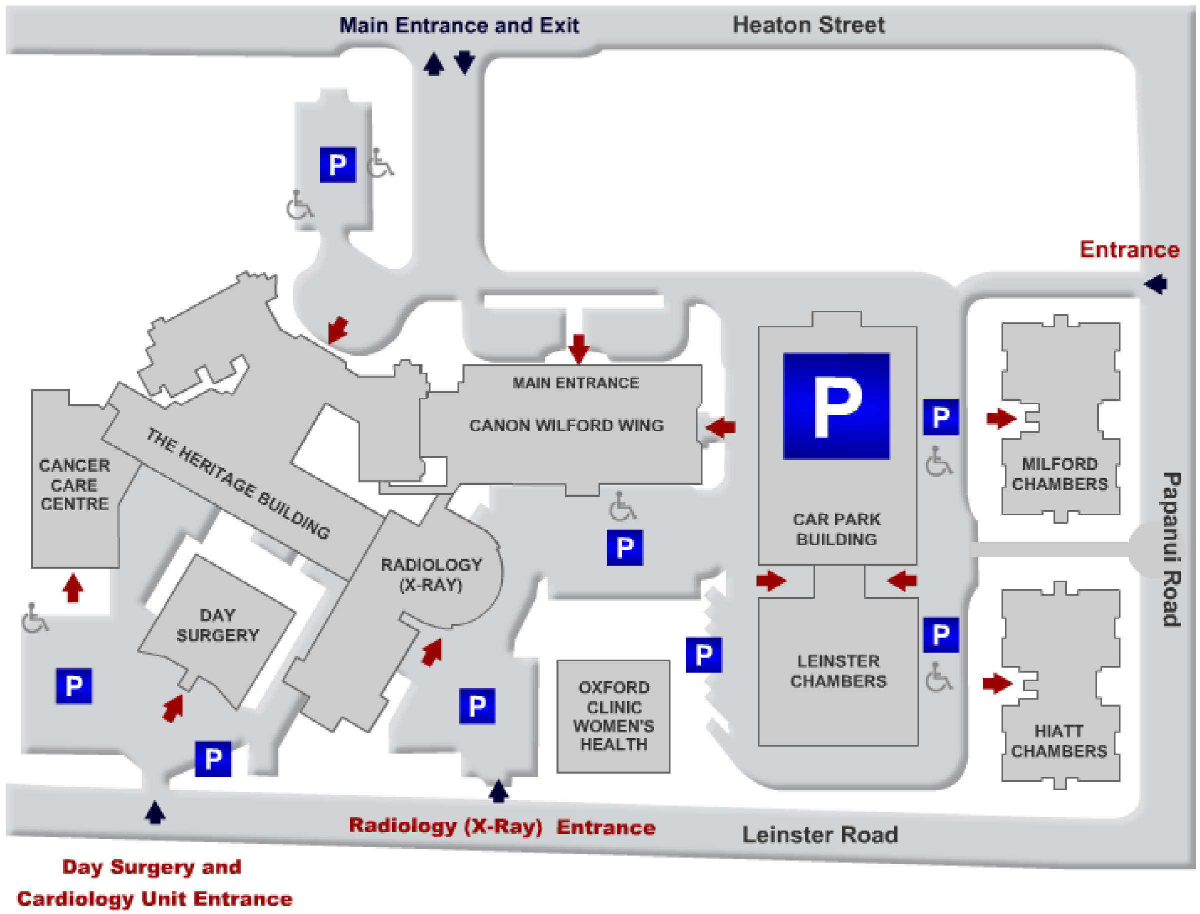

Figure 3.8: Map of St George's Hospital, the Maternity building is labeled as the Heritage building (St Georges)

The Cancer Centre (St Georges Hospital) (Figure 3.14) was damaged when liquefaction induced the unbalanced and insufficiently anchored structure to tilt. The liquefaction (Figure 3.11) also caused damage to the buildings foundations and the lowest floor to flood. The unbalanced mass was a result of a 1.5 meter thick concrete ceiling required for the Linear accelerator located in the basement of the building. This disproportionally weighted the buildings mass on one end of the building and caused the building to behave asymmetrically.

The main recovery wards and operating theatres in St George's Canon Wilford wing (Figure 3.10) were closed because of the loss of services and widespread nonstructural damage to walls (Figure 3.12) (Table 3.9). Central suction was one of the services immediately lost; however, it was one of the first things to be repaired. The entire hospital was evacuated in different stages; it took 20 minutes to get 17 mothers and 17 babies out of the maternity building. As well, 35 patients from the adult wards had to be evacuated down very narrow stairs in the Canon Wilford wing.

Figure 3.9: St George's Hospital Cancer Care Centre

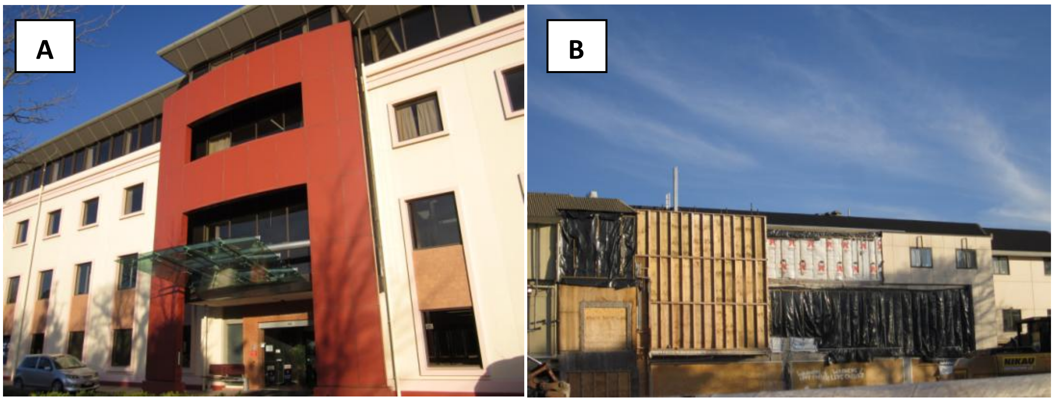

Figure 3.10: (A) The north side of St George's Hospital Canon Wilford wing (B) The wall adjacent to the Canon Wilford wing following the demolition of to the maternity building.

Figure 3.11: Liquefaction induced blistering in the Radiology car park

Figure 3.12: (A) Separation Joint in the Canon Wilford wing adjacent to lift shaft. (B) Cosmetic damage to columns adjacent to a vertically displaced separation joint

3.4.1.3 Burwood Hospital

Burwood hospitals Allan Bean Centre for rehabilitation learning and research suffered major structural damage and slumped despite being one of the newest buildings on site. The spinal unit tilted and the old mortuary has subsequently been demolished. The less severe nonstructural damage has required disruptive repairs and bed closures. The orthopaedic rehabilitation unit and the brain injury units also required significant and disruptive repairs. The Burwood Hospital Spinal Unit treated paralysed and major trauma earthquake casualties following the Christchurch earthquake. The birthing unit suffered minor damage in the Christchurch earthquake and was closed for two months to decrease the sewerage, power and water demand (The Press 2012). The Burwood Orthopaedic Rehab Unit (ORU) was operating below capacity (10-20 beds out of a normal 28) as of the 17th of May, 2012 due to earthquake repairs (CDHB 2012e).

Table 3.9: Number of Days services Lost or Reduced, Canterbury Province, New Zealand, 2011 (Kirsch et al)

	Hospital					
Service	**Christchurch**	**Princess Margaret**	**St George's**	**Kaikoura**	**Akaroa**	**Ellesmere**
Inpatient services						
Inpatient wards	14 d	-	14 d	Normal	Normal	Normal
Surgical	14 d	NA	30 d	NA	NA	NA
Obstetrics- Gynecology	14 d	NA	30 d	Normal	Normal	NA
Pediatric	14 d	NA	NA	NA	NA	NA
Psychiatric	-	Normal	NA	NA	NA	NA
Dialysis	-	NA	NA	NA	NA	NA
Outpatient Services						
ED	Normal	-	NA	NA	Normal	NA
Outpatient clinics	2 d	14 d	NA	NA	Normal	NA
Psychiatry	-	NA	NA	NA	NA	NA
Rehabilitation	7 d	NA	NA	NA	-	NA
Support services						
Plain radiographs	Normal	Normal	14 d	Normal	CHCH	NA
Computed Tomography	11 hr	NA	30 d	NA	CHCH	NA
Ultrasound	Normal	NA	14 d	NA	-	NA
Laboratory	Normal	Normal	7 d	Normal	CHCH	NA
Blood bank	Normal	1 d	Normal	Normal	3 d	NA
Nonclinical services						
Administration	Normal	Normal	Reduced	Normal	Normal	Normal
Medical records	Normal	Normal	Normal	Normal	Normal	Normal
Food Preparation	Normal	3 d	Off site	Normal	Normal	Normal
Laundry Services	2 d	7 d	Off site	Normal	Did own	Normal

3.4.1.4 Hillmorton Hospital

Hillmorton Hospital was severely disrupted following the Christchurch earthquake. The disruption was a result of the hospital having to increase the mental health capacity to accommodate an extra 180 displaced staff from Christchurch. The staff had to be accommodated because there mental health treatment facilities were badly damaged during the Christchurch earthquake. The Five CDHB mental health service buildings were unusable as of the 20th of July, 212, three were scheduled for demolition and two were in the process of repairs. Staff resignations have significantly increased since the Christchurch earthquake. The Hillmorton Hospital chapel was closed due to earthquake damage. The

Lincoln Green rehabilitation services building was also badly damaged but was unused before the earthquake (The Press 2012).

3.4.2 Regional Hospitals which sustained damage

3.4.2.1 Ashburton Hospital

The surgical theatres in Ashburton were closed on the 31st of January, 2012 following the structural assessment of unreinforced masonry buildings, the buildings were found to be at risk of collapse during a significant earthquake. The surgical facilities were subsequently relocated to Christchurch Hospital. Prior to this there were no facilities closures (CDHB 2012d).

3.4.2.2 Akaroa hospital

Akaroa Hospital (Figures 3.1 & 3.13) lost electricity and water but had sufficient backup systems (Table 3.2). The facilities only suffered minor nonstructural cracking following the Christchurch earthquake; however, after the Darfield earthquake the hospital was closed for one week due to damage to the chimneys, which were subsequently removed. Akaroa Hospital was closed at the end of January 2012 after engineering inspections deemed the building unsafe, as of the 16th of July, 2012 the earthquake damaged hospital facilities have yet to be reopened (CDHB 2012). A new reduced capacity Akaroa Hospital was opened following the closure of the old facilities at Heartlands Community Centre Rue Lavaud road. The services located at Akaroa hospital include:

- Medical and surgical Rehabilitation (five beds).
- Maternity (two beds).
- Physiotherapy.
- Medical centre.
- Day patient care.

The preliminary structural investigations were conducted by the 10th of July, 2011 the initial investigation didn't find any reason to close the facilities. However, the detailed structural observations completed between the 19th of July, 2011 and the 6th of December, 2011found faulty connections of the diaphragms to the walls at roof and floor levels (Figure 3.14), this deemed the building to be to be earthquake prone under Section 122 of the Building Act. The Building act requires buildings to be closed if they do not have the strength to resist a moderate earthquake. A moderate earthquake is defined as an earthquake that would generate loads one third as strong as those used to design an equivalent new building (Holmes Consultancy Group. 2012).

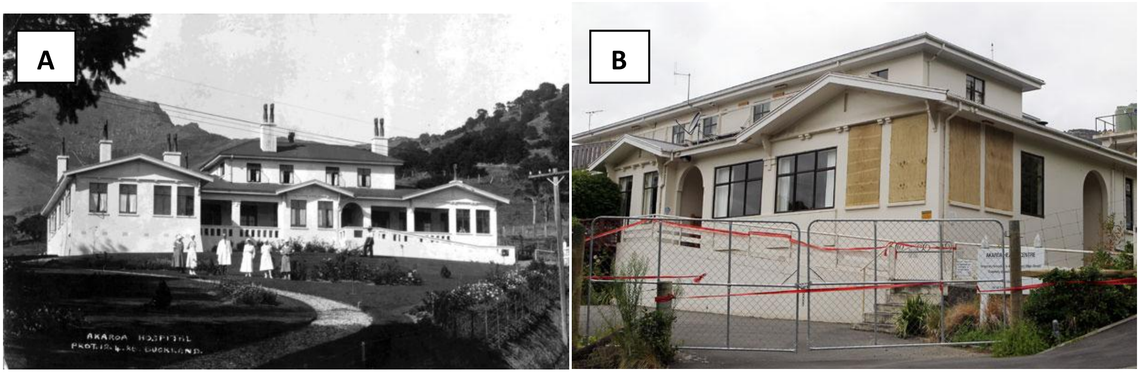

Figure 3.13: (A) The main Akaroa Hospital building in 1926. (B) The main Akaroa Hospital following closure in December 2011 with chimneys removed. Source (Stylianou. 2012, April 11). ***Source (KeteScap. 2010).***

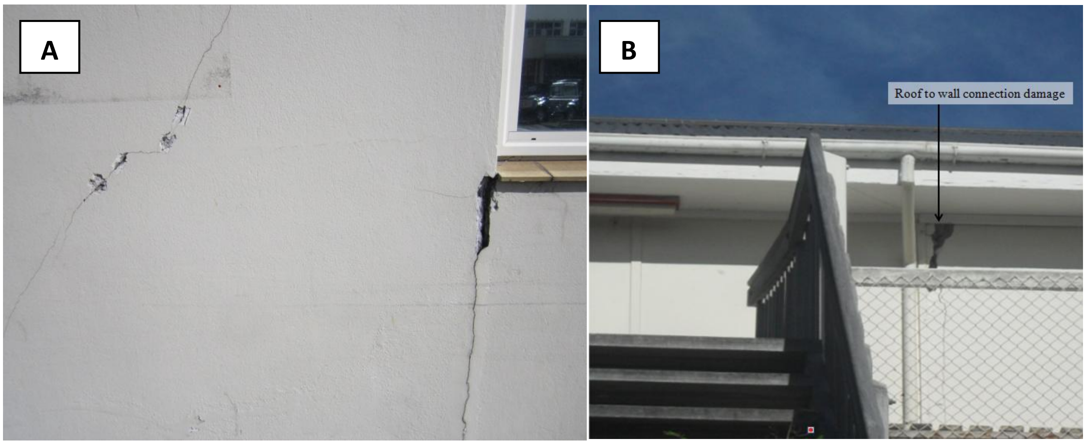

Figure 3.14: (A) Akroa Hospital Structural cracking (B) Akaroa Hospital Structural damage roof wall conection

3.5 Summary of Functional Loss and Deployed Residual Capacity in the Aftermath of the Earthquake for the CDHB Public and Private Hospital System

Following the Christchurch earthquake all of the hospitals in Canterbury were disrupted to varying degrees even if the facilities did not sustain physical damage. Two weeks after the 22nd of February, 2011 St Georges Maternity and Burwood Birthing unit were both closed. The regional hospitals were able to perform their own services such as laundry (usually done at Hillmorton Hospital) and food preparation in the aftermath of the earthquake (Table 3.9) and in some cases perform services for Christchurch's' hospitals. When Christchurch Hospital lost its services Timaru Hospital needed additional staff to provide Christchurch hospital with clean laundry, it handled 3 tonnes in the first delivery. Ashburton Hospital helped supply and source the Princess Margaret Hospital clean linen for 7 days after the 22nd of February, 2011. However, the existing linen stock had to be rationed and conserved (Section 3.3).

Canterbury's regional Hospitals also helped redistribute the capacity from damaged Christchurch hospitals'. Elderly care and/or maternity patients were transferred from Christchurch to the regional hospital's in the days after the earthquake (Table 3.5), even though in some cases the regional hospital's sustained damage, as in the case of Akaroa hospital (Section 3.4.2.2).

3.6 Conclusion

The damage that impacted the Christchurch Hospital following the Christchurch earthquake included minor structural damage to both clinical and support buildings, nonstructural damage to ceiling tiles and light fittings, outages of all the city lifelines systems, and damage to internal services and back-up generators. For all the CDHB and private hospital facilities, the widespread nonstructural damage was more disruptive than the minor/moderate structural damage sustained by the buildings. All buildings had been built or retrofitted to comply with the requirement of NZ Seismic Design Standards (SNZ 2004). In Christchurch Hospital, nonstructural damage to suspended ceilings, light fittings, and water piping forced wards to be evacuated during the emergency phase and to remain closed in the longer-term, as well as requiring lengthily disruptive repairs to be carried out in the following months. The loss of short term and long term capacity at Christchurch Hospital has been accommodated by outsourcing elective surgery and relocating wards to other hospitals. The loss of; water, sewage, power, caused disruption to the Canterbury Hospital network's functionality and to the delivery of health care in the days and weeks following the earthquake. The Christchurch earthquake indicated it would be beneficial for organizational planning in modern hospitals to focus on identifying nonstructural and functional vulnerabilities within critical facilities. As well as mitigating their possible impact by introducing anti seismic engineering measures, redundancy systems and back up resources.

Some Christchurch hospitals that were not equipped to deal with emergency casualties received earthquake casualties in the immediate hours after the earthquake. It would be beneficial for specialised hospitals to have some emergency treatment capacity. However, the more socialised Canterbury health system was able to integrate and redistribute capacity more effectively than the more privatised US healthcare system would have been able to following Hurricane Katrina.

The influence of individuals within the post Christchurch earthquake hospital network was pronounced during the emergency phase. A small amount of maintenance staff working overtime insured that the Christchurch Hospital backup power system continued to operate during the emergency phase. The majority of the clinical and nonclinical staff performed duties beyond the level required by their employers, a maintenance staff member responsible for re-priming a blocked generator siphoned fuel from their own vehicle. The staff wellbeing was hugely important following the earthquake. Clinical staff were willing to work after hours in the emergency phase. However, in the longer-term fatigue caused by the continuing aftershocks lead to an increase in resignations (Section 4.2.4).

4. Chapter Four: Review and implementation of hospital functionality/fragility assessment methodology

4.1Introduction

The purpose of Chapter Four is to analyze a variety of hospital risk assessment approaches, and determine their applicability for use within the post Christchurch earthquake Christchurch hospital network. The chapter's content covers methodology for individual hospital assessment and for holistic hospital network assessment. The data collated in Chapter Three is utilized within Chapter Four to test the methodology which is also presented and critiqued within Chapter Four. The final objective of Chapter Four is to define which areas of the hospital risk assessment methodology were affective and the areas which were ineffective at identifying vulnerability.

De Boer et al. (1989) defined the Medical Severity Index (MSI) to provide a framework for the required holistic response by the healthcare network after a large earthquake (De Boer et al., 1989). The scale uses the following three factors to describe the health-care system;

- "Medical rescue capacity"
- "Medical transport and network capacity" (holistic assessment)
- "Hospital treatment capacity".

The MSI can be used to categories the methodologies covered in this chapter with the exception of the "medical rescue capacity" which has little to do with the hospital and transport network and therefore is not included. The "Hospital treatment capacity" covers the physical and organizational components of individual hospitals. The methodology critiqued in Section 4.2 is: Hossain et al., (2012), Kafali et al., (2003), and the World Health Organizations (WHO) Nonstructural vulnerability, Structural vulnerability and the administrative/organizational vulnerability evaluations (2006).The "Medical transport and network capacity" covers the hospital networks availability of transport resources and residual capacity of the facilities. The methodology provided by Cimellaro et al., (2010), Masi et al., (2012) and the PDNA (2010) (critiqued in Section 4.3) are encompassed in the "Medical transport and network capacity" category.

The WHO (2006) methodology defines risk evaluation as either qualitative or quantitative. Qualitative methods are used to evaluate the safety of a large quantity of hospitals. This is achieved by utilizing score assignment methods which are structured to expose deficiencies in seismically hazardous buildings in order to define upgrading strategies (WHO 2006). Quantitative methods are better used to define the important specific aspects of building resilience; the Kafali et al., (2003) method (Section 4.2.1) outlines a quantitative fragility evaluation for individual nonstructural components and then generates an average for the entire nonstructural system (Kafali et al., 2003).

The Hossain et al., (2012) method (Section 4.2.5) outlines a framework for the quantitative evaluation of post earthquake emergency department (ED) functionality by defining it as a system comprised of coordinated processes from the arrival of patients, ED triage, waiting time to see clinical staff, recording of personal details and the patients wait time to be treated by clinical staff (Hossain et al., 2012). While Cimellaro et al., (2010) (Section 4.3.1) also uses quantitative patient waiting time, as well as the transportation network travel time values to define the earthquakes affect on the ability to transport and treat patients (Cimellaro et al., 2010). Masi et al., (2012) (Section 4.3.2) is perhaps the most holistic assessment covered in this chapter it uses elements of quantitative and qualitative assessment to define areas of hospital and hospital network risk with the overall outcome of a priority list for seismic upgrades in facilities (Masi et al., 2012). The PDNA incorporates external factors such as the epidemiology of the burden of disease (BoD). As well, the assessment includes the performance of six interdependent ‘building blocks’ that encompass all the physical and organizational components that make up an individual hospital. The influence of assets, stakeholders, hospital processes’ and the recovery/emergency preparedness plans are also taken into account. The methods mentioned above are scored in Table 4.1 in order to define the method to implement.

Table 4.1: The net scores given to the assessment methodology based on the coverage, time taken to implement the method, ease of obtaining data and the applicability to Christchurch.

Methodology	**Coverage**	**Time**	**Ease of obtaining Data**	**Applicability to Christchurch**	**Net Score**
Kafali et al., (2003)	1	4	4	5	14
WHO (2006) Structural	1	4	5	5	15
WHO (2006) Nonstructural	0.5	3	2	5	10.5
WHO (2006) Organizational	1	4	2	5	12
(Hossain et al., 2012)	0.5	3	1	5	9.5
Cimellaro et al. (2010)	2	2	1	5	10
(Masi et al., 2012).	1.5	3	1	5	10.5
(PDNA 2010)	2	2	2	5	11
(Miniati et al., 2012)	2	2	1	5	10

The scores depicted in Table 4.1 are out of 5, with the best possible score being 5. The “Coverage” indicates how much the methodology includes (a score of 5 indicates the method includes all the elements that influence hospital vulnerability). The “Time” is a score given to the time taken to use the method, 5 being relatively quick and 1 being relatively slow. A value of 5 for the “Ease of obtaining data” means that method is relatively easy to obtain data for. The “Applicability to Christchurch” scores the methods on whether or not the methods are applicable to be used in the

Christchurch Hospital network, 5 being applicable and 1 being not applicable. The Scope, Inputs, Outputs and Limitations for the methods in Table 4.2 are defined below in Section 4.2.

4.2 Assessment Methodology

4.2.1 Hospital treatment capacity

- **Kafali et al., (2003) Fragility Analysis for Nonstructural Systems in Critical Facilities**

- **Scope**: Nonstructural systems.
- **Inputs**: Moment magnitude, source to site distance and spectral density of ground acceleration.
- **Outputs**: Approximate system fragility, the state of each component and whether or not the nonstructural system will fail for a given force (Appendix B).
- **Limitations**: Only includes the nonstructural system.

- **WHO (2006) Nonstructural vulnerability evaluation HNVE-001/1, HNVE-001/2 and HNVE-001/3**

- **Scope**: Nonstructural elements for individual hospital buildings
- **Inputs**: The number of buildings, nonstructural elements, seismic intensity, type of risk and the priority of the nonstructural elements.
- **Outputs**: Qualitative measure of probability for; Loss of function (LF), Property loss (PL) and Life safety (LS) outputs (Appendix C).
- **Limitations**: Only includes the nonstructural system and provides a qualitative output.

- **WHO (2006) Structural vulnerability assessment HSVE-001 and HSVE-002**

- **Scope**: Structural components in individual hospital buildings.
- **Inputs**: Structural design characteristics, land characteristics, year of construction, Modified Mercalli Intensity scale (MMI) number of stories and the building materials used.
- **Outputs**: Quantitative risk vulnerability value for individual facilities (Appendix D).
- **Limitations**: Only includes the structural system, provides a qualitative output reliant on MMI.

- **WHO (2006) Administrative/organizational vulnerability evaluation assessment HOVE-001/1 and HOVE-001/2**

- **Scope**: Organizational structure of individual hospital facilities.
- **Inputs**: Assigned personnel, emergency supplies, medical equipment and backup systems.
- **Outputs**: A Qualitative rating of the administrative/ organization vulnerability. The capability assessment considers the allocation of resources and personnel to the various medical services

existing at the health facility. Four parameters define the capability of each of the medical services; assigned personnel, medical equipment, emergency supplies and backup systems (Appendix E).

- **Limitations**: Only includes the organizational environment.

- **Modeling coordination in hospital emergency departments through social network analysis following disasters (Hossain et al., 2012)**

-
- **Scope**: The Emergency Department of an individual hospital.
- **Inputs**: Time taken for the full diagnosis of a patient, Time taken for diagnosis, Average waiting time, the Average Length of Visit (ALV), the number of patients who have revisited the ED within 72 hours, the ratio of deaths in the ED to the number of people seen in ED and the number of undiagnosed patients who have left the hospital.
- **Outputs**: Testing of predefined hypotheses regarding the performance of a hospitals ED (Appendix F).
- **Limitations**: Does not include any other departments but the ED.

4.2.2 Medical transport and network capacity (holistic assessment)

- **Organizational model of a hospital system, Cimellaro et al. (2010)**

- **Scope**: The city wide hospital and transport network.
- **Inputs**: ED waiting time (saturated or unsaturated), Number of spare beds, Operating rooms, Waiting time (normal unsaturated conditions), Waiting time during saturated conditions, Number of patients treated (saturated conditions), Number of patients requiring treatment and Total number of patients not treated.
- **Outputs**: A quantitative measure of the hospital's emergency department and the functional ability of the network to quickly transport patients to the ED (Appendix G).
- **Limitations**: Does not include any other departments but the ED.

- **Vulnerability assessment and seismic risk reduction strategies of hospitals in Basilicata region (Italy)(Masi et al., 2012).**

- **Scope**: Hospital buildings and the nationwide hospital network.
- **Inputs**: The financial limit of the organization, probability of spectral ground acceleration of a given size and the buildings; capacity to withstand PGA, the demand to withstand PGA, the life safety, the average occupancy and the size of the hospital network.
- **Outputs**: Life Safety (SLV), Damage Limitation (SLD) limit states and time risk curves (Appendix H).

- **Limitations**: Does not include the nonstructural system.

- **Post Disaster Needs Assessments (PDNA 2010)**

- **Scope**: The assessment aims to cover the causes of a disaster affecting the health sector including the vulnerability of the sectors, the community and the assets to hazard.
- **Inputs**: The service delivery, health workforce, information, medical products, financing, leadership and the national epidemiological profile.
- **Outputs**: A plan for the further assessment of the health sector and a budget for upgrading facilities (Appendix I).
- **Limitations**: Does not include any physical elements.

- **Methodology for rapid seismic risk assessment of health structures: Case study of the hospital system Florence, Italy (Miniati et al., 2012)**

- **Scope**: Holistic assessment of the hospital network facilities.
- **Inputs**: Emergency department, Intensive care unit, Hospital beds, Morgue, Laboratory, Fire suppression system, Accessibility and internal viability, Power network, Gas network, Diagnostic, Surgical operation Back-up generator, Other equipment.
- **Outputs**: An Estimation of the reduction of hospital treatment capacity (Appendix J).
- **Limitations**: Does not include the Structural and nonstructural systems.

4.3 Application and Discussion

The application of each methodology within the post Christchurch earthquake Christchurch hospital network is constrained by the scope and availability of data able to be collected and collated, and the scope of the assessments (Table 4.2). The WHO structural vulnerability assessment was found to be the most applicable method considering the available data. However, the preliminary data suggests nonstructural damage was more common and disruptive within Christchurch following the Christchurch earthquake, this is similar to findings from other modern earthquake stricken hospitals. So in this instance, Masi et al. (2012), Kafali et al. (2003) and WHO (2006) Nonstructural vulnerability evaluation methods were more applicable, as they focus on the affect nonstructural components have on the ability of the hospital system to provide continued healthcare. Masi et al. (2012) interprets the outputs and prioritizes the mitigation techniques identified by incorporating the organizations available finance. Kafali et al. (2003) provides a quantitative measure of the nonstructural damage averaged over the entire facilities. Whereas, the WHO (2006) nonstructural vulnerability evaluation method provides broad quantitative measures to categories the nonstructural damages affect on “loss of function”, “property loss” and “life safety”.

Cimellaro et al. (2010) and Hossain et al. (2012) do not asses the fragility of the hospitals physical components, but instead provide measures of post earthquake ED functionality, in order to quantify the deference in the pre earthquake and post earthquake quality of healthcare. Cimellaro et al. (2010) is more applicable in the post earthquake Christchurch environment as it aims to quantify the affect the transportation network plays in delaying the treatment of patients in the ED. The WHO (2006) administrative/organizational vulnerability evaluation also aims to assess the hospitals organizational processes but from a qualitative pre earthquake tense and with focus on the entire hospitals administrative/organizational vulnerability rather than just the ED. The PDNA and Miniati et al. (2012) both aim to assess all the components of an individual hospital including both physical and organizational components. The PDNA and Miniati et al. (2012) data demands and scope make them to difficult to implement in the course of this study, however given the resources and time the assessments would be highly effective in quantifying the seismic hazard to the entire hospital.

The best application of methodology for the assessment of the Christchurch hospital network would be the combination of four methods. The first, Cimellaro et al. (2010) in order to define the earthquakes affect on patient care and the transport network. The second and third, the WHO's (2006) structural and nonstructural vulnerability assessment's which quantify the extent of physical damage (structural and nonstructural). And lastly Masi et al. (2012) which extends on the WHO's (2006) structural vulnerability assessment by defining the appropriate threshold to mitigate damage. However, simply measuring the affect of the earthquake induced physical damage and ED functionality will exclude the importance of the organizational environment. Ideally the organizational environment must be assessed. However collecting data from the organizational environment involves invasive interaction with staff. Excessive disruption isn't appreciated in hospital networks where staff are often strained, particularly in the aftermath of a major disaster.

The WHO (2006) administrative/organizational vulnerability evaluation method may also be of importance even though it provides a general qualitative assessment, it is important to gage the adaptive ability of the organizational environment. The organizational environment can influence the impact the earthquake damage has on the physical environment by influencing the classification of damage and the level of maintenance. As well, the organizational environment affects the running of the ED by influencing the staff-patient interaction processes and to a certain extent the capacity and the length of stay. However, the intrusive nature of the required data collection rules it out of this study.

Table 4.2: Summary of the components that make up the assessed methodology (methods include blocked components).

Methodology	**Structural**	**Nonstructural**	**Patient treatment functionality**	**Financial**	**Organizational**	**epidemiological profile**	**lifelines/Supply network**	**MMI**	**Transport network**	**Data availability**
Cimellaro et al. (2010):	■	■			■				■	
Masi et al. (2012):	■			■				■		
PDNA (2010):				■	■	■	■			
Hossain et al. (2012):			■							
Kafali et al. (2003):		■						■		■
WHO Nonstructural vulnerability (2006)		■								
WHO Structural vulnerability (2006)	■							■		■
WHO organizational vulnerability (2006)					■		■			
Miniati et al. (2012)		■	■		■		■			

Taking into account the time taken to implement the methodology, the ease of obtaining data, the data availability displayed and the applicability to Christchurch (Tables 4.1 & 4.2) the following list ranks the importance of the evaluated methods for application within the post Christchurch earthquake Christchurch hospital network. The list is structured to cover all the factors that influence seismic vulnerability. The easiest methods (based on the scores calculated in Table 4.1) are prioritized:

1. WHO (2006) structural vulnerability assessment
2. WHO (2006) nonstructural vulnerability assessment
3. Cimellaro et al. (2010) Organizational model of a hospital system
4. Masi et al. (2012) Vulnerability assessment and seismic risk reduction strategies of hospitals in Basilicata region
5. WHO (2006) administrative/organizational vulnerability evaluation

Ideally all the methods would be implemented to capture the entire healthcare systems vulnerability including the physical elements, the ED, the inter-hospital transport network and the organizational/financial environment. However the large quantity of indicators for the five assessments as well as the difficulty in obtaining data from busy clinical and nonclinical persons within the hospital network requires time and willingness within the organization to achieve correctly. In the course of this thesis there was insufficient time to generate results from all the methods listed above. Therefore, in order to conduct a detailed and complete assessment of all the components that influence hospital/hospital network seismic vulnerability, a considerable amount of time is needed. A key weakness of hospital seismic assessment methodology is the difficulty of assessing all the components.

WHO (2006) structural vulnerability assessment has 14 indicators compared to 21 for the nonstructural assessment and 29 for the organizational assessment. The difficulty in implementing the ED functionality assessments is not due to the number of indicators but the invasive process of data collection; specifically the waiting time (WT). The WHO (2006) administrative/organizational vulnerability evaluation also requires intrusive data collection in the form of expert opinion from professionals within the organization to obtain the qualitative grades of performance.

4.4 WHO (2006) structural vulnerability assessment implementation

The WHO (2006) Structural vulnerability assessment was chosen based on the scores calculated in Table 4.1. The scores were calculated based on the coverage of the methodology, the time required to implement the method, the ease of obtaining data and the applicability of the method to the Christchurch hospital network.

The WHO (2006) Structural vulnerability assessment is based on the Macro seismic vulnerability method (Giovinazzi 2005, Lagomarsino and Giovinazzi 2006). This method assesses the seismic vulnerability in terms of a vulnerability index (V), and of a ductility index (Q), both are evaluated taking into account the building typology and its constructive features. According to the Macro seismic method, and therefore the WHO Structural vulnerability assessment method, the correlation between the seismic input and the expected damages to building structures (either a single building or group of buildings) is expressed in terms of vulnerability curves described by a closed analytical function (Equation 1).

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+6.25\cdot V-13.1}{Q}\right)\right] \quad (1)$$

where I is the seismic input described in terms of a Macro seismic Intensity measure, according to the Modified Mercalli Intensity scale or European Macro seismic Scale, EMS-98 (Grunthal 1998). The Macro seismic Intensity measure I is considered, in the framework of the macro seismic approach, as a continuous parameter evaluated with respect to rigid soil conditions; possible amplification effects due to different soil conditions are accounted for within the vulnerability parameter (V).

V and Q are respectively, the vulnerability index and the ductility index summarizing the structural, constructive and geometrical features of buildings that might influence the seismic response and performance when subjected to earthquake forces. It is worth highlighting that the WHO (2006) method assumes Q=2.3 for all the building typologies.

μ_D is the expected mean physical damage for the building or building groups' described according to a five damage grade scale (EMS-98 damage grades scale, Grunthal 1998), namely: D_1 slight damage; D_2 moderate damage; D_3 heavy damage; D_4 extensive damage, D_5 collapse/destruction; plus the absence of damage D_0, no damage. The WHO (2006) method used a simplified three grade damage scale, distinguishing between: "Low Damage" when $\mu_D<1.5$; "Moderate Damage" $1.5<\mu_D<3.5$; "High Damage" when $\mu_D>3.5$.

4.4.1 Seismic vulnerability assessment of Christchurch hospital buildings

According to the WHO (2006) Structural vulnerability assessment method, the seismic vulnerability of hospital buildings can be assessed in term of a vulnerability index V. The vulnerability index V accounts for the typological vulnerability, V^* (e.g. a different seismic behavior is expected for unreinforced masonry building compared to the seismic performance of seismically designed reinforced concrete buildings) and the influence of a few further factors which are based on the seismic response, including soil conditions, the building construction age, the building construction type and geometrical features and its maintenance conditions.
The WHO (2006) structural model incorporates vulnerability indices for the following buildings typologies:

- Simple stone masonry (M1.2)
- Unreinforced masonry with wooden floors (M3.1)
- Unreinforced masonry with reinforced concrete floors (M3.4)
- Strengthened masonry (M5)
- Reinforced concrete moment-resistant frame (RC1)
- Reinforced concrete shear wall (RC2)
- Reinforced concrete frames with regularly distributed unreinforced masonry infill walls (RC3.1)
- Irregular reinforced concrete frames (RC3.4)
- Reinforced concrete dual-system (RC4)
- Precast concrete tilt-up walls (RC5)
- Precast concrete frames with concrete shear walls (RC6).

Timber and steel building types are not included in the WHO method.

The WHO (2006) structural model incorporates vulnerability index modifiers ΔV_m for building height, maintenance conditions, construction year and few other geometrical and constructive features.

The necessary data to implement the WHO structural vulnerability assessment for Christchurch hospital buildings, were made available by the Rhise Group and by the CDHB, and are presented in Table 4.4. The standard of maintenance for all the CDHB and the private facilities is regarded as being "good" based on information provided by Christchurch Hospital's facilities manager Alan Bavis. The methodology states that long buildings are usually exposed to torsion or horizontal rotation during ground movement. The methodology does not include dimensions for lengthy buildings therefore all buildings with lengths twice as great as their height are considered to be subject to torsion during strong ground motion.
The resulting typological index V* for each single building of the Canterbury network and the total vulnerability index $V = V^* + \Delta V_m$ are presented in Table 4.5.

4.4.2 Hazard Intensity Measures

MMI, which is a subjective qualitative measure of earthquake intensity, was chosen as the Hazard Intensity measure for implementing the WHO (2006) structural vulnerability assessment method. The following three sources of MMI measurements were available for the Christchurch earthquake;

- USGS MMI;
- GNS felt reports;
- GNS MMI isoseismal map

The USGS MMI shake map is an automatically generated map which combines instrumental shaking measurements, the local geology, the location of the earthquake and the magnitude to estimate the MMI (USGS 2012). The MMI values derived from the GNS felt reports were generated by averaging the felt report values that were created by citizens who felt the earthquake (Geonet 2012). The felt reports are created on a webpage (Geonet) and grouped in the suburbs were the citizens were located during the Christchurch earthquake. The GNS isoseismal map was generated using MMI values from the felt reports and the interpolated PGA.

The GNS isoseismal MMI data was not used for this study because it was not available at the time the assessment methodology results were calculated (Section 4.5.2). Both the USGS MMI values and the GNS felt reports were used in this study in order to understand the sensitivity of the method to the hazard definition, or in other words to what extent the WHO (2006) structural vulnerability assessment methodology generates different outputs for different MMIs.

4.5 Predicted physical damage according to the WHO (2006) method and comparison with observed damage

The WHO (2006) structural vulnerability assessment is calculated twice using, the resulting vulnerability indexes presented in Table 4.5 and different MMI value sources;

1. The GNS felt reports MMI (Section 4.5.1)
2. The USGS MMI shake map (Section 4.5.2)

The WHO (2006) Vulnerability values which are presented as vulnerability curves below for the buildings are compared with the post Christchurch earthquake damage which those buildings sustained in order to define whether or not the buildings vulnerability and predicted physical damage was correctly identified in the WHO (2006) assessment methodology.

4.5.1 Predicted damage when using GNS felt reports MMI

The GNS MMI data used for this analysis was compiled by calculating the weighted average of the GNS felt reports for the areas where the Hospitals are situated (Figure 4.1). The felt reports are created by members of the public who complete on line surveys of their interpretation of the shaking intensity. The MMI source is used because the data is the most conservative of all the MMI data for the Christchurch earthquake and therefore is considered to be the minimum MMI for the WHO structural vulnerability assessment.

The predicted levels of damage are outlined in Table 4.2. All but 45 St Asaph Street (Christchurch hospital) and St Georges Hospital maternity building were classed as having “Low damage” the two exceptions were both classed as having “moderate and high damage respectively”. Analysis of the results suggests that the methodology underestimates the Canterbury hospital network earthquake hazard. This is evident because Akaroa Hospital and St George’s Cancer centre sustained damage rendering the facilities inoperable during the Canterbury earthquakes. However, Akaroa Hospital was closed as a result of the delayed identification of structural damage most likely caused by the Christchurch earthquake, and exacerbated by all the major aftershocks during 2011

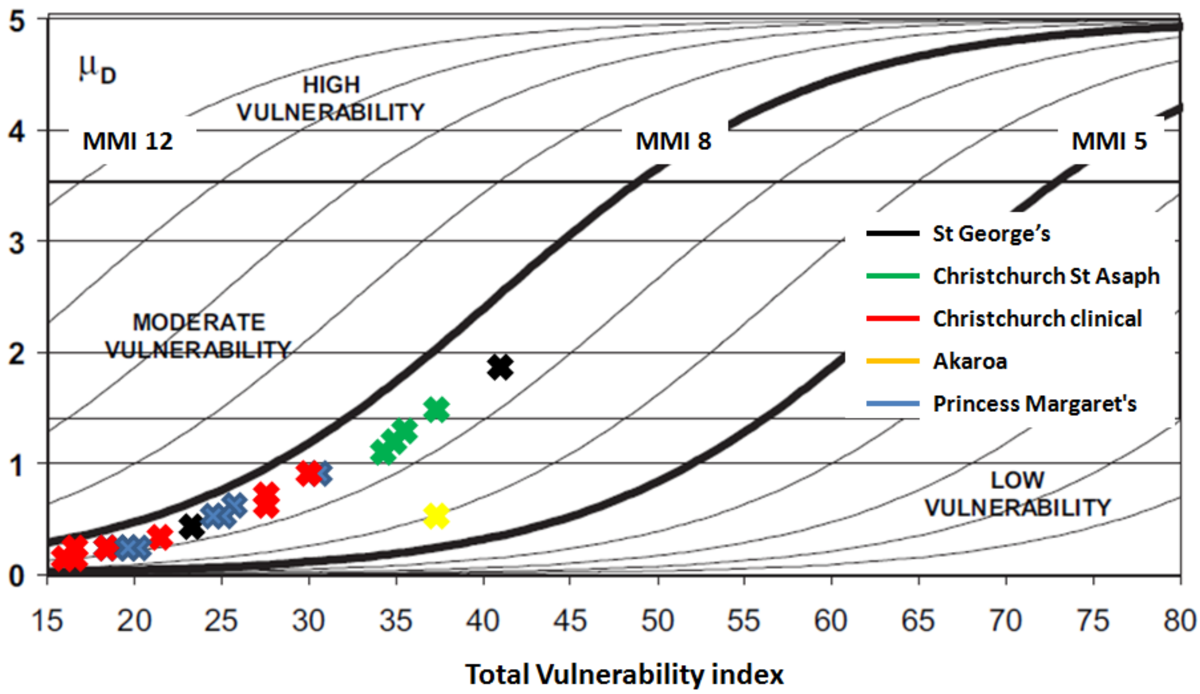

Figure 4.1: Expected damage grade and vulnerability vs total vulnerability index of Canterbury Hospitals for the GNS felt report weighted average (minimum) MMI data (WHO 2006).

4.5.2 USGS MMI data

For the purpose of this study the USGS MMI data is considered to be the maximum MMI. The USGS MMI data was created by interpolating the PGA in order to define the affect the acceleration had on the physical environment. The USGS was the largest of any of the other MMI sources which were available at the time of the analysis. Therefore the values are referred to as the max MMI. Using the USGS MMI data, the St Georges Maternity building was the only building to be classified as having a High expected level of damage. The buildings where a Moderate level of damage was predicted are included below (Figures 4.3 & 4.5);

- Princess Margaret's Hospitals Main Wards A,B,E,F,H&J (Figure 4.2) , the Maintenance building and the Recreation Hall.
- Christchurch Hospitals Parkside building, Riverside building and the Food services buildings.
- St Asaph Streets 33, 41 and 45 buildings.
- And the 235 Antigua Street building.

Figure 4.2: (A) Princess Margaret's Hospital Main Ward -A,B,E,F,H &J. (B) Princess Margaret's Hospital K wards

The St George's Hospital Maternity building was close to being classified with a "moderate" damage level ($\mu_D<3.5$). As structural damage closed the St Georges maternity building immediately after the Christchurch earthquake and the 45 St Asaph street building (Christchurch hospital) (upper moderate damage level of 3.19) a month after the earthquake. Using the max MMI is more reflective of the observed damage in Christchurch. However the USGS data still categorised the Akaroa Hospitals Christchurch earthquake MMI as 6 (the same as the GNS felt reports), therefore the Akaroa Hospital was still classed as having a low expected damage level when the building was closed as a result of structural damage. The St Georges Cancer centre was still classed as having a low expected damage using the max MMI. The mis-categorisation of the Cancer centre (St Georges Hospital) was more than likely due to the low vulnerability index of 24 (Table 4.5). Because the method doesn't include a soil modifying index or an index that covers disproportionately balanced mass in buildings (Section 3.4.1.2). The 235 Antigua street Building (Christchurch hospital) was correctly categorised as having moderate damage level using maximum MMI (Table 4.5) as cracking to structural reinforcing were observed following the post-earthquake engineering surveys (Holmes Consultancy Group 2012).

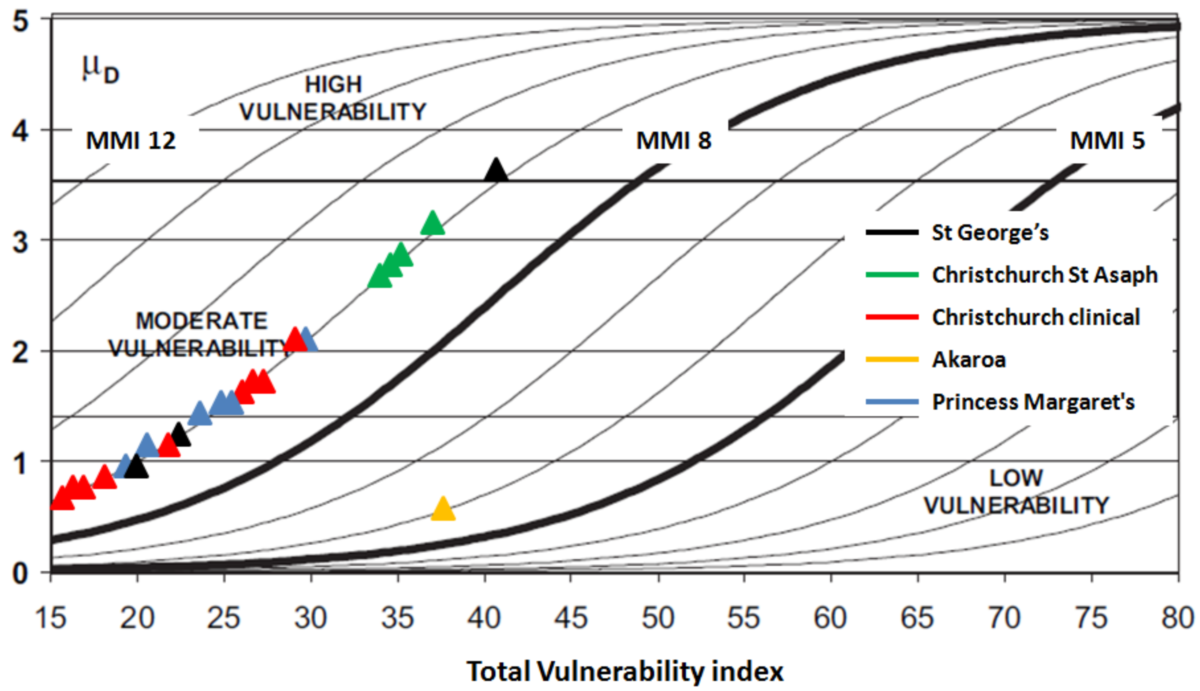

Figure 4.3: Expected damage grade and vulnerability vs total vulnerability index of Canterbury Hospitals for the USGS (maximum) MMI data (WHO 2006).

Table 4.4: Canterbury Hospital Network characteristics (Rhise network).

Hospital	**Building**	**Year**	**Code Category**	**Soil Category**	**Construction type**	**Construction class**	**Stories**	**Min MMI felt reports**	**Max MMI USGS**
Akaroa	Main building	1928	A	A	Reinforced masonry	M5	2	6	6
St George's	Maternity building	1928	A	C	RM/URM	M5	3	7.3	9
	Canon Wilford wing	1990	C	C	Concrete shear wall	RC2	5	7.3	9
	Cancer Centre	2000	C	C	Concrete frame	RC6	3	7.3	9
PMH	Main Ward -A,B,E,F,H &J	1960	A	A	Concrete frame	RC1	7	7.3	9
	C Block	1975	B	A	Concrete frame	RC1	7	7.3	9
	Chapel	1970	B	A	Concrete frame	RC1	1	7.3	9
	K Block	1973	B	A	Concrete frame	RC1	6	7.3	9
	PSE	1973	B	A	Concrete frame	RC1	-	7.3	9
	Day Hospital	1984	B	A	Concrete frame	RC3.1	1	7.3	9
	Maintenance	1964	A	A	Concrete frame	RC1	2	7.3	9
	Boiler house	1982	B	A	Concrete frame	RC3.1	1	7.3	9
	The Heathcote Building	1960	A	A	Concrete frame	RC1	7	7.3	9
	Recreation Hall	1964	A	A	Concrete frame	RC1	1	7.3	9
Christchurch	Parkside	1991	B	C	Concrete	RC6	5	7.4	9
	Riverside	1980	B	C	Concrete	RC6	9	7.4	9
	Food Services	1970	B	C	Concrete	RC6	5	7.4	9
	Oncology	1990	C	C	Concrete	RC6	4	7.4	9
	Professional Development Unit	1958	A	C	Steel Trusses	-	1	7.4	9
	Whanau	2002	C	C	Timber	-	1	7.4	9
	Health Labs	1991	C	C	Concrete	RC6	5	7.4	9
	21 St Asaph Street	2002	C	C	Timber Trussed	-	1	7.4	9
	33 St Asaph St (Sexual health centre)	1955	A	C	Concrete	RC6	2	7.4	9
	41 St Asaph St (sterile services)	1955	A	C	Concrete	RC6	3	7.4	9
	45 St Asaph St (Orthotics South island ltd)	1955	A	C	Concrete	RC6	4	7.4	9
	235 Antigua St	1955	A	C	Concrete	RC6	2	7.4	9
	Christchurch Women's	2004	C	C	Concrete	RC6	10	7.4	9
	Diabetes Building	2006	C	C	CP and C Beams	RC6	4	7.4	9
	Avon Generator	1978	B	C	Concrete	RC6	1	7.4	9
	Staff Car park building	2003	C	C	Steel Bracing/Concrete	-	3	7.4	9

Table 4.5: Canterbury Hospital modifiers and net vulnerability indices (Rhise network).

Hospital	Building	Soil	Maintenance	Plan irregularity	Vertical irregularity	Soft storey	Short columns	Foundation type	Ground slope	Story/code	Code level	V*	V	Max MMI USGS	Min MMI felt reports	Min μD	Min Damage level	Max μD	Max Damage level
Akaroa	Main building	-1	0	0	1	0	0	2	1	-1	0	35	37	6	6	0.52	Low	0.52	Low
St George's	Maternity building	2	0	0	0	0	1	2	0	1	0	35	41	9	7.3	1.79	Mod	3.50	High
	Canon Wilford/ Radiology	1	0	0	0	1	0	0	0	0	-8	17	11	9	7.3	0.10	Low	0.43	Low
	Cancer Centre	1	0	0	0	0	0	0	0	-2	-8	25	16	9	7.3	0.18	Low	0.69	Low
Princess Margaret's	Main Ward A,B,E,F,H &J	-1	0	0	0	0	1	2	0	0	8	20	30	9	7.3	0.72	Low	2.12	Mod
	C Block	-2	0	0	0	0	1	0	0	0	0	20	19	9	7.3	0.24	Low	0.91	Low
	Chapel	-2	0	0	0	0	0	0	0	-2	0	20	16	9	7.3	0.18	Low	0.69	Low
	K Block	-2	0	0	0	0	1	0	0	0	0	20	19	9	7.3	0.24	Low	0.91	Low
	PSE	-2	0	0	0	0	1	0	0	0	0	20	19	9	7.3	0.24	Low	0.91	Low
	Day Hospital	-2	0	0	0	0	0	0	0	-2	0	20	16	9	7.3	0.18	Low	0.69	Low
	Maintenance	-1	0	0	0	0	0	2	0	-2	8	20	27	9	7.3	0.54	Low	1.74	Mod
	Boiler house	-2	0	0	0	0	0	0	0	-2	0	20	16	9	7.3	0.18	Low	0.69	Low
	The Heathcote Building	-1	0	1	0	0	0	2	0	0	0	20	22	9	7.3	0.33	Low	1.18	Low
	Recreation Hall	-1	0	0	0	0	1	2	0	-2	8	20	28	9	7.3	0.60	Low	1.86	Mod
Christchurch	Parkside	1	0	0	0	0	0	0	0	0	0	25	26	9	7.4	0.56	Low	1.62	Mod
	Riverside	1	0	0	0	0	1	0	0	3	0	25	30	9	7.4	0.82	Low	2.12	Mod
	Food Services	1	0	0	0	0	0	0	0	0	0	25	26	9	7.4	0.56	Low	1.62	Mod
	Oncology	1	0	0	0	0	0	0	0	0	-8	25	18	9	7.4	0.25	Low	0.83	Low
	Health Labs	1	0	0	0	0	0	0	0	0	-8	25	18	9	7.4	0.25	Low	0.83	Low
	33 St Asaph St	2	0	0	0	0	1	2	0	-2	8	25	36	9	7.4	1.37	Low	2.93	Mod
	41 St Asaph St	2	0	0	0	0	1	2	0	-2	8	25	36	9	7.4	1.37	Low	2.93	Mod
	45 St Asaph St	2	0	0	0	0	1	2	0	0	8	25	38	9	7.4	1.60	Mod	3.19	Mod
	235 Antigua St	2	0	0	0	0	1	2	0	-2	8	25	36	9	7.4	1.37	Low	2.93	Mod
	Christchurch Women's	1	0	0	0	0	0	0	0	2	-8	25	20	9	7.4	0.31	Low	1.00	Low
	Diabetes Building	1	0	0	0	0	0	0	0	0	-8	25	18	9	7.4	0.25	Low	0.83	Low
	Avon Generator	1	0	0	0	0	0	0	0	-2	0	25	24	9	7.4799	0.46	Low	1.39	Low

4.6 Discussion

4.6.1 Most effective MMI

The MMI values that were used for the WHO (2006) vulnerability assessment are as follows:

1. The GNS felt reports MMI (Section 4.6.1).
2. The USGS MMI shake map (Section 4.6.2).

The vulnerability values calculated with the USGS MMI data (maximum) and the GNS felt reports MMI data (minimum) for the St Georges Maternity building is depicted in Figure 4.4. St Georges maternity Wing was structurally damaged beyond the point it could be safely occupied. The level of damage is consistent with the WHO (2006) predicted damage value of 3.55 (Table 4.5) ("high damage level") which was calculated with the maximum USGS MMI. However, the damage following the Christchurch earthquake is not consistent with the WHO (2006) vulnerability value of 1.79 ("low damage level") that was resulting with the use of GNS felt reports MMI data (minimum) (Figure 4.4).

When the damage factors responsible for the buildings closure are covered in the WHO structural vulnerability assessment using the maximum MMI is more affective. Because the maximum MMI retrieved from the USGS shake maps is more representative of the observed damage. For the purpose of the rest of the study the Maximum USGS MMI data is therefore used to analyse whether or not the WHO (2006) structural vulnerability assessment identified vulnerable buildings (Section 4.6.2).

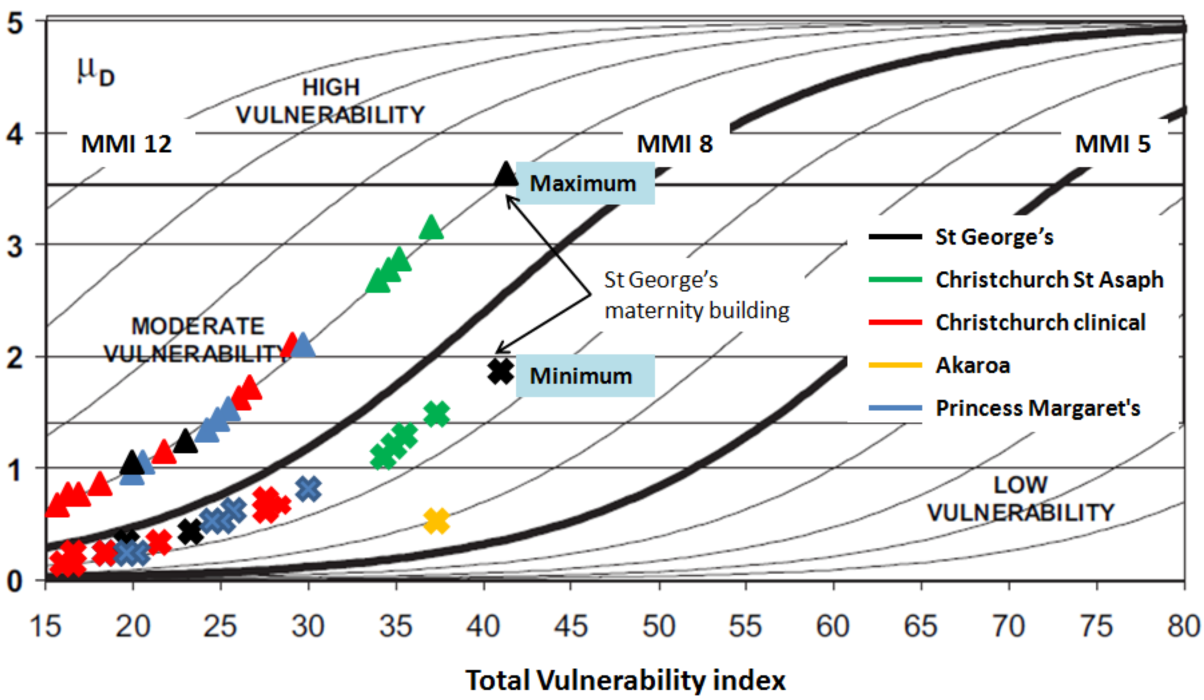

Figure 4.4: The maximum (USGS MMI) and minimum (GNNS felt reports MMI) vulnerability classification (WHO 2006)

4.6.2 Overall effectiveness and limitations of the WHO (2006) methodology

The WHO (2006) structural vulnerability assessment methodology was successful in most cases. Of all the structurally compromised buildings in the Christchurch hospital network following the Christchurch earthquake the method identified the 11 out of the 13 buildings were expected to experience “moderately” or “highly” damage levels (Section 4.6.2). The two buildings that were structurally compromised following the Christchurch earthquake that the WHO (2006) assessment methodology did not classified as expected to experience “moderate” or “high” level of damage were the St Georges Cancer care centre and the Akaroa Hospital building (Section 4.6.2).

Akaroa Hospital may have been classed as having a low damage because the methodology does not include the cumulative effect of aftershocks. The cumulative effect of aftershocks has an important influence upon the fragility of structural systems. Especially after rich aftershock sequences comprised of many earthquakes such as that of the Canterbury earthquakes, with each event structural systems are likely to be weakened further. The structurally damaged St George’s cancer care centre was classed as having a “low” vulnerability to seismicity because the WHO (2006) assessment methodology does not include modifiers for the soil the building is built on and the balance of mass in the building (Section 3.4.1.2) (Figure 4.2).

It is worth highlighting that the WHO (2006) does not define what is meant by high, moderate or low level of damage. For example it is not clear whether a “high” level of damage refers to high susceptibility of collapse or high susceptibility of permanent closure.

The vulnerability values for the professional development unit (Steel Trusses), Whanau (Timber), 21 St Asaph (Timber Trussed) and car packing building (Steel Bracing and Concrete) are not included in the application of the WHO (2006) structural assessment methodology. The buildings could not be calculated because the construction types were no included in the methodology. However, with the exception of the Christchurch Hospital car parking building none of the buildings not included in the application of the WHO (2006) methodology were structurally damaged (Figure 4.2).

The St Georges Cancer centre was built with two of its three stories beneath ground level, it was severely disrupted when soft sediment liquefied and flooded the lowest floor. The liquefaction combined with the buildings disproportionately balanced mass caused the building to tilt (Section 3.2). The Soil modifying indice in the WHO (2006) Structural assessment does not define separate categories for the depth buildings storeys are situated in soils classed C (soft). In some cases facilities had un-determinable modifiers; St Georges Hospital Radiology building which contains the radiological services has areas with soft stories.

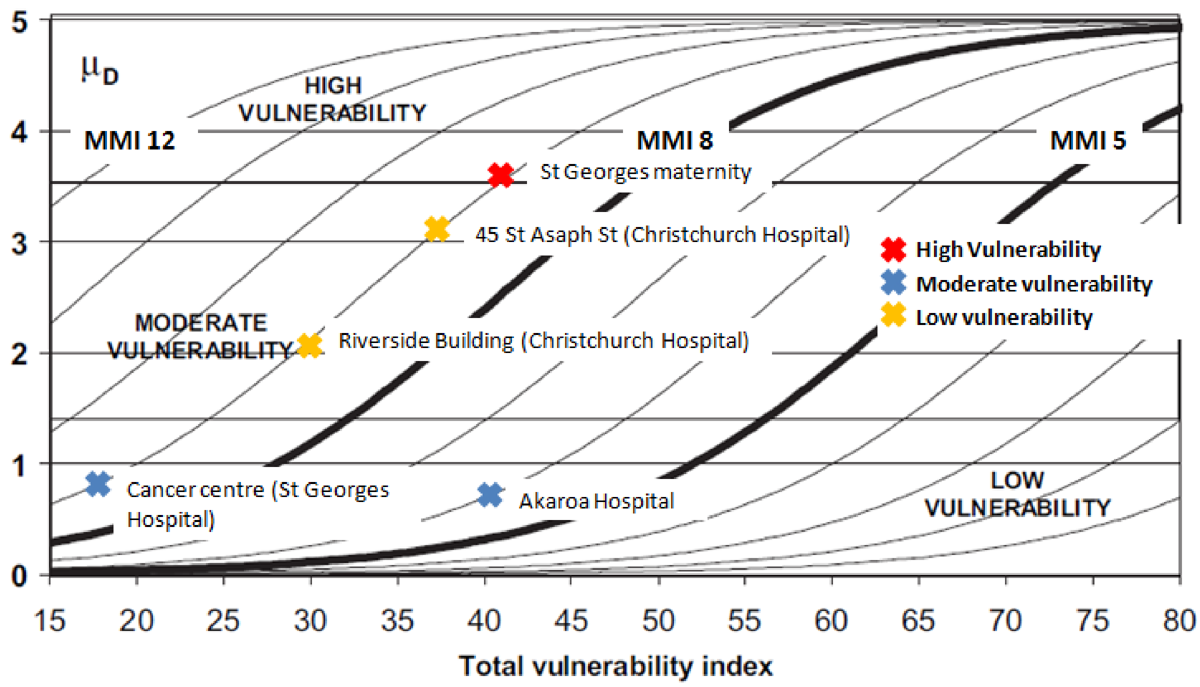

Figure 4.5: The expected damage grade and vulnerability vs total vulnerability index of the structural damaged hospitals in the Canterbury Hospital network for the maximum USGS MMI data (WHO 2006).

4.7 Conclusions

The WHO (2006) structural vulnerability assessment does not incorporate all the factors that influence hospital network seismic vulnerability. The WHO (2006) structural vulnerability assessment underestimated the structural seismic vulnerability of certain buildings' in the Christchurch hospital network. The seismic vulnerability of the buildings was underestimated because the factors that caused the buildings to be damaged were not included in the WHO (2006) methodology. However the method did assess 11 of the 13 buildings that were structurally compromised in some way as having a "high" or "moderate" expected damage levels. The variability in MMI data creates significantly different predicted damage levels for buildings when the method is implemented in Christchurch (Figure 4.5).

The nonstructural systems within the Canterbury hospital network are not assessed in this chapter because the complexity of nonstructural systems also makes them more challenging to quantify and thus assess. The exception of the nonstructural assessment in this study is a major limitation. However, it could not be avoided because the time available to collect the data was too limited to capture the large number of nonstructural indicators needed for the nonstructural vulnerability methodologies. The more complicated nonstructural and organizational assessment methodologies may be more successfully implemented by the hospital or hospital networks controlling organisations rather than an outside party. The controlling organisation has the benefit of existing data from within the organization.

5. Chapter Five: Analysis of the inter-hospital patient transfers post Christchurch earthquake

5.1 Introduction

The purpose of Chapter Five is to analyze the Christchurch hospital network's holistic response to the Christchurch earthquake using knowledge drawn from the review of assessment methodology presented in Chapter Four. The holistic assessment methodology is used to define the areas of the Canterbury hospital network that increased resilence and the areas that hindered the response. The principle focus of the hospital network response assessment is the inter-hospital patient transfer and capacity redistribution. This was chosen because it is an effective indicator of the ability of hospitals' ability to operate as an integrated network. Following a disaster it is an effective indicator because the ability to quickly and easily transfer patients within a partially damaged hospital network is indicative of a network integrating to insure patients are adequately treated. The methodological approach to achieve this is as follows.

Firstly; physical damage, source of casualties, Christchurch Hospital network capacity, transport resources, patient transfer and ALOS data for the period immediately after the Christchurch earthquake is presented for Christchurch Hospital. This data is then used to analyze the redistribution of capacity within the Christchurch hospital network. Secondly a methodological approach is generated for calculating the inter-hospital transfer time based on the holistic assessment methodology previously reviewed. The intention of this approach is to constrain what influences the speed and distance of patient transfers in a hospital network and the characteristics of hospital networks and earthquakes that cause the need for inter-hospital transfer.

5.1.1 Data requirements

Effective holistic assessment methodology for hospital network functionality and capacity redistribution is dependent on all the components that enable a hospital network to function adequately being incorporated. They include the; local built environment (structural components, nonstructural components, the external built environment (internal and external supply, lifelines and transport network), the natural environment (PGA, Liquefaction Resistance and land characteristics) and the organizational environment (financial organization, organizational structure and staff) (Section 2.1).

Defining how a hospital network performed in post disaster tense and assessing pre disaster vulnerability is limited by the availability of data and the time available to collect it. Based on the findings from the literature review (Chapter Two) and Chapter Four, the principle data requirements for holistic assessment methodology are;

1. Casualties. The input of patients to facilities (where the casualties will likely come from, the types of injuries and the background patient input from non earthquake related injuries and illnesses') (Section 5.2.1).
2. Physical damage. The physical damage to the hospital network (hospitals, lifelines and transport network) (Section 5.2.2).
3. Functional impact. The ALOS at the facility and the likely ALOS for casualties (Section 5.2.3).
4. Capacity redistribution. The availability and location of network capacity (at a national, regional and local level) (Section 5.2.4).
5. Mode of patient transfer. The required transport time and available transport resources for transfer between hospitals (Section 5.2.5).

All the factors that influence the flow and treatment capacity of patients should ideally be considered in a holistic assessment, or at least the factors that are the most influential.

The location of the receiving facilities is determined by whether or not the hospitals in the entire region or city must be evacuated or just an individual hospital. If one hospital has to be evacuated patients can be more easily transferred to undamaged hospitals which are close by, using road transportation or helicopter. If there is little residual capacity in the surrounding city or region patients will have to be transferred by fixed wing or helicopter to other regions (Section 2.7.1.1) (HHS 2011).

Inter hospital transfer is dependent on a variety of transport modes in order to transfer patients. Transfer by road is the most common mode of transfer for short distance transfers, fixed wing and helicopter transfers are more common for longer distances. Prior earthquake based case studies in the published literature confirm traffic congestion is common following earthquakes that impact urban areas (Ukai 1996). The resulting traffic congestion can greatly increase the time taken for patients to be transferred by road between hospitals. In order to predict the transit time within a transport network following an earthquake the; roads (including individual lanes), bridges, airports and ports that are likely to be closed must be identified and the effect of the increased demand on the operational areas of the transport network must be estimated.

The location and quantity of hospital to hospital transfers that will be required is dependent on; the estimated number of casualties, the severity of casualties, the epidemiological profile, the ALOS (background and earthquake casualties), the hospital capacity and the hospital functionality. The ease which individual organizations can redistribute capacity by transferring patients is dependent on the national, regional and local organizational structure which the individual hospitals operate within.

5.2 Patient treatment at hospitals following the Christchurch earthquake

5.2.1 Casualties following the Christchurch earthquake

A total of 185 people died and 7171 were injured during the Christchurch earthquake. The median age of the Christchurch earthquake casualties was 48.8 years (Johnston et al 2013). Of the 7,171 injuries reported following the earthquake 64.8 percent were female and 35.2 percent were male (Johnston et al 2013). The injuries were mainly a result of falling objects such as; collapsing roofs, rock falls and other falling physical objects (Johnston et al 2013). 169 of the 181 fatalities identified through the police disaster victim identification process were located in Christchurch's CBD (further expanded in section 3.3.1) (New Zealand Police 2011). A large number of the estimated 7171non fatal injuries were also caused within the CBD (Figure 5.1). The most common types of injuries caused by the Christchurch earthquake are depicted in Table 5.1.

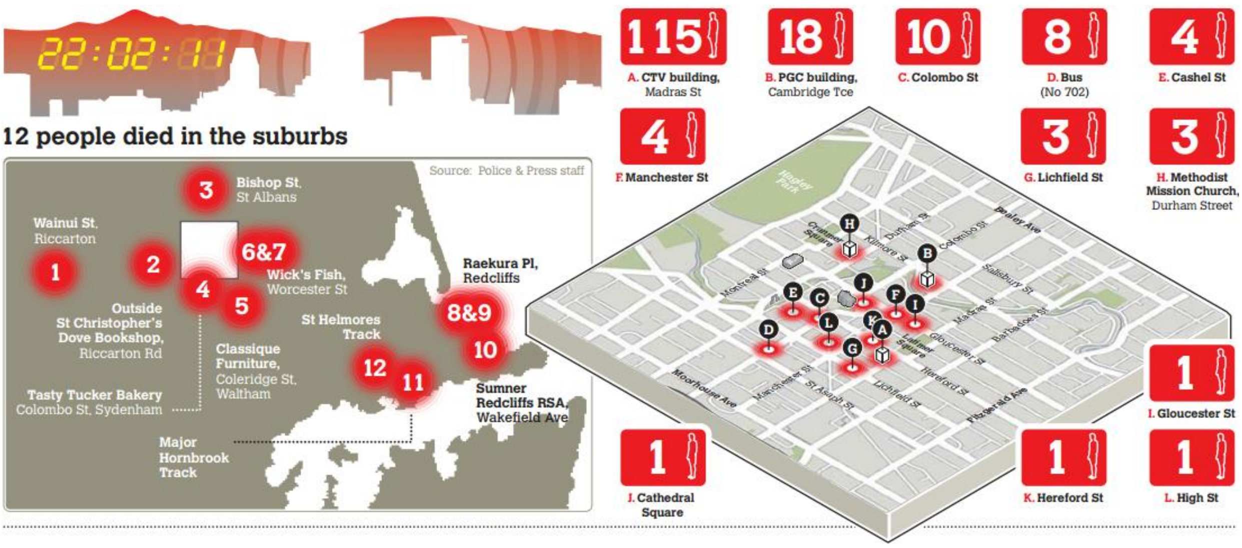

Figure 5.1: The confirmed location of Christchurch earthquake fatalities (Source: New Zealand Police 2011).

Table 5.1: The five most common types of injuries caused by the Christchurch earthquake (from Johnston et al 2013)

Location	Percent	Number
Lower back/spine	16.4	1173
Neck, Back of Head Vertebrae	9.8	700
Shoulder including clavicle/blade	8.2	586
Knee	8	571
Upper and Lower Arm	7	499

5.2.2 Physical damage to the Canterbury hospital network

The physical damage following the Christchurch earthquake was limited to Christchurch's hospitals and some of the hospitals in the other areas of Canterbury. The remaining South Island and North Island hospitals were largely unaffected by the earthquake. Structural and non structural damage was the main form of damage that caused functionality loss in Christchurch's hospitals (examined in detail in Sections 3.2.1 & 3.2.2). The loss of lifelines and utilities also afflicted all of Christchurch's hospitals to varying degrees (Section 3.2.3). St Georges Hospital (Section 3.4.1.2) was completely closed in part as a result of the loss of power and water. The functionality of the Princess Margaret Hospital (Section 3.4.1.1) was also reduced for a number of weeks as a result of water loss.

Even though all the hospitals in Christchurch were physically damaged to varying degrees, the larger hospitals still received transferred patients from Christchurch Hospital. The severity and type of functionality loss in Canterbury's hospital network is summarized in detail in Chapter Three. The Liquefaction resistance (LRI), PGA and MMI for all the Hospitals Canterbury are summarized in Table 5.2. The high PGA, LRI and MMI values are mostly restricted to the Hospitals in Christchurch or near to Christchurch (Table 5.2). The net loss of hospital functionality impacted how patients were treated in the Christchurch hospital network following the Christchurch earthquake and in some cases required patients to be transferred.

Table 5.2: Construction type, latitude and longitude, Liquefaction resistance Index (LRI), PGA, USGS MMI, GNS MMI and location for hospitals in Christchurch and Canterbury following the Christchurch earthquake

Hospital	Construction	Latitude and longitude	LRI Zone	PGA	USGS MMI	GNS MMI	Location
Burwood Hospital		43°28'51.80"S-172°41'2.14"E	3	0.32 (SD 0.385)	8	7.3	Christchurch
Christchurch Hospital	Concrete	43°32'2.40"S- 172°37'34.54"E	2	0.4 (SD 0.1925)	9	7.48	
Christchurch Women's Hospital	Concrete sheer wall	43°32'2.60"S-172°37'31.09"E	2	0.4 (SD 0.1925)	9	7.48	
Hillmorton Hospital	Concrete sheer wall	43°33'9.62"S-172°35'41.48"E	3	0.31 (SD 0.33)	9	7.3	
Nurse Maude Memorial Hospital	Concrete sheer wall	43°30'39.77"S-172°37'20.60"E	2	0.34 (SD 0.33)	9	4-7	
Parklands Hospital		43°30'5.85"S-172°36'42.14"E	3	0.27 (SD 0.33)	9	7.3	
Princess Margaret Hospital	Concrete frame	43°34'15.99"S- 172°37'16.18"E	0	0.45 (SD 0.3025)	9	7.3	
Rosewood rest home	Timber/RM	43°31'31.85"S-172°40'50.90"E	1	0.62 (SD 0.1925)	9	3-7	
Southern Cross Hospital	Concrete sheer wall	43°31'12.64"S-172°38'4.70"E	3	0.45 (SD 0.22)	9	7.3	
St Georges Hospital	Concrete sheer wall/RM	43°30'7.22"S-172°36'39.11"E	3	0.27 (SD 0.33)	9	7.3	
Akaroa Hospital	RM	43°48'49.77"S-172°57'39.50"E	0	-	6	6	Rural Canterbury
Ashburton	RM	43°53'39.26"S-171°44'47.59"E	0	-	5	3-5	
Darfield	Timber	43°29'14.04"S-172° 7'3.66"E	0	-	5	3-5	
Ellesmere	Timber	43°45'32.36"S-172°18'11.03"E	0	-	6	3-5	
Kaikoura	RM	42°24'14.01"S-173°40'55.61"E	0	-	3	2-3	
Lincoln	Timber	43°38'6.34"S-172°29'20.36"E	0	0.17 (SD 0.4125)	7	3-5	
Oxford	Timber	43°18'10.10"S-172°11'33.83"E	0	-	5	3-7	
Rangiora	Timber	43°17'23.47"S-172°35'27.51"E	0	0.1 (SD 0.4675)	6	3-5	
Timaru	Concrete sheer wall	44°24'29.71"S-171°15'21.51"E	0	-	4	3-4	
Waikari	Timber	42°58'6.52"S-172°41'31.27"E	0	-	4	4-7	

5.2.3 Functional impact

Transfers from Christchurch Hospital continued in the weeks after the Christchurch earthquake because of the reduced functionality caused by the physical damage and loss of services (Section 3.2). There is a loose negative linear trend ($R^2 = 0.0433$) between the ALOS for each ward and the number of patients transferred from those individual wards (Figure 5.2). This suggests that the wards with a lower ALOS are more likely to require patient transfers than wards with a higher ALOS when the wards are stressed with capacity loss and an influx of patients requiring treatment. This may be because the wards that treated the more severe patients such as the ICU and CICU couldn't discharge patients or transfer them until they were relatively stable. However each ward has different patient treatment characteristics that determine whether or not patients are transferred to other wards within the hospital to be treated or retained and treated permanently in another ward. The effect of the varied patient treatment characteristics for individual wards will likely influence the ALOS for the individual wards.

The ALOS for patients during the two weeks following the Christchurch earthquake at Christchurch Hospital is collated in Appendices M and N for all the patients at the hospital (Appendix L) (Presented in Figure 5.3) and for earthquake patients (Appendix M). The data in Appendix L is for all the individual wards in Christchurch Hospital. Appendix M just depicts the ALOS for earthquake related injuries (Presented in Figure 5.3), the wards the patients were treated in and the number of transfers from those wards. A comparison of the ALOS for the earthquake casualties and for all the patients in Christchurch Hospital is presented in Figure 5.3.

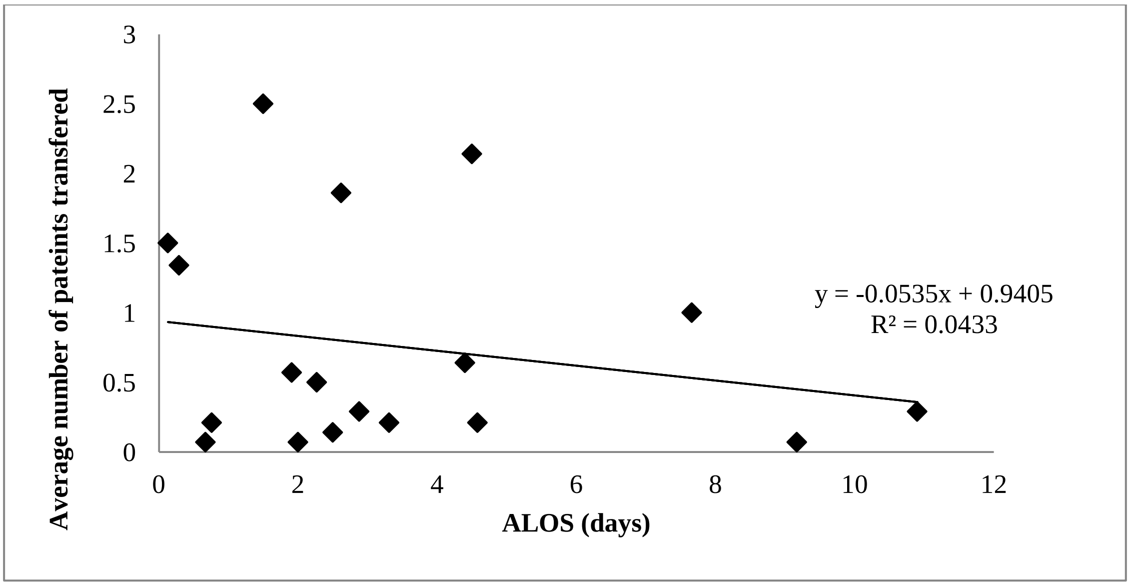

Figure 5.2: The ALOS (days) for individual wards compared with the average number of patients transferred from that individual ward at Christchurch Hospital in the two weeks following the Christchurch earthquake.

The ALOS for all the wards at Christchurch Hospital in the two weeks following the Christchurch earthquake was 2.41 days (Figure 5.4). The majority of the severe injuries caused by the earthquake (Table 5.1) were treated in the wards listed in Table 5.3. The ALOS for these wards was 4.99 days (the ALOS includes both earthquake and non earthquake patients). The ALOS for the period between the 14th and the 20th February, 2011 (before the Christchurch earthquake) for all the Christchurch Hospital wards was 3.3 days. The ALOS for the period between the 11th and the 14th of February, 2013 for all the Christchurch Hospital wards was 1.6 days. The ALOS for the two weeks following the Christchurch earthquake for all the wards at Christchurch Hospital is lower than the two weeks prior to the February earthquake. However the ALOS for the wards that treated the severe earthquake casualties (Tab le 5.3) is still higher than the ALOS for the two weeks prior to the Christchurch earthquake. The lower ALOS following the Christchurch earthquake for all the wards is likely a result of transfers and discharges from the Hospital.

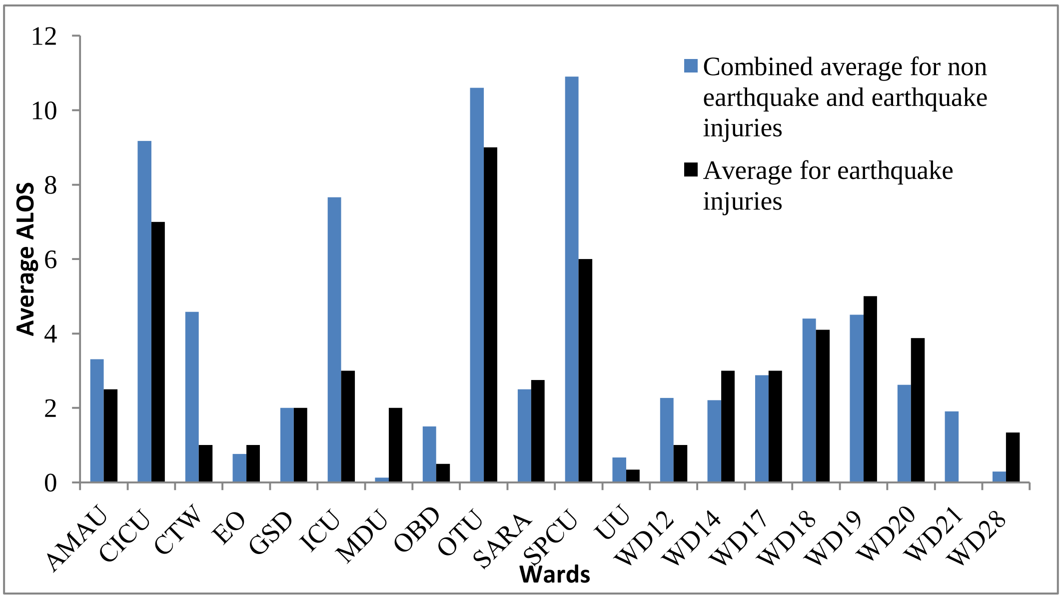

Figure 5.3: The ALOS (days) for earthquake injuries and the combined ALOS (days) for all the patients in the hospital for the two weeks following the Christchurch earthquake (Appendix L & N).

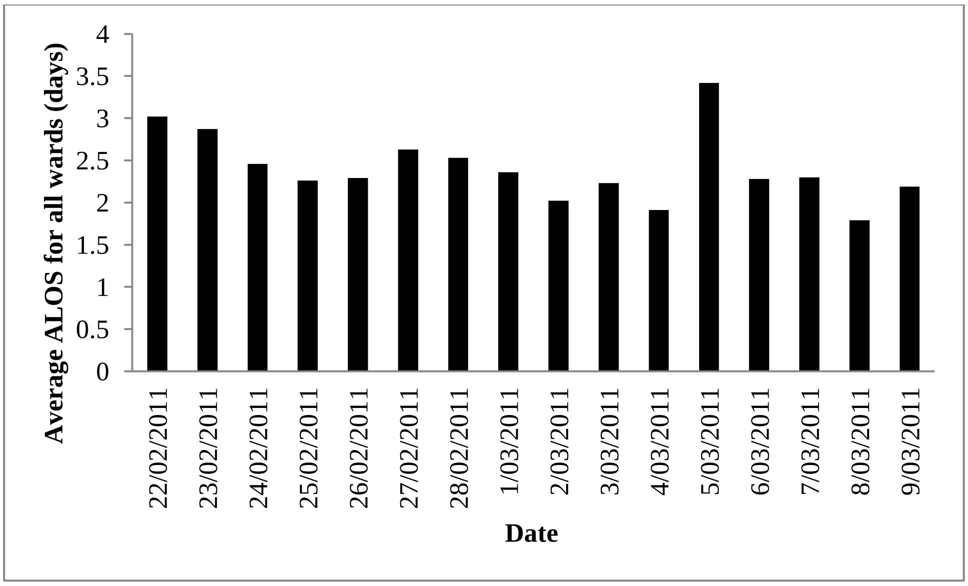

Figure 5.4: The daily ALOS (days) for all the wards in Christchurch Hospital during the two weeks following the Christchurch earthquake for both earthquake and non earthquake patients (Appendix L).

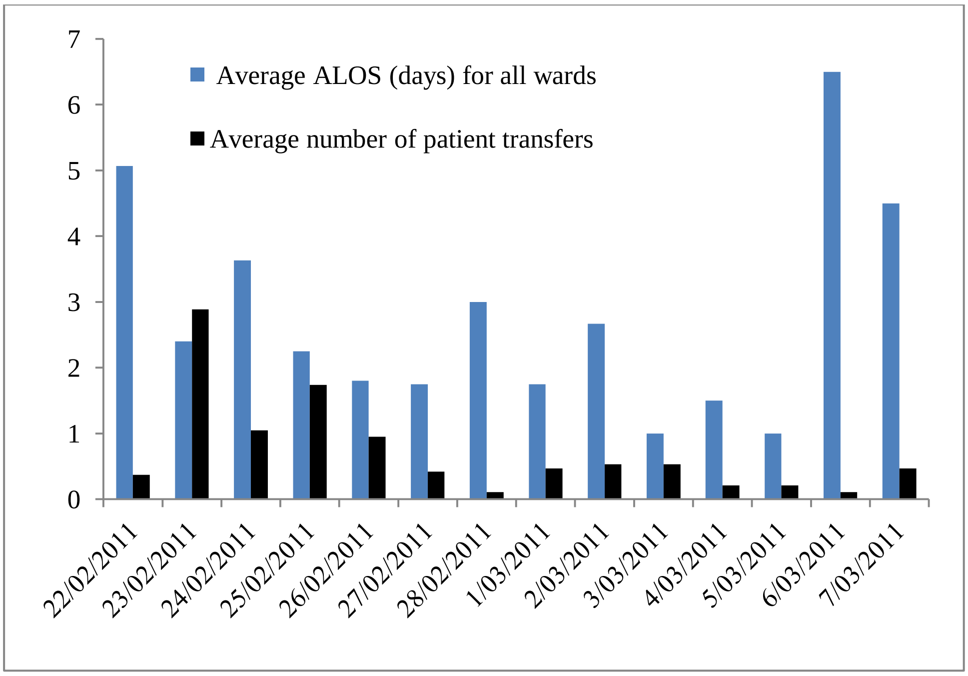

Figure 5.5: The daily ALOS for earthquake patients and the daily average number of transfers from Christchurch Hospital (all wards) during the two weeks following the Christchurch earthquake for earthquake causalities only (Appendix M).

The ALOS fluctuates largely and there is no observable trend (Figure 5.5). The average number of patient transfers for the two weeks following the Christchurch earthquake peaks the day after the Christchurch earthquake and then remains relatively constant (Figure 5.5).

5.2.4 Capacity redistribution

5.2.4.1 Location of patient hospitalization following the Christchurch earthquake

The majority of the Christchurch earthquake casualties were treated at Christchurch Hospital because; it was the largest hospital in Canterbury, central to the location of the earthquake casualties and it had the only Emergency Department in Christchurch. All of the earthquake casualties that the Christchurch Hospital received were treated in the wards presented in Appendix M. The Christchurch Hospital wards where the most severe earthquake casualties were treated are presented in Table 5.3. The other Hospitals in Christchurch didn't have the same patient treatment capabilities, as New Zealand's hospital networks are structured so individual hospitals in a given city only provide a relatively specialized centralized set of services, but can freely exchange patients' between hospitals. Because each of the hospitals in Christchurch provided relatively unique services the Christchurch Hospital network in its entirety was able to provide all the necessary services. However, the mass casualty event wasn't large enough to overwhelm the Christchurch hospital network capacity. As well the hospitals weren't sufficiently damaged to the point they were overwhelmed with the existing casualties.

Table 5.3: The Christchurch Hospital wards that received the severe earthquake casualties (ALOS for both non earthquake related and earthquake related patients)

Ward	Service	ALOS
AMAU	Adult Medical Assessment Unit	3.31
EO	Emergency observation	0.76
ICU	Intensive care unit	7.66
OTU	Orthopaedic Trauma Unit	10.6
SPCU	The SPCU is responsible for the treatment of un-well surgical patients	10.9
Ward 16 (SARA)	Ward 16 is a 16 bed General Surgical unit that specializes in the upper GI. The SARA is structured to provide an area where patients can be clinically assessed by the general surgical team.	2.5
Ward 18	The ward exclusively provides services for acute trauma and spinal injury patients.	44
Ward 19	The ward exclusively provides services for acute trauma and spinal injury patients.	4.5
Ward 28	Neurology & Neurosurgery for post-operative craniotomy and spinal surgery, head injury, neurological patients who must be invasively monitored.	0.29
Average		**4.99**

(CDHB. 2012b).

Because Christchurch Hospital's functionality was reduced (Section 3.2) patients had to be transferred in order to continue to provide healthcare to both earthquake and non earthquake injured patients. Severe earthquake casualties were transferred to ICUs as distant as the North Island, along with other non earthquake patients including geriatric patients.

5.2.4.2 Inter hospital transfer process

Christchurch Hospital accounted for 387 of the 455 outgoing transfers from Canterbury hospitals in the two weeks following the Christchurch earthquake. This was because Christchurch Hospital received the majority of the earthquake casualties and also sustained physical damage (Section 3.2) and therefore had to free up capacity. Ashburton Hospital and Burwood Hospital account for most of the remaining out going transfers (Table 4.2). Therefore the Canterbury inter-hospital transfer response for the first two weeks following the Christchurch earthquake was dominated by outgoing patients from Christchurch Hospital which also received the majority of the earthquake casualties. Therefore, for the purpose of this study Christchurch Hospital is considered the point source for all the Canterbury hospital transfers in the two weeks following the Christchurch earthquake.

5.2.4.3 Cause of inter hospital transfers

The decision to transfer patients from Christchurch Hospital was made within the hospital's organizational environment in liaison with senior staff from the other hospitals in New Zealand which were chosen to receive transferred patients. The transfer and discharge of patients immediately after the Christchurch earthquake was largely cautionary in expectation of large numbers of casualties and a necessity which was caused by a 19 percent reduction in permanent capacity within Christchurch Hospital's facilities.

5.2.4.4 The destination of patient transfers

The destination for all the inter-hospital transfers from Christchurch Hospital in the two weeks following the Christchurch earthquake are summarized in Table 5.6. Patients were transferred to 33 different hospitals throughout Christchurch (Figure 5.8), Canterbury (Figure 5.7) and New Zealand (Figure 5.6). The location of the hospitals include; 9 in Christchurch (189 patients transferred) (Figure 5.8), 10 in the rest of Canterbury (183 patients transferred), 6 in the other regions of the South Island excluding Canterbury (33 patients transferred) and 8 in the North Island (38 patients transferred) (Table 3.3). Burwood Hospital and Princess Margaret Hospital are the closest large (100 or more beds) hospitals to Christchurch Hospital, they accounted for 81 of the 186 received transfers within Canterbury (Table 5.6).

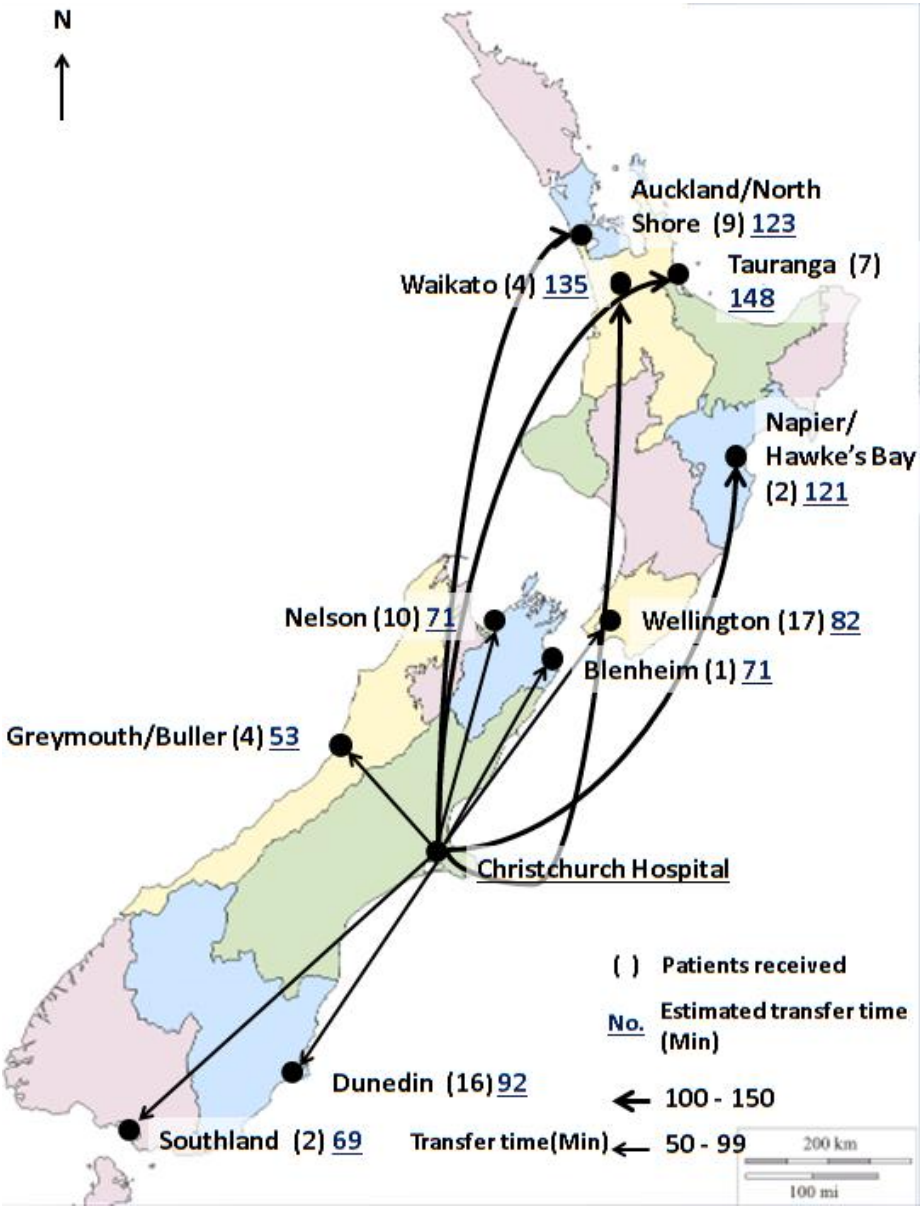

Figure 5.6: The citys outside of Canterbury which recieved the outgoing pateint transfers from Chrsitchurch Hospital during the two weeks following the Christchurch earthquake.

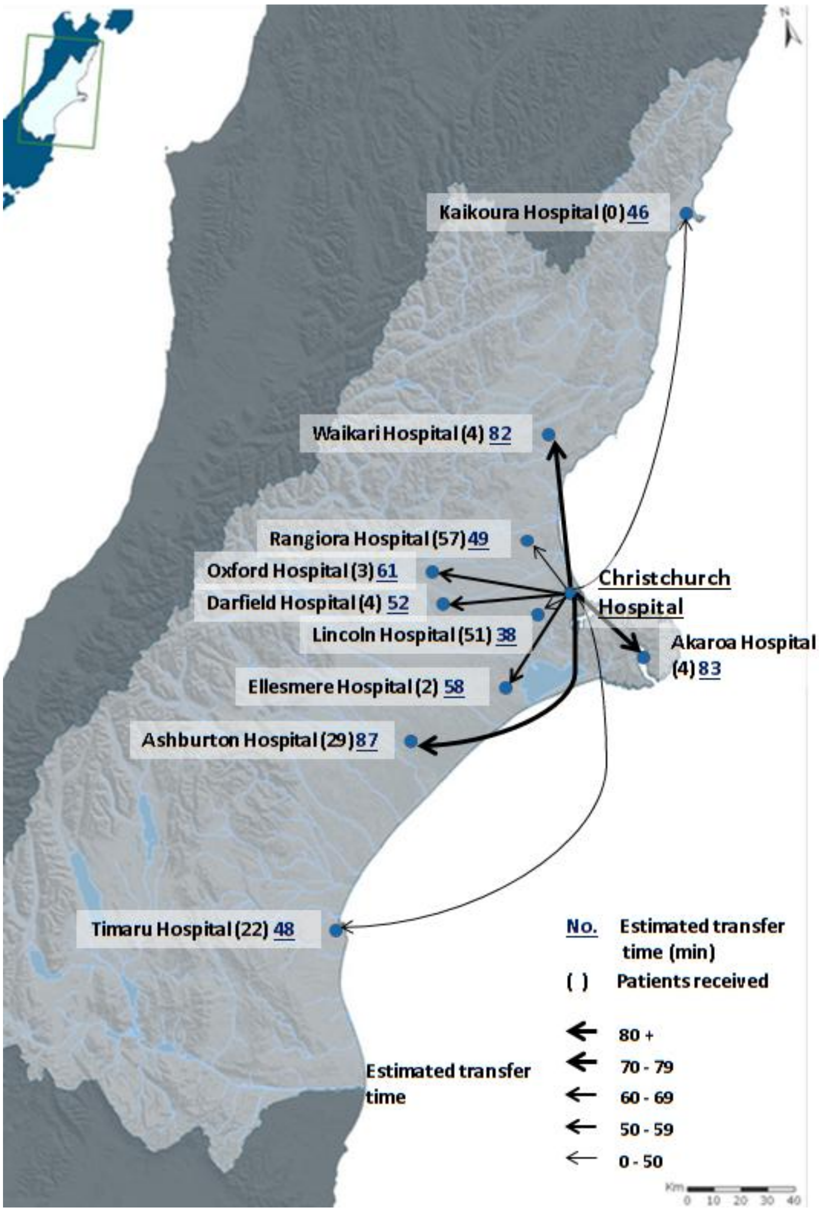

Figure 5.7: The citys and towns within Canterbury which recieved the outgoing pateint transfers from Chrsitchurch Hospital during the two weeks following the Christchurch earthquake.

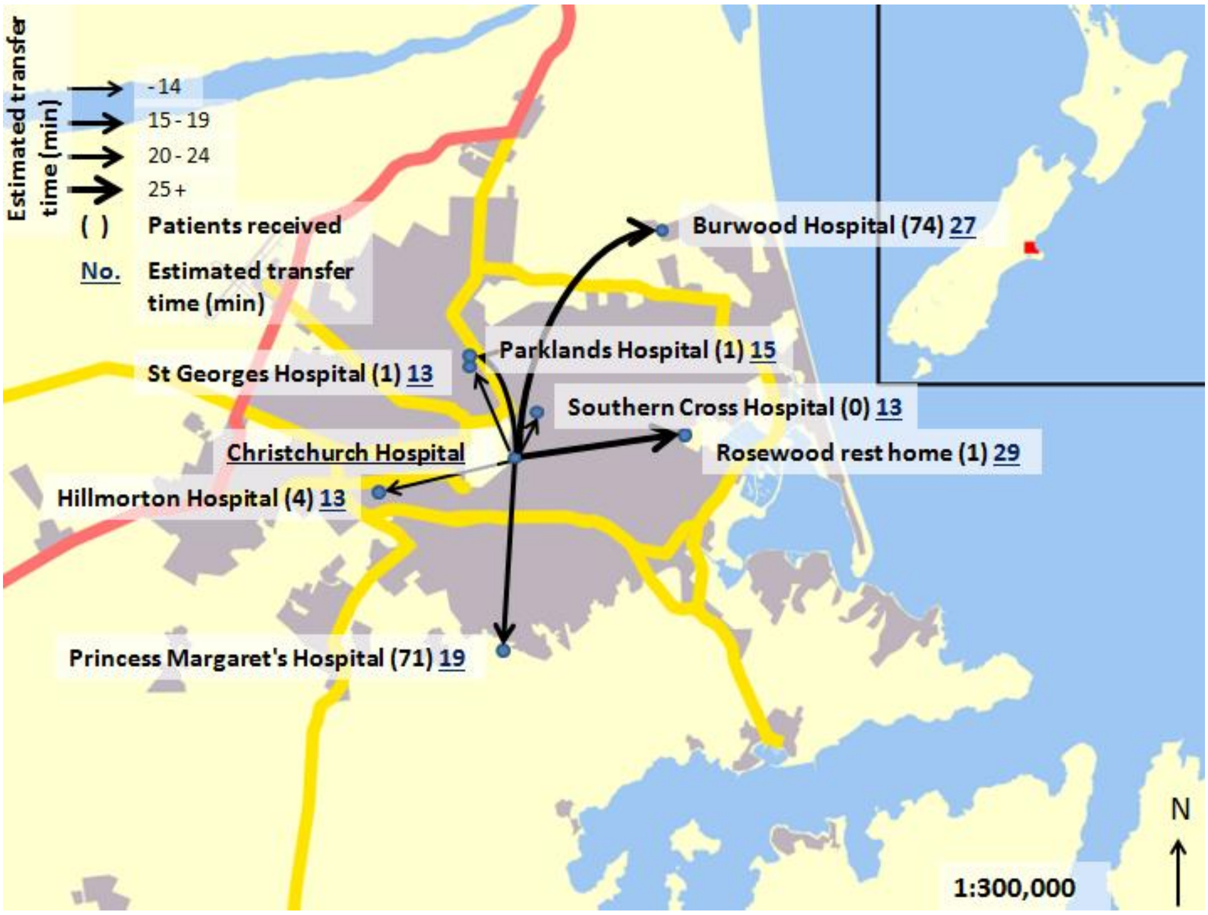

Figure 5.8: The citys within Christchurch which recieved the outgoing pateint transfers from Chrsitchurch Hospital during the two weeks following the Christchurch earthquake.

5.2.5 Mode of patient transfer following the Christchurch earthquake

The mode of inter hospital transfer is dependent on; the severity and scope of the earthquake, the number of causalities, the location of the receiving facilities, the availability of transport resources, the transport network damage and the state of the individual patient being transferred. The Christchurch earthquake was a low casualty localized event. Because the total fatalities only accounted for 0.0005 percent of the population of Christchurch and the earthquake damage was mostly confined to Christchurch and the neighboring townships. This meant that following the Christchurch earthquake there were few casualties and there was adequate residual capacity within Christchurch and the neighboring regions. As a result transport resources were relatively abundant within Christchurch in the two weeks following the Christchurch earthquake.

The main mode of transfer for the less critical patients within Christchurch and Canterbury was via road. The transfer of elderly patients from Christchurch Hospital (wards 29-31) (Table 3.5) to Princess Margaret Hospital on the night of the Christchurch earthquake was via furniture trucks. However, transfer by road (Table 5.7) to the hospitals in the rest of the South Island and the North Island would have taken too long. Fixed wing flights and helicopters were used for the long distance transfers in order to reduce the transfer time (Table 5.5 & 5.6).

The Christchurch Airport handled all the fixed wing transfers from Christchurch Hospital. The airports functionality was not impeded by the Christchurch earthquake except for an immediate 30 minute closure of the runway for a damage assessment following the Christchurch earthquake (Stuff. 2011).

The transport services responsible for the patient transfers by fixed wing and helicopter to the receiving hospitals following the Christchurch earthquake are provided in Table 5.4. The data does not have a constrained time period and therefore is not consistent with the other patient transfer data presented in throughout Chapters 3, 4 and 5. There were 12 different fixed wing and helicopter providers (excluding the New Zealand Air Force) that transferred patients following the Christchurch earthquake. The Canterbury Air Retrieval service (fixed wing), Life flight Auckland (fixed wing) and Life flight Wellington (fixed wing) account for most of the transfers. 55 of the 65 transfers were by fixed wing; just 10 patients were transferred by helicopter (Table 5.4).

Table 5.4: The transfers by Helicopter and fixed wing from Christchurch's hospitals' within the first days after the Christchurch earthquake (Rhise network)

Transport service	**Patients transferred**	**Destination (assumed)**
Canterbury Air Retrieval service (fixed wing)	26	Canterbury
Life flight Auckland (fixed wing)	9	Auckland
Life flight Wellington (fixed wing)	9	Wellington
Hawke's Bay (fixed wing)	5	Hawke's Bay
Helicopters NZ	2	Canterbury
Waikato Air Ambulance (fixed wing)	3	Waikato
Westpac Helicopter (Wellington)	1	Wellington
Otago Helicopters	6	Dunedin
Nelson Helicopters	1	Nelson
Mainland Air (Otago) fixed wing	1	Dunedin
Tauranga (fixed wing)	1	Tauranga
Nelson Air Ambulance (fixed wing)	1	Nelson
Total	65	

Table 5.5: Estimated transfer time by fixed wing for patient transfers from Christchurch Hospital in the two weeks following the Christchurch earthquake

Receiving facility	**Distance (km) by road** Between Christchurch Hospital and Christchurch Airport	**Time (min) on road** From Christchurch hospital to Christchurch Airport	**Distance (km) by fixed wing** Between Christchurch Airport to nearest airport of receiving facility	**Time (min) by fixed wing** From Christchurch Airport to nearest airport of receiving facility	**Distance (km) by road** Between nearest airport and receiving facility	**Time (min) on road** From nearest airport to receiving facility	**Total Time (min)** for transfer by fixed wing	***Number of patient transfers received in the weeks following the Christchurch earthquake***	**Mode of transfer**
Auckland city	10	18	746.33	80	18.6	25	**123**	***2***	Fixed wing
HAS	10	18	-	-	-	-	**-**	***1***	-
Hawke's Bay	10	18	552.72	90	22.5	25	**133**	***1***	Fixed wing
Middlemore	10	18	746.33	80	10.1	16	**114**	***2***	Fixed wing
Napier (Atawhai)	10	18	575.24	90	10.8	13	**121**	***1***	Fixed wing
North Shore	10	18	746.33	80	30.6	36	**134**	***2***	Fixed wing
Tauranga	10	18	715.9	115	8.7	15	**148**	***2***	Fixed wing
Waikato	10	18	666.92	100	13.2	17	**135**	***2***	Fixed wing
Wellington	10	18	304.42	55	4.9	9	**82**	***13***	Fixed wing

Table 5.6: Estimated transfer time by helicopter for patient transfers from Christchurch Hospital in the two weeks following the Christchurch earthquake

Receiving facility	**Total Time (min)** for transfer Helicopter	***Number of patient transfers received in the weeks following the Christchurch earthquake***	**Mode of transfer**
Timaru	**48**	***14***	Road/helicopter
Kaikoura Hospital	**46**	***0***	Road/helicopter
Grey Base	**53**	***3***	Road/helicopter
Wairau	**71**	***1***	Helicopter/Fixed wing
Buller	**-**	***1***	Helicopter
Dunedin	**92**	***11***	Helicopter
Southland	**69**	***2***	Road/helicopter
Nelson	**71**	***7***	Helicopter/Fixed wing

Table 5.7: Estimated transfer time by road for patient transfers from Christchurch Hospital in the two weeks following the Christchurch earthquake

Hospital	**Distance (km) by road** Between Christchurch Hospital and receiving facility under normal conditions	**Time (min) on road** From Christchurch hospital to receiving facility under normal conditions	**Mode of transfer**
Southern Cross	4.1	13	Road
Hillmorton	3.3	13	Road
St Georges	4.9	13	Road
Parklands hospital	6.1	15	Road
PMH	5.2	19	Road
Rosewood rest home	7.2	29	Road
Burwood Hospital	15.7	27	Road
Lincoln	19.8	38	Road
Rangiora	32.6	49	Road
Ellesmere	40.3	58	Road
Darfield	44	52	Road
Oxford	57.9	61	Road
Waikari Hospital	73.9	82	Road
Akaroa Hospital	81.4	83	Road
Ashburton Hospital	84.7	87	Road

5.3 Conceptual model for patient transfers based on key statistics

Models for complex integrated systems like hospital networks are rare because of the extensive data requirements that are needed to generate outputs (Section 4.4). The purpose of Figure 5.9 is to define the connections between the components necessary for the assessment of the network wide inter-hospital transfer process. The spatially extensive transport network (road, air and sea transport networks') respond in a unique way geographically to seismicity and traffic congestion. Therefore, predicting how the transport network will be impeded depends on the characteristics of the underlying land, how the seismicity interacts with the land, the built environment (seismic performance of the system), the rate which damage can be repaired and the likely flow of people within the transport network (the demand on the system and the redundancy of the system).

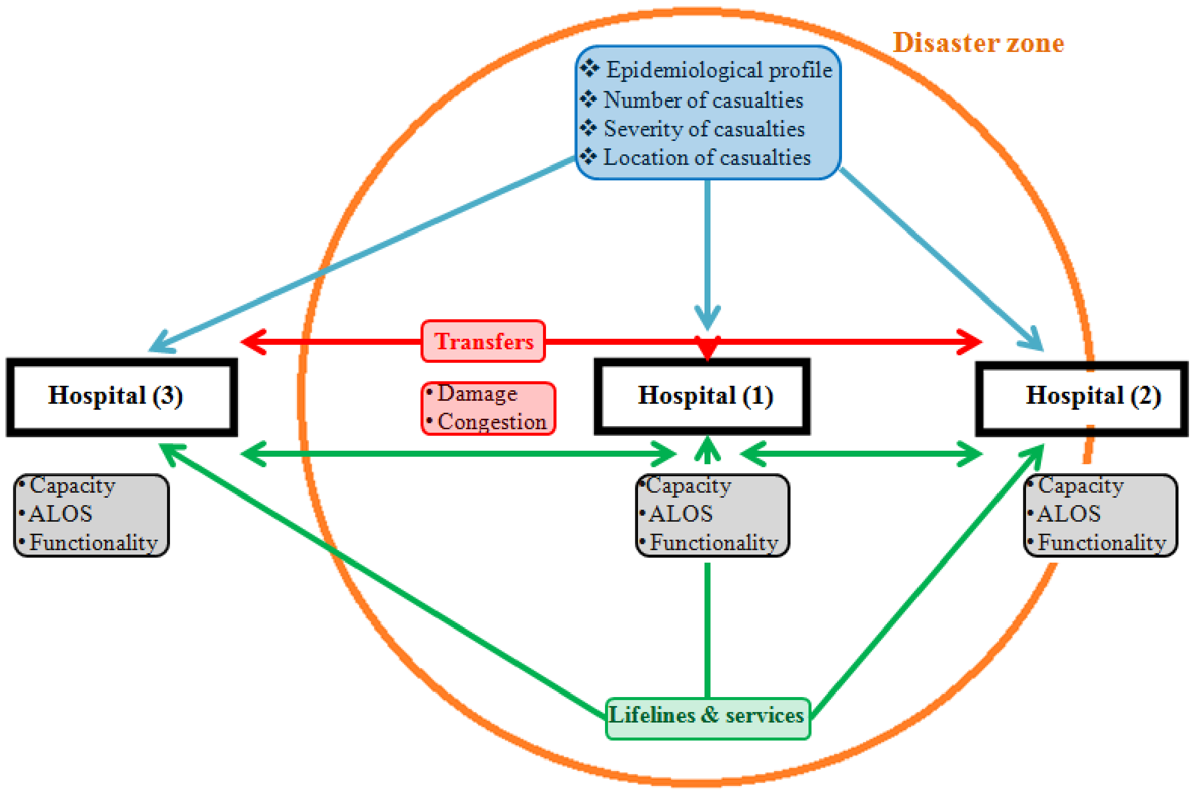

Figure 5.9: Holistic model for hospital networks following a local disaster

Similarly the lifelines and services networks are exposed to spatially variable land characteristics and ground acceleration following earthquakes and thus will be affected in a varied nature. Hospitals outside the disaster zone may have reduced functionality if they depend on lifelines or services situated or provided within the disaster zone (Figure 5.9). The functionality of hospitals situated outside the disaster zone may be reduced by the secondary effects of the earthquake in order to surge capacity and provide services such as laundry, food or lab work for hospitals within the disaster zone (e.g. Timaru Hospital, Section 4.6) or if the services they rely on are provided in the disaster zone. For example Timaru Hospital is located 147 km south of the Christchurch earthquake epicenter and neither the hospital nor its lifelines were damaged. However, it immediately reduced its capacity in expectation of transfers (which the hospital received) and provided laundry services for Christchurch Hospital (Section 4.3). The disaster zone in Figure 5.9 is limited to the area that has primary physical earthquake damage. For the purpose of this study primary physical earthquake damage is classed as physical damage which was caused directly by the ground acceleration.

5.4 Inter-hospital patient transfer time calculation

An appropriate method for determining the probable travel time of an inter hospital patient transfer following a destructive but localized earthquake with relatively few casualties in a city with plentiful transport resources would include the following variables:

- The destination

- Mode of transfer
- The availability of network capacity
- The (state) condition of the patient.

Estimating the transfer time is dependent on the: available exit routes within the hospital, available staff, available transportation resources, location of receiving care sites, number of patients and mix of patient acuity, patient transportation requirements and the road and traffic conditions. The mode of transfer is critical in determining how long patient transfers take. In order to be effective the means of transfer must be properly equipped and staffed (Section 2.7.1.1) (HHS 2011).

The distance to the hospital chosen for transfer is the main variable (destination). It is modified by the availability of capacity in the network (residual capacity). The road condition is vital in determining the time of transfer for road transfers. However the state of the patient and destination determines the mode of transfer (road, fixed wing or helicopter). The state of the patient modifies the mode of transfer because patients in a severe state are most likely to be transferred by the fastest means such as helicopter or fixed wing. The connections between the factors described above are summarized in Figure 5.10.

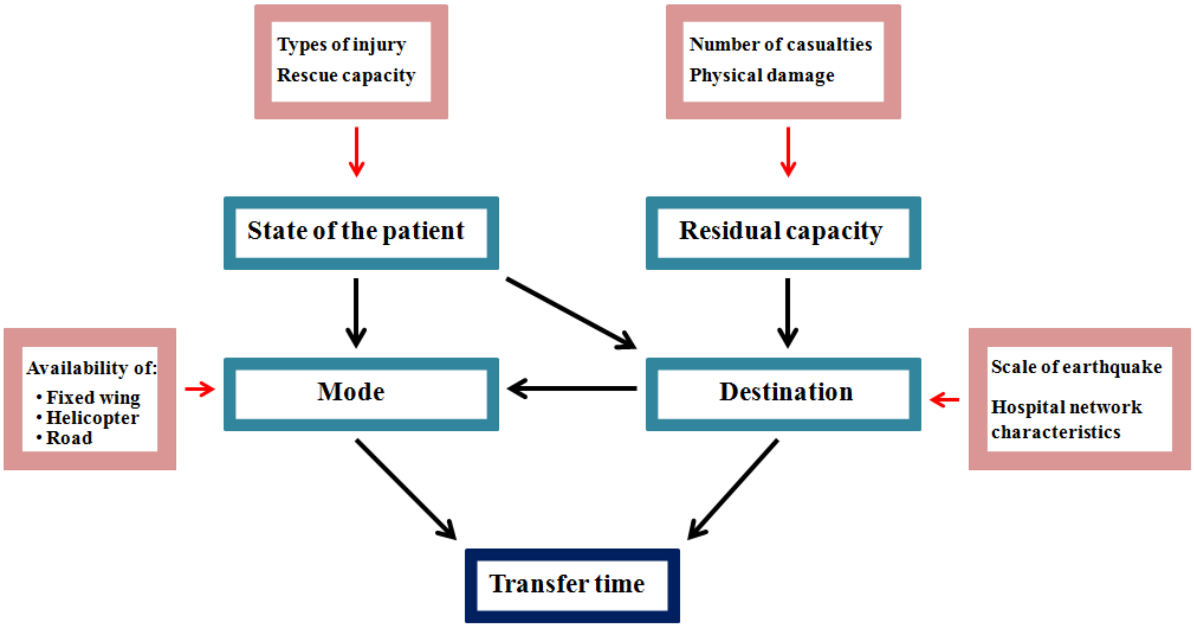

Figure 5.10: The components that determine transfer time; the state of the patient, residual capacity, destination, mode and the factors that influence the components.

5.5 Results and Analysis

The results which are analyzed in Section 5.5 are comprised of data derived from Section 5.2 and Chapter Three and framed with the conceptual methodology proposed in Sections 5.4 and 5.

5.5.1 Implementation of conceptual model for predicting the location of patient transfers

The conceptual model which is implemented is in this section is outlined in detail in Section 5.4. The data which is interpreted within the conceptual model is drawn from the post Christchurch earthquake Christchurch hospital network data presented in Chapter Four. The level of functionality loss (Figure 5.9) in Canterbury's hospitals and the influence functionality loss had on inter hospital transfers can be calculated quantitatively if the number of functions lost are known (defined further in Section 5.1.1) (Table 5.8). For the purpose of this study the functionality loss is calculated as a percentage of hospital functions which were reduced at some point during the two weeks following the Christchurch earthquake. The following functions were used for the calculation (Table 3.2):

- Electricity
- Back up electricity
- Water
- Sewer
- Telephone
- Computers
- Medical gases
- Suction

If the loss of functionality was not known then it was estimated to be 50% for category 1 hospitals (Figure 5.9), 10% for category 2 hospitals (Figure 5.9) and 0% for category 3 hospitals (Figure 5.9). The estimates are based on the known values from other hospitals in the same category. The ALOS is only known for Christchurch hospital because the data is too difficult to obtain for each individual hospital that received Christchurch Hospital transfers. The hospital capacity is depicted as a ratio of the post Christchurch earthquake bed capacity and the capacity immediately prior to the Christchurch earthquake.

Category 1 hospitals are classed as being completely within the disaster zone, category 2 hospitals are classed as being partially within the disaster zone and category 3 hospitals are classed as being completely outside the zone of primary physical earthquake damage (Figure 5.9).

The category 1 hospitals were only located in Christchurch, the category 2 hospitals that were on the edge of the zone of primary physical earthquake damage were located in the towns that are adjacent to Christchurch. All the hospitals in category 3 are located in either in areas in Canterbury far away from Christchurch or the other regions in the South Island or in the North Island. The reduction in hospital bed capacity was limited to category 1 hospitals (Table 5.8).

Table 5.8: The capacity of the receiving hospitals, Maximum functionality loss, estimated transfer time and number of patient transfers received for the Hospitals that received patient transfers from Christchurch Hospital in the two weeks following the Christchurch earthquake.

Class of hospital (1,2,3)	**Hospital**	**Capacity of hospital (Post EQ: Pre EQ)**	**Maximum Functionality loss (%)**	**Estimated transfer time from Christchurch Hospital (min)**	***Number of patient transfers received***
Hospital 1 (fully in the disaster zone)	Christchurch Hospital	522:650	50%	**-**	**-**
	CWH	148:148	**-**	**-**	**-**
	Southern Cross Hospital	87:87	50% (estimated)	**13**	-
	Hillmorton Hospital	159:159	50% (estimated)	**13**	***4***
	St Georges Hospital	80:101	50%	**13**	***1***
	Parklands hospital	-	50% (estimated)	**15**	***1***
	PMH Hospital	109:109	50%	**19**	***41***
	Rosewood rest home	24:24	50% (estimated)	**29**	***1***
	Burwood Hospital	150:150	50% (estimated)	**27**	***41***
Hospital 2 (Partially in the disaster zone)	Lincoln Hospital	7:7	10% (estimated)	**38**	***24***
	Rangiora Hospital	13:13	10% (estimated)	**49**	***29***
	Ellesmere Hospital	10:10	0%	**58**	***0***
	Darfield Hospital	8:8	10% (estimated)	**52**	***2***
	Oxford Hospital	15:15	10% (estimated)	**61**	***1***
	Waikari Hospital	11:11	0%	**82**	***3***
	Akaroa Hospital	8:8	38%	**83**	***4***
	Ashburton Hospital	74:74	10% (estimated)	**87**	***20***
Hospital 3 (outside of the disaster zone)	Timaru Hospital	131:131	0%	**48**	***14***
	Kaikoura Hospital	26:26	0%	**46**	***0***
	Grey Base Hospital	-	0%	**53**	***3***
	Wairau Hospital	91:91	0%	**71**	***1***
	Buller Hospital	55:55	0%	**-**	***1***
	Dunedin Hospital	388:388	0%	**92**	***11***
	Southland Hospital	181:181	0%	**69**	***2***
	Nelson Hospital	173:173	0%	**71**	***7***
	Auckland city Hospital	710:710	0%	**123**	***2***
	Hawke's Bay (Royston)	400:400	0%	**133**	***1***
	Middlemore Hospital	97:97	0%	**114**	***2***
	Napier Hospital	41:41	0%	**121**	***1***
	North Shore Hospital	307:307	0%	**134**	***2***
	Tauranga Hospital	349:349	0%	**148**	***2***
	Waikato Hospital	600:600	0%	**135**	***2***
	Wellington Hospital	434:434	0%	**82**	***13***
	Average	**1.8**	**17%**	**69.3**	***7.64***

5.5.2 Inter-hospital patient transfer time estimation for the patient transfers from Christchurch Hospital in the two weeks following the Christchurch earthquake

The average transfer time for all transfers from Christchurch Hospital in the two weeks following the Christchurch earthquake was not available from Canterbury DHB. Therefore estimated transfer times were calculated using the data presented in Appendix M and Appendix K. The inter Christchurch hospital road transfer time and distance data in Appendix K is based on the April 2011 peak PM traffic data (Blyleven 2012) and the road and bridge closure data (Figure 5.6) from Land Information New Zealand (Koordinates). The April, 2011 peak PM travel data was the best detailed traffic congestion data because it is the first available data following the 22nd of February, 2011. The transfer time in Appendix K was calculated using the following equation.

2. Time of transfer = Distance (km)/ the road speed (km/h)

The distance incorporates roads and bridges that were closed in the two weeks following the Christchurch earthquake (Figure 5.11). And the road speed is the median of the value range presented in the April 2011 traffic data (Blyleven 2012). The time of transfer for the individual roads that are assumed to be used for inter-hospital transfer were calculated separately because the road speed varies between the different roads. The time for inter-hospital road transfers in Christchurch for the two weeks following the Christchurch earthquake is the sum of all road transfer times' (calculated using equation 2) for the individual roads that were used. The estimated patient transfer time by road is depicted in Table 5.7.

The data in Appendix O, Table 5.6 Table 5.7 incorporates travel time data for road, fixed wing and helicopter flights to the more distant hospitals. The travel times by road for transfers to hospitals outside of Christchurch were calculated using Google Earth. The quickest mode of transfer was assumed if the mode of transfer was not known (Table 5.5). Plotting the travel time verse travel distance (Figure 5.12) shows that there are three distinctive groups for transfers by road (Table 5.7), helicopter (Table 5.6) and fixed wing (Table 5.5).

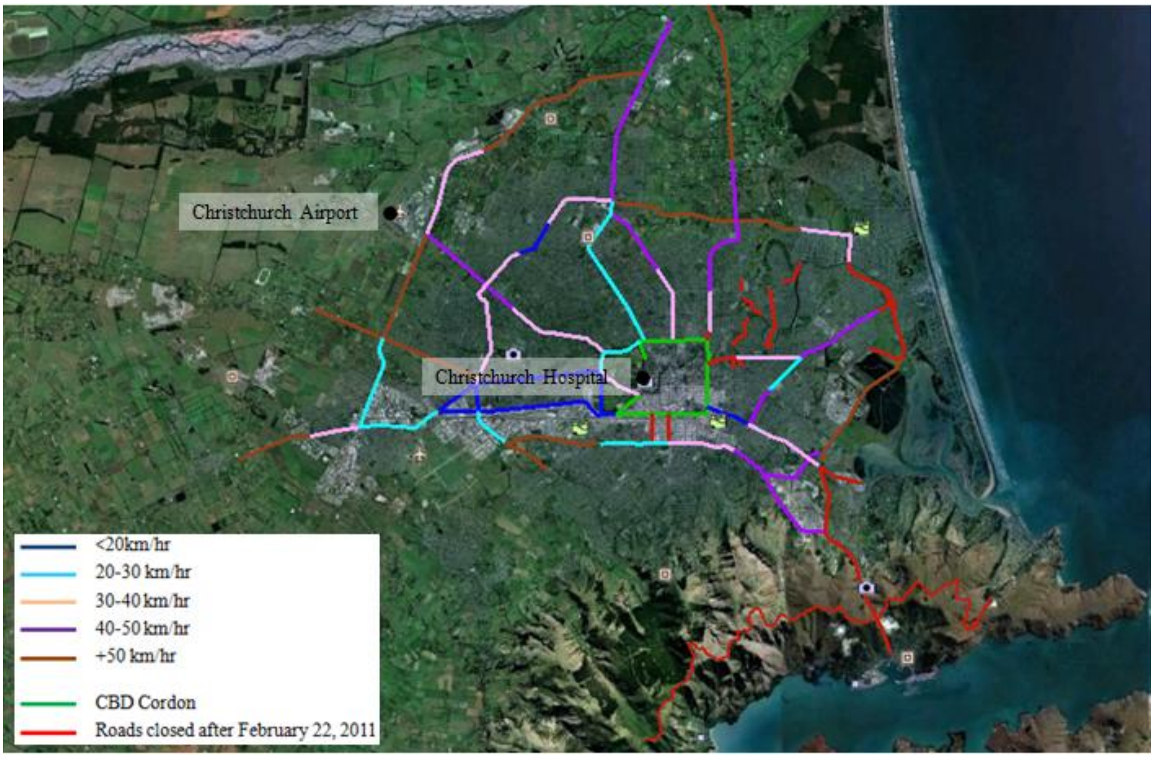

Figure 5.11: Map of road closures and traffic times in Christchurch in the two weeks following the Christchurch earthquake (Google Earth) (red roads were closed for the entire two weeks).

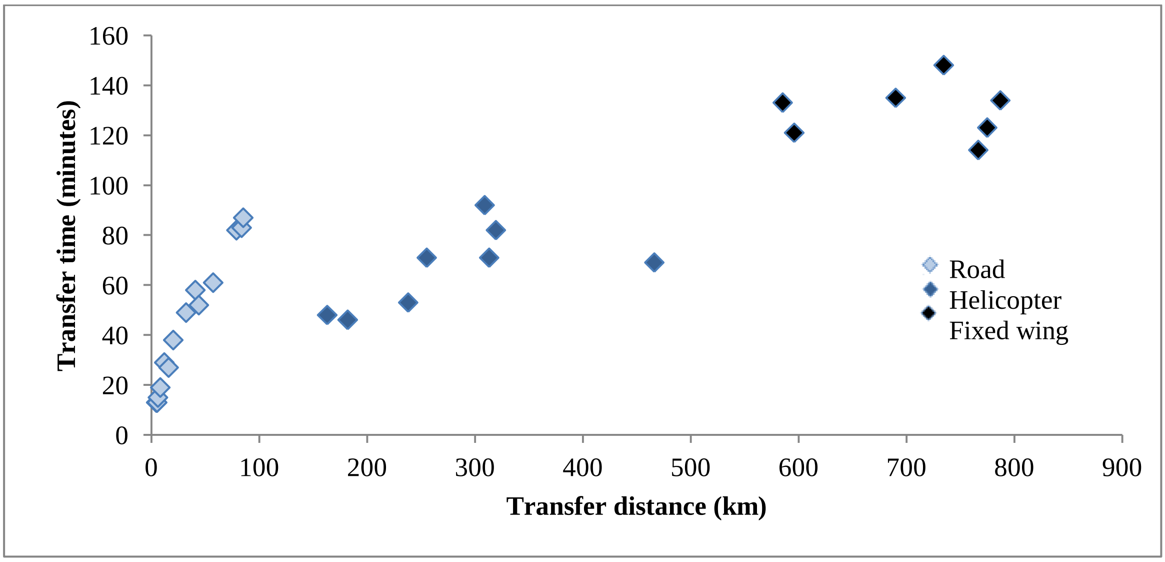

Figure 5.12: The transfer time verse transfer distance for the patient transfers by Road, Fixed wing and Helicopter.

The road network travel times depicted in Figure 5.11 are used to calculate the travel times and distances in Appendix K and Table 5.11. Figure 5.11 was created using PM peak travel time data for April 2011. The road network travel times for transfers by road to areas outside of Christchurch were calculated using Google Earth. As well the road transfer times between the receiving facilities in centers outside of Christchurch and the nearest airport were calculated using Google Earth for the transfers that involved fixed wing and helicopter transfers. It is assumed that the travel times for April

2011 are the same as the travel time for the two weeks following the Christchurch earthquake. As well, the road/bridge closures and the CBD cordon are assumed to be the same throughout the two weeks following the Christchurch earthquake. The Road and bridge closure data was obtained from Land Information New Zealand (Koordinates) and the April 2011 traffic data was obtained from Blyleven et al. (2012).

The fixed wing and helicopter transfer times presented in Table 5.6 and Table 5.5 were calculated by firstly using Google Earth to obtain the shortest possible distances from Christchurch Airport (assuming the shortest distance is taken) to the nearest airport to the receiving facility. And secondly, the average speed for the fixed wing and helicopters used for the transfers were obtained. The speeds used are 225 km/h for the BK-117-B2 helicopter (CWCART 2013) and an average of 540 km/h for The Cessna 421C (NZAAS 2013) and C-130H Hercules fixed wing aircraft (NZRAF 2013) (assuming the entire trip is at average speed). Thirdly the transfer times are calculated using the following formula (equation 3):

3. Distance of transfer (D) /Average speed for the mode of transfer (Av)

The average transfer time using the assumptions and data mentioned above for all the patients transferred from the Christchurch Hospital over the two weeks following the Christchurch earthquake was 69.3 minutes per patient (Appendix O). The study is limited by only having road network congestion data from April, 2011, ideally the data would be from the two weeks after the Christchurch earthquake. However, it is difficult to collect traffic congestion data immediately after an earthquake due to the extensive logistics required. The study is also limited by assuming that the air travels were by the shortest distance and with an average speed for the specific mode of transfer the entire time. Not knowing the exact transfer route for the road transfers is also a limitation of this study. The estimated times for transfers (Appendix O) are based on the assumption that the flights were not delayed and there was no additional time between the road transfer and the fixed wing flight.

The use of helicopters and fixed wing flights to move patients within Christchurch and between cities greatly reduced the transfer travel time. This was possible because of the low number of patients requiring transfer and air resources were not stressed beyond the point where patients that needed to be transferred could not be.

Where the transfer time from Christchurch Hospital to the receiving facility was calculated for all the three modes of transfer (road, fixed wing and helicopter), the transfer time was on average;

- 240 percent greater for road transfers than fixed wing transfers
- 340 percent greater for road transfers than helicopter transfers
- 160 percent greater for fixed wing transfers than helicopter transfers

The helicopter transfers for the estimated average speeds used to calculate the transfer times (Appendix O) were the fastest followed by fixed wing transfers and then lastly transfers by road. However the BK-117-B2 helicopter only has a range of 540 kilometers. Whereas, the Cessna 421C (NZAAS 2013) and C-130H Hercules (NZRAF 2013) have ranges of 2,755 km and 3,800 km respectively. This means that most of the hospitals in the North Island are out of range for BK-117-B2 helicopter (CWCART 2013) transfers from Christchurch Hospital.

5.5.3 Inter hospital transfer time equations

An estimation of the travel time by road (Tt_R) (equation 3), helicopter (Tt_H) (equation 5) and fixed wing (Tt_F) (equation 6) are presented below in equations 3-5.

4. $Tt_R = 0.89d + 14.17$ Road
5. $Tt_H = 0.09d + 41.52$ Helicopter
6. $Tt_F = 0.093d + 62.81$ Fixed wing

The (Tt) is the time taken to travel from Christchurch hospital to the receiving facility. The Tt_F includes the time taken by road from Christchurch Hospital to the Christchurch Airport and the time taken to travel by road from the receiving airport to the receiving hospital (Appendix N). The Tt is measured in minutes and the distance (d) is measured in Kilometers. The equations were generated with the post Christchurch earthquake Christchurch Hospital transfer data which is presented in Appendix N and in Figure 5.12. The calculations are based on the assumptions presented in Section 5.5.2. The equations are only valid within the transfer distance ranges for road, helicopter and fixed wing transfers from Christchurch Hospital, to the receiving hospitals in the two weeks following the Christchurch earthquake (Appendix N). The ranges are as follows:

- Road transfer = 3km - 85km
- Helicopter transfer = 147km - 466km
- Fixed wing transfer = 319km – 787km

5.6 Discussion

The aim of Section 5.6 is to draw on the results presented above in Chapter Five in order to define the factors that increased the short term resilence of the Canterbury Hospital network (Section 5.6.1) and the long term resilence (Section 5.6.2) of Christchurch Hospital following the Christchurch earthquake. Christchurch Hospital is the primary focus of long term resilence indicators within the Canterbury hospital network. This is because throughout this study Christchurch hospital was the focus of the long term analysis in order to draw as many conclusions from the most damaged and important hospital in the Canterbury hospital network (Section 3.2.1). The process of analysis in Section 5.6 is structured with “A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities” by Bruneau et al (2003). The frame work enables the different components that contribute to the resilience of the physical, organizational, social and economic systems to be defined in the following four categories (Bruneau et al., 2003):

- Robustness: The strength, or the ability of elements, systems and components to withstand a given level of stress without suffering degradation or loss of function.
- Redundancy: The extent to which elements and systems are capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality
- Resourcefulness: The capacity to identify problems, establish priorities and mobilize resources when conditions exist that threaten to disrupt the continued provision of healthcare.
- Rapidity: The capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.
  (Bruneau et al., 2003)

Table 5.9: The performance criteria for the measures of resilence (Bruneau et al., 2003)

Performance criteria	**Robustness**	**Redundancy**	**Resourcefulness**	**Rapidity**
Technical performance measure	Maximize availability of buildings and equipment (units) and #% of functions operational after small earthquake)(technical unit to be defined)	Backup/duplicate systems, equipment and supplies (e.g.,#% available for small earthquake)	Integrated fragility models to assess system vulnerability and damage	Buildings and equipment are fully functional immediately after EQ
Organisational performance measure	Emergency organization and infrastructure in place; critical functions identified	Alternative sites and procedures identified for providing medical care	Plans and procedures for mutual aid & emergency transfer of patients to undamaged hospitals	Maximize provision of critical medical and health care services; minimize avoidable negative health outcomes
Social performance measure	All injuries treated in first day	Volunteers were managed with limited disruption	Volunteers were managed with limited disruption	All injuries treated in first day
Economic performance measures	No damage to building or critical emergency equipment	Pre-event arrangements for governmental reimbursement and/or insurance	Pre-event arrangements for governmental reimbursement and/or insurance	Procurement of new/ replacement equipment in 1 day

Using the definitions for the performance measures and the performance criteria (table 5.9), the performance measures and criteria are qualitatively defined and quantitatively scored below in Table 5.10, for the post Christchurch earthquake Christchurch hospital network. The qualitative measures and quantitative scores are based on the results, discussions and conclusions presented in Chapters' 4 and 5. The performance measures, criteria and their assigned scores for the post Christchurch earthquake Christchurch hospital network (Table 5.10) are discussed below in Sections 5.6.1 and 5.6.2 and summarized in Section 5.6.3. The discussion is intended to highlight the areas of the Canterbury hospital network that account for the post Christchurch earthquake resilence.

Table 5.10: The performance of the Canterbury hospital network for the measures of resilence

Performance criteria/score	**Robustness**	**Score**	**Redundancy**	**Score**	**Resourcefulness**	**Score**	**Rapidity**	**Score**	**Total**
Technical performance measure	Was able to maximise the use of residual building capacity	4/5	Some backup systems and supplies were lost for short periods of time	3/5	Integrated fragility models to assess system vulnerability and damage	-	There was slight damage to the buildings and equipment	3/5	**10/15**
Organisational performance measure	The emergency organization and infrastructure was in place. The critical functions were known	5/5	Alternative sites were identified prior to the earthquake that could provide healthcare	5/5	There were pre-existing plans and procedures for patient transfers	5/5	The provision of healthcare services was maximised. The negative health outcomes were minimized to a certain degree (transfers)	4/5	**19/20**
Social performance measure	All the earthquake injuries were treated in first day	5/5	Volunteers were turned away because they got in the way of the clinical staff	4/5	Volunteers were turned away because they got in the way of the clinical staff	4/5	All the injuries were able to be treated in the first day	5/5	**18/20**

Performance criteria/score	Robustness	Score	Redundancy	Score	Resourcefulness	Score	Rapidity	Score	Total
Economic performance measures	There was slight damage to buildings and critical emergency equipment	3/5	There were government earthquake funds available, however there were lengthy insurance issues (EQC)	4/5	There were government earthquake funds available, however there were lengthy insurance issues (EQC)	4/5	New/replace ment equipment was available in 1 day	5/5	**16/20**
Total	**17/20**		**16/20**		**13/15**		**17/20**		**63/75**

The social performance measure for the redundancy and resourcefulness criteria in Bruneau et al (2003) is defined as “Volunteers encouraged to assist at acute care hospitals”. However the presence of volunteers at Christchurch Hospital was identified by clinical staff as a source of disruption (Section 3.3.1). Therefore the definition is altered to “Volunteers were managed with limited disruption” to be more reflective of the post Christchurch earthquake, Christchurch hospital network (Table 5.9).

5.6.1 Short term resilence of the Canterbury hospital network

For the purpose of this study, the resilence exhibited in the short term is defined as the period starting immediately after the Christchurch earthquake and ending 6 months later. The loss of hospital functionality in the short term was limited to the category 1 and 2 hospitals (Figure 5.9) situated in Christchurch and the surrounding townships (Table 5.2). The functionality of the Canterbury hospital network was only reduced by around 50 percent (Table 5.2) for a short period of time. The functional loss was caused because the Christchurch hospital network was physically damaged and as a result lost essential services, lifelines and back up resources (Table 3.2). However, it was not damaged to the point it was not fully functional (Table 5.10).

Because the functionality loss as a result of physical damage in the Canterbury hospital network was only partial, patients could still be transferred between hospitals in order to surge capacity at the most important facilities (such as Christchurch Hospital). Patients could still be transferred between partially damaged and partially functionally reduced hospitals in Christchurch and treated adequately because the functionality was only partial. The reasons’ the Christchurch/Canterbury hospital network was able to surge capacity are highlighted in Table 5.10 under the organizational performance measure for all four criteria (Table 5.10). The key reasons are; alternative hospitals were pre -

identified, emergency plans were in place and preexisting plans were available to aid the patient transfer process (Table 5.10).

Christchurch Hospital had to free up capacity because it had the only ICU in Christchurch and therefore was required to treat the most severe earthquake casualties. 365 out of the 457 patients that were transferred from Christchurch Hospital in the two weeks following the Christchurch earthquake were transferred to other hospitals in Canterbury. This was made possible because the net capacity for all of Canterbury's hospitals prior to the Christchurch earthquake was 1822 beds, of which only 149 beds were lost during the earthquake (Table 5.8). As well, the critical emergency equipment for the Christchurch hospital network was largely undamaged. This was the result of the relatively strong economic performance (Table 5.10) with respect to the mitigation of the seismic hazard. The slight to moderate degree of damage to non essential physical components was a result of the underestimation of the seismic hazard (Section 1.3.2).

There were 7171 Christchurch earthquake casualties in total, even considering a number of the casualties wouldn't have required hospital treatment, the Canterbury hospital network still needed to transfer patients to other areas of New Zealand in order to relieve strain on the Christchurch hospital network. The remaining 92 patients that weren't transferred to hospitals in Canterbury were transferred to hospitals in the other regions in the South Island and the North Island. The transfer of patients to other hospitals in New Zealand accounted for the high Social performance measure in Table 5.10 for the robustness and rapidity criteria. This was because the quick transfers enabled patients to be hospitalized and treated within the first day of being injured.

The transfers to the other regions of New Zealand were by helicopter and fixed wing (Tables 5.5-5.6). The transfers by air were made possible because there was a wide range of transport services available that were capable of transferring hospitalized patients long distances (Table 5.4). The availability of air transfer resources meant that the Christchurch hospital network was able to maximize the use of residual building capacity (Table 5.10).

The factors responsible for the short term resilence of the Canterbury hospital network are as follows:

1. Continued partial functionality within the Christchurch hospital network (Table 5.8) (Table 5.10)
2. The relatively low amount of casualties requiring hospital treatment compared to the available regional hospital capacity (Section 5.2.1)
3. The availability of residual capacity within the national hospital network (Table 5.8) (Table 5.10)
4. The availability of transport resources (Tables' 5.4-5.7) (Table 5.10)
5. The ability to transfer patients quickly (Appendix N) (Table 5.10)

5.6.2 Long term resilence of Christchurch Hospital

For the purpose of this study, the resilence exhibited in the long term is defined as the period which starts 6 months after the Christchurch earthquake and is complete when the functionality of Christchurch Hospital is restored to its pre earthquake level. At present (31st March, 2013) this period is ongoing because the functionality of Christchurch Hospital has not been fully restored. Christchurch Hospital was the most strained hospital in the Canterbury hospital network following the Christchurch earthquake as a result of long term capacity loss (Table 3.3) and lengthy earthquake repair work (Section 3.2). It is also the largest hospital in Canterbury (Table 5.8) and the most important in terms of treating patients in severe conditions.

The ALOS for the two weeks before the Christchurch earthquake for all the Christchurch Hospital wards was 3.3 days (Section 5.2.3). The ALOS for the period between the 11th and the 14th of February, 2013 for all the Christchurch Hospital wards was 1.6 days. The lower ALOS for the two weeks following the Christchurch earthquake for all the Christchurch Hospital wards (2.41 days) is likely a result of transfers and discharges, which were executed in order to surge capacity and relieve strain on the hospital. The even lower ALOS (1.6 days) for the period between the 11th and the 13th of February, 2013 is likely a result of the efforts made by Christchurch Hospital to reduce the demand on in-hospital treatment, with measures such as CREST and MMS (Explained further in Section 3.3.2). Christchurch Hospital was able to reduce the demand on in-hospital treatment following the Christchurch earthquake, because the provision of healthcare services was maximised for the given capacity by the hospitals organizational structure (Table 5.10).

The functional loss calculated in Table 5.8 was less of an issue in the long term at Christchurch Hospital (Section 3.2.4) than the short term. The damage that caused the worst functional loss was remedied in the immediate days and weeks following the Christchurch earthquake because the damaged services and lifelines that contributed to the loss of the most vital functions were prioritized.

The long term challenges for resilence were a result of the permanent loss of bed capacity following the Christchurch earthquake (Section 3.3.2). As well, the earthquake damage to non essential physical elements resulted in partial lost capacity in the long term. Because, the work that was required to remediate the cosmetic earthquake damage to the interior of the hospital required areas of the hospital to be closed (Section 3.2.3). The repairs were managed with disciplined planning and collaboration between Clinical and maintenance staff (Section 3.2.3). However, insurance issues prolonged certain areas of the repair work (Section 3.2.2) which are categorized in Table 5.10 as a measure of rapidity for the organizational environment.

The factors responsible for the long term resilence of the Canterbury hospital network are as follows:

1. Relatively robust buildings, lifelines and services (Sections 3.2.2-3.2.4)
2. The outsourcing of elective surgeries to other hospitals (Section 3.3.2)

3. Community care initiatives (Section 3.3.2)
4. Well planned cosmetic damage repair work (Section 3.2.3)

5.6.3 Summary

Robustness and redundancy are measures of a hospital networks ability to withstand a seismic hazard and limit immediate functional loss. Resourcefulness and rapidity are measures which define how quickly the hospital network can regain the level of pre-earthquake functionality following an earthquake (Table 5.9). The Robustness and redundancy of the Canterbury hospital network following the Christchurch earthquake was relatively strong, because strong measures were taken by the network to mitigate earthquake damage and remain operational. Although the earthquake damage and functionality loss was relatively moderate (Table 5.8), it still required significant work in order to reinstate the Canterbury hospital networks original capacity and functionality.

The resourcefulness of the Canterbury Hospital network is the main contributing factor to the Canterbury hospital networks relatively strong rapidity. The rapidity of the functional response was strong as all the essential services were restored in the short term (Section 5.6.1). The rapidity with regard to the bed capacity wasn’t as strong, because the lost capacity was largely a result of destroyed buildings (Section 2.4.1). Replacing lost building capacity is more complicated than repairing functionality to services because it requires new building stock to be constructed (Section 3.2.2).

5.7 Conclusion

The Christchurch earthquake caused relatively little infrastructure damage and few casualties. The physical damage to facilities and transport infrastructure was not severe enough to warrant entire hospitals to be evacuated and to seriously impede the inter-hospital transfer process. However, because there was some permanent capacity loss and a number of casualties requiring treatment, hospital transfers were necessary. The transfers were necessary in order to provide continued treatment to the population, but the relatively low volume of required transfers meant that transport resources were not constrained.

The type of inter-hospital transfer process which is required after an earthquake is very unique depending on the characteristics of the earthquake, previous transfer planning and the built environment. The relative abundance of transport resources, good transfer planning and the relatively resilient built environment in Christchurch meant that fixed wing, helicopter and road transfers could all be utilized to reduce the time for patient transfers. Because fixed wing and helicopters were available patients could be transferred to hospitals situated 300km to750km away in the North Island and distant areas of the South Island.

The estimation of transfer time can be broken down into four components; the State of the patient, Residual capacity, Mode and Destination. The four components are all interconnected and influenced by a variety of factors related to the earthquake, previous transfer planning and the built environment. Hospital evacuation and transfer is identified in the literature as a source of risk for patients. If the transfer process is unplanned and time consuming the patient may be exposed to unnecessary risk. Therefore, it would pay for hospitals to evaluate the probable time required to transport patients given the expected seismic risk.

6 Chapter six: Conclusions and recommendations

Earthquakes pose a significant risk to the ability of hospitals and hospital networks to perform adequate and continuous healthcare. Hospitals and hospital networks are complex systems because they rely on a large quantity of services to provide continuous health care. Hospitals are comprised of many physical components and buildings which often have physical components added on following construction to accommodate advances in technology. The need to accommodate new technology and the wide range of services requires hospitals to constantly evolve; the continually changing nature of hospitals makes seismic risk reduction a constant challenge.

This research aims to identify and recommend ways to increase the resilience of hospitals and hospital networks to earthquake induced physical damage and organizational disruption and further define ways to provide continued healthcare following large earthquakes. The main objectives are;

- Prepare a literature review in order to draw common themes from post disaster hospital case studies. As well, the review of literature is intended to determine the key components of hospitals and hospital networks that increase resilence and impeded post disaster functionality.
- Define how the Canterbury hospital network was prepared in light of the perceived seismic hazards in the short term and long term leading up to the Christchurch earthquake and how the disaster management strategies, seismic zoning, anti-seismic building codes influenced the Canterbury hospital networks seismic resilience.
- Define how the physical and organizational elements of the Christchurch hospital network performed following the Christchurch earthquake.
- Assess the merit and apply physical and organizational seismic vulnerability assessment methodology with data from Christchurch’s post Christchurch earthquake hospital network, in order to define gaps in the methodology.
- Develop a conceptual model in order to predict the location and speed of patient redistribution following functional loss to hospitals.
- Provide recommendations for other hospital networks in seismically active cities by highlighting factors that contributed to a resilient response, and the factors that impeded functionality.

6.1 Conclusions drawn from the literature

Following the review of post disaster hospital literature it is apparent that following large earthquakes damage to services and nonstructural components in hospitals and hospital networks is far more common than structural damage (Section 2.4.2). Structural damage may be rarer but if facilities are structurally compromised beyond the level required for safe occupation the capacity will be permanently lost until the facility is transferred or replaced. Severe nonstructural damage and services damage within hospitals is highly disruptive during the emergency response phase and can even cause hospital operations to be ceased all together. Slight to moderate nonstructural damage can be remediated with continued hospital operation. However, carrying out repair work with continued operation of clinical facilities is highly disruptive and adds to staff fatigue. As well, miss-categorising nonthreatening nonstructural damage as life threatening structural damage can cause facilities to be unnecessarily evacuated (Section 2.7.1).

Hospital network resilience coincides with strong anti-seismic design criteria for structural, nonstructural and service components combined with good knowledge of the local seismic hazard (Section 2.3) and affective organisational management. However, the challenge of increasing robustness into nonstructural systems is difficult, because nonstructural systems are comprised of many unique components with differing interconnecting relationships. The relationships between nonstructural components and the structural system in some cases can encourage nonstructural damage. Non-structural and structural damage can cause or exacerbate services damage, because services are connected to both the structural and nonstructural system (Section 2.4.3). Nonstructural components are often water damaged when the complex heterogeneous water services are damaged. In summary all the groups that make up the physical components of a hospital are interconnected; the consequences of damage can negatively influence another group of components. Backup systems need to be regularly tested, seismically braced and maintained. As well they must be assessed with regards to the secondary consequences of strong seismicity in order to be resilient (Section 4.2.4).

The high complexity of hospital systems presents problems for seismic vulnerability analysis, because of the many connections between the different components and the nature by which the failures can be propagated between components. The large amount of components and their inter-connections can potentially produce numerous negative outcomes during strong seismicity. The emergency phase of a mass casualty disaster also adds complexity to hospitals and hospital networks by increasing the demand on patient care services. Therefore the emergency phase also adds complexity to seismic vulnerability analysis methodology.

6.2 Conclusions from the Christchurch Hospital network

The most disruptive damage to the Canterbury Hospital network following the Christchurch earthquake included minor structural damage to both clinical and support buildings and nonstructural damage to ceiling tiles and light fittings (Section 4.2.3). Within Christchurch there were outages to all the cities lifelines for various times, as well as damage to back-up utilities and internal services.

The nonstructural damage was more widespread and more disruptive than the minor/moderate structural damage within the Canterbury hospital network, and was especially severe in the

Christchurch hospitals. At the time of the earthquake all the hospitals complied with the current New Zealand Seismic Design Standards (Section 2.3.2)

The loss of short term and long term capacity at Christchurch Hospital was managed by outsourcing elective surgery, relocating wards to other hospitals and by reducing the demand for hospital care by implementing community care measures such as CREST and MMS (Section 4.5.2). The Christchurch earthquake proved it would be beneficial for organizational planning in modern hospitals to focus on identifying vulnerabilities in non-structural and service systems within critical facilities. Similarly to what was stated in the literature and observed in international case studies, most of the loss of capacity caused by structural damage in the Christchurch hospital network following the Christchurch earthquake is still lost 24 months after the 22nd of February, 2011

The hospital-to-hospital transfers from Christchurch Hospital to receiving facilities were not jeopardised by earthquake damage or lack of resources. The use of fixed wing and helicopter transfers greatly reduced the time taken for patients that were transferred from Christchurch Hospital. By using assumptions on the transfer path and traffic congestion it is estimated that the time of road transfers increased on average by 7 minutes per transfer in the first two weeks following the Christchurch earthquake (section 5.4). As no patients died during transfer the increase in transfer time had negligible impact, however the increase in road transfer time may have increased demand on helicopter transfers. As well, the number of earthquake casualties did not over run the regional hospital facilities (Section 4.3.1). All though some patients were transferred to other regions they were stable. The majority of the transfers from the Canterbury region were from Christchurch Hospital. Most of the transfers from Christchurch Hospital were from the Orthopaedic wards (Ward 18 and ward 19), Neurology & Neurosurgery (ward 28), the Medical Day Unit (MDU) and the Christchurch Women's Hospital maternity wards.

The public hospitals within the Canterbury hospital network operated at occupancies' in the high 90 percentile range prior to the Christchurch earthquake (which is considered very high internationally). All indications show that even with the disruption and loss in capacity the Christchurch hospital network has still provided the population with an adequate level of health care following the Canterbury earthquakes. This suggests that the Canterbury hospital network had in place or built seismic resilience into its network at an organizational level (Section 2.1.5). The consensus from individuals within the CDHB and the private sector is that the strong existing relationships between the public hospital, private hospital and general care sectors meant that the capacity redistribution and demand reducing measures were able to be planned and implemented with relative ease. As well, relationships between CDHB staff and emergency operators such as the fire service were beneficial during the emergency phase. Another factor, which helped the Christchurch hospital network response to the Christchurch earthquake, was the fact that the CDHB planned to accommodate a large increase in patients following the earthquakes, but in the end there was no large increase in patients. It was also recognised that the Darfield earthquake helped prepare the Canterbury hospital network by way of introducing backup measures and planning for the likely outcomes of another large earthquake.

Strong interconnections between individuals and organizations in the CDHB and the greater New Zealand healthcare system were fostered by the social based healthcare structure and likely increased the earthquake resilience of the network significantly (chapter 3). Where individuals are more aware of an earthquakes affect on the entire health care network rather than just the facility they operate within, then they are likely to make decisions that increase the resilience of the entire network and not just the individual facility. The positive outcome of strong hospital network connections is to streamline the outsourcing of services and redistribute capacity if required during the emergency response and recovery phases of a disaster, and ultimately insure a greater chance of continuous post disaster healthcare.

The healthcare assessment methodology which was analysed in the thesis recognises the importance of external and internal lifelines and supply networks. The lifelines and supply networks differ from the essential components of individual hospitals in that they are spatially extensive and controlled by separate stakeholders. The transport network is an essential lifeline required for redistributing capacity, wide spread destruction of transport infrastructure and increased traffic are common after large earthquakes. Traffic congestion is defined in the literature as a problem for capacity redistribution following hospital evacuations (Section 3.3.1).

Because of their wide extent transport and lifelines networks that supply and connect hospital networks respond uniquely in different sectors to seismicity. Therefore, predicting how the transport and lifelines network will be impeded depends on the how the seismicity interacts with the likely flow of people, the characteristics of the underlying land and the infrastructure. The functionality of hospitals situated outside the zone of primary physical earthquake damage may be reduced if they depend on lifelines or services situated or provided within the disaster zone (Figure 5.2). The loss of functionality caused by the secondary effects of the earthquake may also extend to hospitals beyond the zone of primary physical damage, in order to accommodate patients from the disaster zone patients may need to be discharged from hospitals nearby but not in the zone of primary damage (Section 5.3).

Closures within the transport network are dependent on the organizational environments' (Section 2.1.5) ability to mitigate and plan for damage prior to earthquakes, the perception of the risk posed by earthquake damaged infrastructure, the process of post earthquake assessment and the speed which damage is able to be repaired following the earthquake (Section 5.3).

The size and distribution of hospital to hospital transfers that may be required following an earthquake is dependent on; the estimated number of casualties, the severity of casualties, the epidemiological profile, the ALOS (under normal conditions and for earthquake casualties), the hospital capacity and the hospital functionality. The national, regional and local organizational structure controls how easily hospitals can redistribute capacity (Section 5.3).

The best application of methodology for the assessment of a hospital network is the combination of methodology that incorporates all the environments. Simply measuring the affect of the earthquake induced physical damage will exclude the importance of the built environment, organizational environment, social environment and the natural environment. The organizational environment can influence the impact the earthquake has on the physical environment by determining the level of maintenance and the seismic design standard criteria for buildings and lifelines. Post earthquake, the organizational environment influences how the damage is classified. The organizational environments role in post earthquake damage assessment is difficult, because it is highly complicated to quickly assemble assessment teams and have them organized after large earthquakes in urban areas. As well, the organizational environment influences the social environment by defining the level of care, which is available to the community and the sections of the community that have access to the healthcare (Section 2.1.5).

The WHO (2006) structural vulnerability assessment is structured to provide a vulnerability indexes to buildings using their structural characteristics and to provide the likelihood of damage to be expected in the event of an earthquake (described in terms of MMI). In this research the seismic vulnerability assessment for hospital systems proposed by WHO (2006) was applied to the Canterbury hospital network and the results were compared with the post Christchurch earthquake damage observations. The WHO (2006) methodology underestimated the seismic vulnerability of 2 out of the total of 13 buildings that were structurally damaged when the maximum MMI was used for the calculations (section 4.4).

The St George’s Cancer Care centre (which was structurally damaged) was deemed to have low vulnerability because the WHO (2006) structural vulnerability assessment methodology does not include a modifier for buildings with unbalanced mass and multiple stories in very soft saturated sediment (Section 3.5.2.1). The unbalanced mass, multiple stories beneath ground level and liquefiable soils that characterised the St George’s Cancer Care centre site caused the structural failure of the building. As well, the WHO (2006) structural vulnerability assessment does not include measures that incorporate the cumulative effect of aftershocks which may explain why the Akaroa Hospital was classed as having a low seismic vulnerability but was structurally damaged. The affect of the Canterbury earthquakes rich aftershock sequence may have had an important influence upon Canterbury’s hospitals, because with each event structural systems are likely to be weakened further.

The structural damage assessment following the Christchurch earthquake may have influenced whether or not previous structural damage was correctly identified, public outrage and over caution may have caused the closure of certain buildings. The delayed identification of the Akaroa Hospitals structural damage was due to the miss interpretation of structural damage during the early assessments. There is also the probability that aftershocks during 2011 exacerbated the Christchurch earthquake structural damage (Section 4.6.1.2).

The Canterbury inter-hospital transfer response for the first two weeks following the Christchurch earthquake was dominated by outgoing patients from Christchurch Hospital which also received the majority of the earthquake casualties. Severe earthquake casualties were transferred to ICUs as distant as the North Island, along with other non earthquake patients including geriatric patients.

The main mode of transfer for the less critical patients within Christchurch and Canterbury was via road. However, transfer by road (Table 5.7) to the hospitals in the rest of the South Island and the North Island would have taken too long. Fixed wing flights and helicopters were used for the long distance transfers in order to reduce the transfer time (Table 5.5 & 5.6).The Christchurch Airport handled all the fixed wing transfers from Christchurch Hospital

The use of helicopters and fixed wing flights to move patients within Christchurch and between cities greatly reduced the transfer travel time. This was possible because of the low number of patients requiring transfer and air resources were not stressed beyond the point where patients that needed to be transferred could not be.

The relative abundance of transport resources, good transfer planning and the relatively resilient built environment in Christchurch meant that fixed wing, helicopter and road transfers could all be utilized to reduce the time for patient transfers. Because fixed wing and helicopters were available, patients could be transferred to hospitals situated 300km to750km away in the North Island and distant areas of the South Island.

New Zealand’s hospitals can be grouped into three categories in order to determine their level of functional loss following the Christchurch earthquake (Section 5.3). Category One hospitals are classed as being completely within the disaster zone, Category Two hospitals are classed as being partially within the disaster zone and Category Three hospitals are classed as being completely outside the zone of primary physical earthquake damage (Figure 5.9). The Category One hospitals were only located in Christchurch, the Category Two hospitals that were on the edge of the zone of primary physical earthquake damage were located in the towns that are adjacent to Christchurch. All the hospitals in category Three are located either in the areas in Canterbury far away from Christchurch or the other regions in the South Island or in the North Island. The Reduction in hospital bed capacity was limited to Category One hospitals (Table 5.8).

6.3 Key recommendations

The key recommendations based on the findings and outcomes from the research are as follows:

1. Nonstructural components are easily damaged in strong seismicity; as well the repairs are costly and disruptive. Reducing the seismic vulnerability of nonstructural elements, particularly suspended ceilings (plaster tile ties) and plaster walls increases resilience. Disruptive post earthquake repairs can be avoided if all nonstructural components are constructed and managed to withstand strong seismicity.
2. Backup systems are vital following large earthquakes. Reducing the vulnerability of back up resources to the secondary consequences of seismicity such as disturbed sediment in backup generator fuel tanks and liquefied silt in back up bores is vital. Even after regular testing it is possible certain areas of vulnerability in backup systems can remain unidentified until an earthquake.
3. Lifelines are integral in insuring hospitals remain operational immediately following a large earthquake. The portions of external lifelines that serve strategic buildings like hospitals need to be differentiated from the lifelines that serve non critical buildings in order to construct and manage them to withstand strong seismicity.
4. Adaptive capacity within the hospital network's Organisational environment is strongly beneficial. Developing adaptive capacity by strengthening inter-hospital network relationships and generating plans to accommodate and redistribute capacity improves resilience. Specific consideration must be given to the framework required for inter hospital transfers and the out sourcing of services prior to earthquakes.
5. Staff ingenuity and experience plays an important role in hospitals during the emergency phase of an earthquake. When staff can adapt under pressure and with limited resources they considerably mitigate the negative effects of earthquake induced hospital disruption.
6. Diverse hospital/ hospital networks are beneficial following large earthquakes. Because earthquake damage is spatially variable; therefore if one area of a spatially diversified hospital network is lost, then another hospital which is able to perform the same functions but located in another area can accommodate the lost capacity.
7. A robust understanding of the seismic hazards probability, magnitude and spatial variability in relation to all the internal and external components that constitute a hospital network is vital in identifying how the physical and organisational components of the hospital network can be made more resilient.
8. Delayed identification of structural and nonstructural damage was a common theme observed throughout the post Christchurch earthquake Canterbury hospital network. Hospital networks

would benefit from having in place the means to conduct very detailed nonstructural and structural assessments immediately after an earthquake.

9. Inter-hospital transfers are common following destructive earthquakes. The process of transferring patients is potentially disrupted by infrastructure damage and depleted transport resources. It would be wise for hospitals to plan for the probable destination of transfers and the required resources to achieve the transfers.

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IV. Appendices

Appendix A: Hospital and provider impact surveys

Johns Hopkins University / University of Canterbury
Health System Impact Survey

Surveyor: ____ Date: _____/_____/_________

Hospital Name: ___________________________________

Hospital Address: ____

Contact name: ___________________________________

Email address: ___________________________________ Tel: _____________________

Contact name: ___________________________________

Email address: ___________________________________ Tel: _____________________

Contact name: ___________________________________

Email address: ___________________________________ Tel: _____________________

Section 1- Baseline Hospital Information

1. What is the estimated size of the population served by/assigned to this hospital?

    ____

Please fill in the following related to general hospital physical capacity and statistics in the year before the earthquake. ***Write in 'NA' if that service or those beds are not available in this facility.***				
In-Patient Capacity				
2. **Non-ICU Medical Patients/Beds** (exclude Psych)	Number of beds[1]	Annual discharges[2]	Avg. LOS (days)[3]	Avg. % occupancy[4]
a. Adult medical				
b. Adult surgical				
c. Pediatric				
d. Obstetric				
e. Other non-ICU beds (*please describe*)				
3. **Monitored beds/Non-ICU**				
a. Adult				
b. Pediatric				
4. **ICU Beds**				
a. Adult medical ICU				
b. Adult surgical ICU				
c. Pediatric ICU				
d. Other ICU beds (*please describe*)				
5. **Psychiatric patients/beds**				
6. ***Total***				
Surgical Capacity	Number of beds/rooms	Annual Procedures	Annual Births	
7. **Operating/Procedure rooms**				
a. Major/In-patient				
b. Minor/Out-patient				
c. Delivery rooms				

1. Number of physically available and staffed beds during normal operations
2. Number of annual patient discharges for each category
3. Average length of stay for each category of patient (in days)
4. Percent of each category of beds occupied on an annual basis

8. What types of surgical procedures are performed at this facility (*check all that apply*)?

a. General surgery ______
b. Cardiovascular/Thoracic ______
c. Gynecologic surgery ______
d. Neurosurgery ______
e. Otolaryngology/ENT ______
f. Ophthalmology surgery ______
g. Orthopedic surgery ______
h. Genitourinary surgery ______
i. Pediatric surgery ______
j. Other surgical procedures ______
k. None ______

Out-Patient Capacity				
9. **Emergency/Accident and Emergency Department**	Number of beds	Annual visits	Avg. LOS (hours)	Avg. % occupancy
a. Emergency Dept/A&E				
b. Ped. Emergency/A&E				
10. **Out-Patient Clinics**				
a. Adult clinics (all)				
b. Pediatric clinics (all)				
c. Psychiatric clinics				
d. Other clinics				
11. **Other out-patient clinical services** *Please describe*				

Staffing Information

12. How many physicians are on active staff (credentialed) at this facility?
    a. Total active medical staff __________
    b. Emergency/A&E department ________
    c. General or thoracic surgeons ________
    d. Orthopedic surgeons ________
    e. Primary care/Internal Medicine ________
    f. Pediatricians ________

13. How many mid-level providers (nurse practitioners, midwives, etc) work at this facility/are on staff at this facility? __________

14. How many nurses work at this facility/are on staff at this facility? __________

15. How many other clinical support staff work at this facility? __________
    a. Laboratory technicians ________
    b. Radiology technicians ________
    c. Clinical technicians/Paramedical ________
    d. Other clinical staff ________

16. How many non-clinical support staff are employed at this facility? __________

Section 2- Event Impact Assessment- Earthquake of February 22nd 2011

Now I am going to ask you a series of questions about how the hospital was impacted by the earthquake. Some of these will be related to the physical damages to the structure, others to the loss of the usual services that a hospital supplies such as surgery, laboratory testing and even laundry.

17. At the time of the earthquake how many patients were hospitalized in the facility? ___________

18. Was the hospital completely closed by the earthquake? Yes ____ No ____

19. Were there any deaths as a result of the earthquake in any of the hospital facilities?
    Yes, patient or visitor ____ Yes, staff ____ No ____
20. Did the hospital suffer any physical damage during the earthquake of February 22nd, 2011?

Yes ____ No ____

If 'No' then skip Questions 21-28

Were ***physical areas*** affected so that *the space was not usable* as a result of the earthquake? These services may have been provided in alternative areas. ***Mark an 'X' for complete loss of a service and a 'P' for partial loss, '0' for no loss and an 'NA' if that service is not offered.***

Hospital Treatment Areas	No Loss	< 24 hours	1-3 days	4-7 days	8-14 days	15-30 days	> 30 days	NA
21. **Non-ICU Floor Beds**								
a. Adult medical								
b. Adult surgical								
c. Pediatric beds								
d. Other non-ICU								
22. **Monitored beds/Non-ICU**								
a. Adult								
b. Pediatric								
23. **ICU Beds**								
a. Adult medical ICU								
b. Adult surgical ICU								
c. Pediatric ICU								
d. Other ICU beds								
24. **Psychiatric Beds**								
25. ***Total Hospital Beds Lost*** ***(estimate actual number)***								
26. **Operating/Procedure Rooms**								
a. Major/In-patient								
b. Minor/Out-patient								
c. Labor and Delivery								
27. **Out-Patient Areas**								
a. Emergency department								
b. Out-patient clinics								
c. Dialysis								
d. Other out-patient *Please describe*								
28. **Other Clinical Areas** *Please describe*								
29. **Non-Clinical Areas**								
a. Kitchen								
b. Laundry								
c. Social Work								
d. Administrative								
e. Medical records								

30. Did the hospital lose any ability to provide <u>any</u> clinical services following the earthquake?

Yes ____ No ____

If 'No' then skip Questions 31-40

Hospital services can still be provided even with the loss of physical areas by using alternative sites. Were services (or functions) usually provided by the hospital lost as a result of the earthquake? This can be due to any reason such as loss of power or water, or lack of staff.

Mark an 'X' for complete loss of a service and a 'P' for partial loss, a '0' for no loss, and an 'NA' if that service is not offered.

Hospital Services	No Loss	<24 hours	1-3 days	4-7 days	8-14 days	15-30 days	> 30 days	**NA**
31. **Accident/Emergency Services**								
32. **Out-Patient Clinic Services**								
a. Medical/Primary care								
b. Surgical clinics								
c. Ob/Gyn clinics								
d. Pediatric clinics								
33. **Surgical Services**								
a. Major operative procedures								
b. Minor procedures								
c. Endoscopic procedures								
d. Other specialty procedures								
34. **Obstetric/Delivery Services**								
35. **Rehab/Physical Therapy**								
36. **Laboratory Services**								
37. **Radiology Services**								
a. Plain radiographs/x-rays								
b. CT scans								
c. MRI								
d. Ultrasound								
e. Interventional procedures								
38. **Blood Bank**								
39. **Non-Clinical Services**								
f. Kitchen								
g. Laundry								
h. Social Work								
i. Administrative								
j. Medical records								
40. **Other** *Please describe*								

Notes:

Mark an 'X' for complete loss of a service and a 'P' for partial loss, or check the 'NA' column if that service is not offered.

Logistic Support/Infrastructure	No Loss	<24 hours	1-3 days	4-7 days	8-14 days	15-30 days	> 30 days	**NA**
41. **Electrical Power**								
a. Municipal power service								
b. Hospital back-up power								
42. **Water**								
a. All municipal water								
b. Municipal *drinking* water								
c. All hospital back-up water								
d. Hospital back-up drinking								
43. **Medical Gases**								
a. Oxygen								
b. Other gases								
44. **Suction**								
45. **HVAC**								
a. Heating system								
b. Cooling/Air conditioning								
46. **Information Systems**								
a. Computer system								
b. Medical records								
47. **Communications**								
a. Telephones, land lines- internal								
b. Telephones, land lines- external								
c. Telephones, cellular								
48. **Elevators**								
49. **Other**								
Please describe								

Please estimate the average number of days that the hospital has in-house stock of the following supplies (prior to the earthquake). **Mark 'NA' if the supply is not used at the hospital.**

Hospital Supplies	1 day	1-3 days	4-7 days	8-14 days	> 14 days	**NA**
50. **Pharmaceuticals/Medicines**						
51. **Medical Gases**						
a. Oxygen						
b. Other						
52. **Blood Products**						
53. **Diagnostic Supplies**						
c. Laboratory						
d. Radiological						
e. Other						
54. **Treatment Supplies**						
a. Dressings and splints						
b. Surgical supplies						
c. Other supplies						
55. **Support Supplies**						
d. Laundry and linens						

e. Personal care items[1]						
56. **Food**						
57. **Other**						
Please describe						

1. Toiletries, etc

Did the hospital run out of any supplies at any time after the earthquake?
Mark an 'X' for complete loss of a supply and a 'P' for partial loss, a '0' for complete loss, or check the 'NA' column if that supply is not used.

Hospital Supplies	No Loss	<24 hours	Days 1-3	Days 4-7	Days 8-14	> 14 days	**NA**
58. **Pharmaceuticals/Medicines**							
59. **Blood Products**							
60. **Diagnostic Supplies**							
f. Laboratory							
g. Radiological							
h. Other							
61. **Treatment Supplies**							
f. Dressings and splints							
g. Surgical supplies							
h. Other supplies							
62. **Support Supplies**							
i. Laundry and linens							
j. Personal care items[1]							
63. **Food**							
64. **Other**							
Please describe							

65. Were there other important pieces of equipment lost? Yes ____ No ____
Please describe

66. Were there other important services lost? Yes ____ No ____
Please describe

Section 3- Response to the Earthquake

67. Please describe the staffing of the hospital after the earthquake compared to normal staffing levels. ***H= higher than normal, N= normal number of staff, L= Lower than normal***

	>24 hours	1-3 days	4-7 days	8-14 days	>14 days	NA
a. Physicians						
b. Mid-levels/NPs						
c. Nurses						
d. Other clinical staff						
e. Other employees/support staff						

68. Please describe the demand for <u>OUT-PATIENT</u> hospital services after the earthquake compared to normal. ***H= higher/more demand than normal, N= normal, L= Less demand than normal***

Out-Patient	>24 hours	1-3 days	4-7 days	8-14 days	>14 days	NA

a. Emergency/A&E services						
b. Surgical services						
c. Medical/Primary care						
d. Ob/Gyn services						
e. Pediatric services						
f. Psychiatric services						
g. Other clinical services						

69. Please describe the demand for <u>IN-PATIENT</u> hospital services after the earthquake compared to normal. ***H= higher/more demand than normal, N= normal, L= Less demand than normal***

In-Patient	>24 hours	1-3 days	4-7 days	8-14 days	>14 days	NA
a. Surgical services						
b. Medical services						
c. Ob/Gyn services						
d. Pediatric services						
e. Psychiatric services						
f. Other clinical services						

70. Did the hospital have to evacuate ANY patients *from the hospital building* after the earthquake?
    a. ICU patients Yes _____ No _____ Number evacuated __________
    b. Non-ICU patients Yes _____ No _____ Number evacuated __________
    c. How long did it take to evacuate ALL these patients outside? (in minutes) __________

71. Did the hospital move patients *to other parts of the hospital* but still *within the hospital* because of earthquake damage?
    a. ICU patients Yes _____ No _____ Number moved __________
    b. Non-ICU patients Yes _____ No _____ Number moved __________
    c. How long did it take to transfer ALL patients within the hospital? (in minutes) __________

72. Did the hospital discharge already hospitalized patients in the first 24 hours after the earthquake to make room for earthquake-related patients?
    a. ICU patients Yes _____ No _____ Number discharged __________
    b. Non-ICU patients Yes _____ No _____ Number discharged __________
    c. How long did it take to discharge the FIRST patient? (in minutes) __________
    d. How long did it take to discharge ALL patients within the hospital? (in minutes) __________

73. Did the hospital transfer patients *to other hospitals* because of earthquake in the first week after the earthquake?

    Yes ____ No ____

74. Did the hospital accept any patients transferred *from other hospitals* as a result of the earthquake in the first week after the earthquake?

    Yes ____ No ____

75. Did the hospital accept any patients transferred *from other facilities* such as nursing homes as a result of the earthquake in the first week after the earthquake?

    Yes ____ No ____

76. If `Yes' to the above questions please fill out the following table with the number of patients transferred for each time period. ***Mark 'NA' if these transfers did not occur.***

Transfers	>24 hours	1-3 days	4-7 days	NA

a. Transferred patients *from* this hospital to another hospital				
b. Transferred *into* this hospital from another hospital				
c. Transferred *into* this hospital from another facility/nursing home				

77. How were the patients transferred between hospitals (*check all that apply*)
    Hospital-based ambulances _______
    Municipal/public ambulances _______
    Private ambulances _______
    Military vehicles _______
    Other government vehicles _______
    Private vehicles _______
    Other *(Please describe)*:
    ____

Section 4- Final Observations

78. What was the most difficult obstacle to providing care? *(Please describe)*
a. 1st day after the earthquake:

b. 1st week after the earthquake:

c. 1st month after the earthquake:

79. In your opinion what was the most important impact of the earthquake that compromised the ability of the hospital to function?

80. In your opinion what is the most important lesson for other hospitals to learn?

Johns Hopkins University / University of Canterbury

Health System Impact Survey

Clinic/Provider Survey

Surveyor: ____ Date: _____/_____/__________

Provider Name: _____________________________________ Clinic Name: ___________________

Clinic Address: ____

Email address: _______________________________ Tel: __________________

Skype: ____________________________________

First I am going to ask you a series of questions to help understand the type of care that is provided by you and this clinic.

Section 1- Clinic Description

1. What type of healthcare services are provided by this clinic/practice? *(Check all that apply)*
    a. General practice _____
    b. Internal medicine _____
    c. Ob/Gyn _____
    d. Pediatrics _____
    e. General surgery _____
    f. Specialty surgery _____
    g. Other _____ *Please describe:*____

2. What is the estimated size of the population served by/assigned to this clinic/practice? ___________

3. Does the clinic provide any of the following services on-site? (*Check all that apply)*

a. Laboratory testing _____ b. Plain x-rays ____ c. CT scans _____

d. Ultrasound _____ e. Minor surgical procedure ____ f. Physical therapy _____

g. Other _____ *Please describe:*

4. How many total providers (doctors, nurse practitioners, etc) are employed here? ___________

5. How many nurses/nurse assistants work here? ___________

6. How many other clinical support staff work here (Laboratory, etc)? ___________

7. How many other non-clinical support staff work here? ___________

8. How many physical treatment areas (beds, etc) are there? ___________

9. How many annual visits are there at this clinic? ___________

Section 2- Event Clinic Impact - Earthquake of February 22nd 2011

Now I am going to ask a series of questions about how the clinic was physically impacted by the earthquake.

10. Did the clinic building(s) suffer any physical damage during the earthquake of February 22nd, 2011?

    Yes ____ No ____

11. Did the clinic lose any ability to provide any clinical services following the earthquake?

    Yes ____ No ____

12. Was the clinic ever completely closed by the earthquake?[1] Yes ____ No ____
    a. If 'Yes', how many days?

       <1 day _____ 1 day _____ 2-3 days _____

       4-7 days _____ 8-14 days _____ >2 weeks _____

13. If closed, did you operate your business at another location?

    Yes ____ No ____

14. Did you have to evacuate staff or patients from the building after the earthquake?

    Yes ____ No ____

15. How long did it take to evacuate everybody? (in minutes) _________

16. Were there any deaths in the building(s)?

    Yes, patient or visitor____ Yes, staff ____ No ____

17. Did the clinic treat any patients injured as a result of the earthquake in the first week after the earthquake?

    Yes ____ No ____

    a. If 'Yes', estimate how many people were treated? ______

Please briefly describe the physical damage:

[1] This can be due to any reason, e.g., physical damage to the building, lack of personnel, loss of power, etc

Were important internal and external logistical services lost to the clinic as a result of the earthquake? ***Mark an 'X' for complete loss of a service and a 'P' for partial loss, or check the 'NA' column if that support service is not offered.***								
Logistic Support/Infrastructure	No Loss	<24 hours	1-3 days	4-7 days	8-14 days	15-30 days	> 30 days	**NA**
18. Electrical Power								
c. Municipal power service								
19. Did the clinic have a back up electrical supply?			Yes _____		No _____			
d. Clinic back-up power lost								
20. Water								
e. Municipal water - All								
f. Municipal water drinking								
21. Did the clinic have a back up water supply?			Yes _____		No _____			
a. Clinic back-up water lost								
22. Medical Gases								
c. Oxygen								
d. Other gases								
23. Suction								
24. HVAC								
c. Heating system								
d. Cooling/Air conditioning								
25. Information Systems								
c. Computer system								
d. Medical records								
26. Communications								
d. Telephone (land lines-internal)								
e. Telephone (land lines-external)								
f. Telephone (cellular)								
27. Elevators								
28. Other (*please describe)*								

29. Were there other important pieces of equipment lost? Yes ____ No ____
Please describe:

30. Were there other important services lost? Yes ____ No ____
Please describe

Did the clinic run out of any supplies after the earthquake?
Mark an 'X' for complete loss of a supply and a 'P' for partial loss, or check the 'NA' column if that supply is not used.

Supplies	No Loss	<24 hours	Days 1-3	Days 4-7	Days 8-14	> 14 days	**NA**
31. Pharmaceuticals/Medicines							
32. Diagnostic Supplies							
i. Laboratory							
j. Radiological							
k. Other							
33. Treatment Supplies							
k. Dressings and splints							
l. Surgical supplies							
m. Other supplies							
34. Support Supplies							
n. Laundry and linens							
o. Personal care items[1]							
35. Other							
Please describe							

Section 3- Response to the Earthquake

Please describe the staffing of the clinic after the earthquake compared to normal staffing levels by the number of days after February 22nd. ***H= higher than normal, N= normal, L= Lower than normal***

	>24 hours	1-3 days	4-7 days	8-14 days	>14 days	NA
36. Physicians/providers						
37. Nurses						
38. Other clinical staff						
39. Employees/support staff						

Please describe the demand for clinical services after the earthquake compared to normal.
H= higher/more than normal, N= normal, L= Less than normal

Out-Patient	>24 hours	1-3 days	4-7 days	8-14 days	>14 days	NA
40. Routine primary care						
41. Injury care						
42. Exacerbated chronic illnesses						
43. Ob/Gyn services						
44. Pediatric services						
45. Psychiatric services						
46. Other clinical services						

47. What was the most difficult obstacle to providing care? *(Please describe)*

1st day after the earthquake:

1st week after the earthquake:

1st month after the earthquake:

48. In your opinion what is the most important lesson for other clinics/practices to learn?

Please complete the following for each of the providers in this clinic:

Did you personally provide care to earthquake victims during the first week after the earthquake?
Check all that apply

49. Provider 1	>24 hours	1-3 days	4-7 days	NA
d. Provided care at your office/clinic				
e. Provided care at a hospital				
f. Provided care at a temporary/field hospital				
g. Provided care outside a health care facility (on the street, etc)				

50. Provider 2	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

51. Provider 3	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

52. Provider 4	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

53. Provider 5	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

54. Provider 6	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

55. Provider 7	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

56. Provider 8	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

57. Provider 9	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

58. Provider 10	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

59. Provider 11	>24 hours	1-3 days	4-7 days	NA
a. Provided care at your office/clinic				
b. Provided care at a hospital				
c. Provided care at a temporary/field hospital				
d. Provided care outside a health care facility (on the street, etc)				

Appendix B: Kafali et al., (2003) Fragility Analysis for Nonstructural Systems in Critical Facilities

Kafali et al. (2003) outlines a method for the estimation of system fragility by Monte Carlo simulation and a second crossing theory method for stochastic processes. The Monte Carlo method outlined below uses linear and nonlinear models for nonstructural components and takes into account the interdependencies between the separate components (Kafali et al., 2003).

The Monte Carlo method

The Monte Carlo method for calculating fragility involves the following calculations;

- The earthquake source to hospital site distance (*m; r*), moment magnitude and ground acceleration at the hospital site using;

$$s_{FF}(\omega, r) = \frac{1}{2\pi t_w} |a(\omega, r)|^{\,2}$$

- The absolute spectral acceleration density at the attachment points with the hospital (first floor and roof floors) using;

$$s_{G_k G_l}(\omega) = s_{FF}(\omega) \sum_{i,j=1}^{n} \phi_i(k)\phi_j(l)\Gamma_i\Gamma_j \tilde{H}_i(\omega)\tilde{H}_j^*(\omega)$$

- correlated absolute acceleration at attachment points *n* samples using;

$$\mathbf{G}^{(q)}(t) = \sum_{j=1}^{q} (\mathbf{A}_j \cos(\omega_j t) + \mathbf{B}_j \sin(\omega_j t))$$

- The *C*1 and *C*2 responses are calculated along with the correlated absolute acceleration sample by using linear/nonlinear dynamic analysis for each component. The output defines whether the nonstructural system fails (whether max*t jR*1(*t*)*j* ¸ *d*1 or max*t jR*2(*t*)*j* ¸ *d*2 occurs).

- Approximate system fragility (*m; r*) using the probability of failure (*Pf* (*m; r*)), calculated by the ratio of the number of nonstructural system failures to the sample number (*n*, *Pf* (*m; r*) ' *nf*=*n*).

Fragility surfaces for the components *C*1 and *C*2 can be obtained by the same procedure. For example, fragility for *Ci* can be estimated by *Pf;Ci*(*m; r*) ' *nf;Ci*=*n*, where *nf;Ci* is the number of times the event max*t jRi*(*t*)*j* ¸ *di* is observed.

Crossing theory method

The mean crossing rate for a system comprised of linear components can be calculated by using the fragility of the nonstructural system and the probability that the stationary systems response process R(*t*) = [*R*1(*t*) *R*2(*t*)]*T* leaves the safe set *A* = (¡*d*1*; d*1)x(¡*d*2*;*

The crossing theory fragility calculation involves the following steps;

- The earthquake source to hospital site distance (*m; r*), moment magnitude and ground acceleration at the hospital site using;

  $$s_{FF}(\omega, r) = \frac{1}{2\pi t_w}|a(\omega, r)|^{\ 2}$$

- The absolute spectral acceleration density at the attachment points with the hospital (first floor and roof floors) using;

  $$s_{G_k G_l}(\omega) = s_{FF}(\omega) \sum_{i,j=1}^{n} \phi_i(k)\phi_j(l)\Gamma_i\Gamma_j \tilde{H}_i(\omega)\tilde{H}_j^*(\omega)$$

- The spectral density nonstructural component linear responses calculated using the appropriate transfer equations outlined in the full methodology.
- The mean nonstructural component crossing rate using;

  $$P[C_i \text{ fails}] \simeq 1 - \exp\left(-\nu_{A_i, C_i} T_w\right).$$

- The upper bound mean nonstructural system crossing rate using;

  $$\nu_A \ \leq \nu_{A_1, C_1} + \nu_{A_2, C_2}.$$

- The fragility of the overall system is calculated using.

  $$\begin{aligned} P[NS \text{ fails}] &= 1 - P[NS \text{ survives}] \\ &= 1 - P[C_1 \text{ survives}, \, C_2 \text{ survives}] \\ &= 1 - P[\mathbf{R}(t) \in A, \, t \in [0, t_w]] \\ &= 1 - P[\mathbf{R}(0) \in A] \, P[N_A(t_w) = 0] \\ &\simeq 1 - \exp\left(-\nu_A \, t_w\right) \end{aligned}$$

Appendix C: WHO (2006) Nonstructural vulnerability evaluation HNVE-001/1, HNVE-001/2 and HNVE-001/3

The World Health Organization WHO; Health facility seismic vulnerability evaluation is based on estimating the expected nonstructural vulnerability and consequences for a given seismic risk. The inputs include the number of buildings, type of nonstructural elements (architectural elements, equipment, furnishings and basic installations and services), seismic intensity, type of risk and the priority of the nonstructural elements. The method is compatible with FEMA-74 which defined the "nonstructural risk ratings" that are considered in the methodologies outputs. The "nonstructural risk ratings" are as follows;

• **Life safety (LS)** risk: The risk of injury inducing failure of individual nonstructural elements such as falling ceiling tiles, not including failures of nonstructural safety systems such as fire sprinklers.

• **Property loss (PL)** risk: The risk with respect to the financial cost of damage only includes the cost of repairs and replacement of the damaged elements not the indirect damage, such as water damage from broken pipes and the loss of data from damaged computers.

The output vulnerability of the facilities and content PL is:

- *"Low (L) vulnerability"*: The component is "reasonably well anchored" and the probability it will be damaged when subjected to deformation is low
- *"Moderate (M) vulnerability"*: There is a "moderate probability" the anchored component will fail when subjected to design forces and building deformation
- *"High (H) vulnerability"*: The component is either unfastened or has inadequate fastening, the probability of damage is high when subjected to design forces and building deformation.

• **Loss of function (LF)** risk: The risk that a particular component will lose functionality including the impact of the functional loss of the component on the operational continuity of the organization, the loss of components due to external lifeline damage is not included.

The outputs for the LF category are:

- *"Low (L) consequences"*: The component will likely not injure occupants or cause functional discontinuity when damage due to its physical characteristics and location in the building.
- *"Moderate (M) consequences"*: The component has a moderate likelihood of injuring occupants or causing functional discontinuity when damaged due to its physical characteristics and location in the building.
- *"High (H) consequences"*: When damaged the component will very probably injure or kill inhabitants and compromise the hospitals ability to operate continuously.

The risk ratings are based on the assumption that the component isn't seismically anchored or braced in any way and that the component's located in a low-rise building or close to the ground level in a high rise building.

The vulnerability/consequences level is determined according to the ranges of TPL or TLF values given in Table 3.5 and Annex 1. The "nonstructural vulnerability/consequences level" is calculated by firstly determining the total PL (TPL) and total LF (TLF) using the following equations;

TPI= [N L x (1) NM x (2) NH x (3)] TIF = [N L x (1) NM x (2) NH x (3)]

where NL, NM and NH are the number of L, M and H risk ratings, respectively, for the corresponding seismic intensity and group of nonstructural elements; (1), (2) and (3) are weighting factors; and NE is the number of the elements under consideration. The vulnerability/consequences level is determined by using Table 3.1.

Table C.1: Vulnerability/consequences level (WHO 2006).

Rating	Low	Moderate	High
Vulnerability level (TPL)	1- 1.7	1.7-2.3	2.3-3
Consequences (TLF)	1- 1.7	1.7-2.3	2.3-3

Appendix D: WHO (2006) Structural vulnerability assessment HSVE-001 and HSVE-002

Structural damage is commonly the broadest calculation for an individual hospital as there are less interacting components than the nonstructural or organizational system of a large hospital. The WHO 2006 structural vulnerability function has five damage states. The states are used to characterize the varied degrees of damage: (1) nonstructural damage; (2) slight structural damage; (3) moderate structural damage; (4) severe structural damage; and (5) collapse. The net risk of earthquake damage is calculated using the following equation;

$\mu_{\mathbf{D}} = 2.5[I + \tanh((1+0.125\ TV_I - 13.1)/2.3)]$

Where μ_D is the mean damage grade, I is the EMS-98 (Table 3.2) seismic intensity and TV_I is the total vulnerability index. The equation incorporates modifying indices including critical building elements such as the foundation type, the numbers of stories, the building code category, construction type, soil type, level of maintenance and ground slope. As well, soft stores and short columns are included as modifiers (Table 3.7). The mean damage grade is given by the European Macro seismic Scale (EMS-18 1998). EMS-98 classifies damage to buildings into five grades, as shown in Table 1. (Wenzel et al., 2008).

Table D.1: EMS-98 classification of damage severity (Wenzel et al. 2008)

Damage Grade (EMS-98)	Description	Damage ratio (%)	CDF (%)	Severity
Grade 1: Negligible to	No structural damage	0-1	0.5	Slight

Slight damage	Slight nonstructural damage			
Grade 2: Moderate damage	Slight Structural damage Moderate nonstructural damage	1-20	10	Slight
Grade 3: Substantial to heavy damage	Moderate structural damage Heavy nonstructural damage	20-60	40	Moderate
Grade 4: Very heavy damage	Heavy structural damage Very heavy nonstructural damage	60-100	80	Major
Grade 5: Destruction	Very heavy structural damage	100	100	Major

Appendix E: WHO (2006) Administrative/organizational vulnerability evaluation assessment HOVE-001/1 and HOVE-001/2

Each of these parameters corresponds to the ability of the medical service to fulfill its tasks under both normal and emergency conditions and is rated according to the following scale:

1) *Optimal*: Efficient allocation of resources and personnel.
2) *Adequate*: Acceptable allocation of resources and personnel; operation can proceed normally.
3) *Minimal*: Barely acceptable allocation of resources or personnel; operation can proceed with certain restrictions.
4) *Inadequate*: Unacceptable assignment of resources or personnel; severe limits on the service in question or impossibility of carrying out the service in question.

The overall capability of the health facility to meet its operational demands under normal and emergency conditions is shown by the ratings given to the medical services with an importance index of 5, 4 or 3, since those services are the most important in the case of an emergency. An overall capability rating of “high” means that all medical services with an importance index of 5 or 4 must have all parameters rated 1 or 2 to be deemed resilient. Those with an importance index of 3 can have an occasional rating of 3. If any of the parameters related to services with an importance index of 5 or 4 are rated 3 (minimal) or 4 (inadequate), the overall capability of the health facility is rated “moderate” or “low”.

Appendix F: Modeling coordination in hospital emergency departments through social network analysis following disasters (Hossain et al., 2012)

The method proposed by Hossain et al. (2012) utilises the coordination theory (explained below) to measure the degree to which connections, centrality and density affect the performance of coordination in emergency departments (ED) where coordination is vital in providing continued healthcare. Hossain et al. (2012) defines coordination as; “two or more actors who perform particular tasks to achieve common goals”. Coordination is further defined in a hospital as a “producer consumer relationship” between the clinical staff (producer) and the patients (consumer) the performance coordination time variables quantify the efficiency which the ED is operating at and are as follows:

- Time taken for the full diagnosis of a patient (from arrival at reception till admission, discharge or transfer).
- Time taken for diagnosis (dependent on the priority of the patient and the number of patients waiting).
- Average waiting time.
- Average Length of stay (ALOS) in the ED.

ii. The hospitals quality of service is measured from three perspectives;

a) The hospitals' medical/physical characteristics (structure).
b) How patients are processed in the hospital (process).
c) The patients health after treatment (outcome).

The quality of ED coordination is quantified by:

i. Revisits; Number of patients who have revisited the ED within 72 hours (Miro et al., 2004).
ii. Deaths; The ratio of deaths in the ED compared to the number of people seen in ED (Miro et al., 2004).
iii. Flights; Number of undiagnosed patients who have left the hospital (Miro et al., 2004).

Performance of coordination in the social network

The performance of ED coordination is influenced by the centrality of the network, density and the characteristics of connections. The 'Centrality of the network' is a concept where the 'star' (most influential part of the system) can impact the ED coordination performance by influencing the other individuals. Density is defined as the connections between points or 'actors' in the network. The 'degree of connection' is defined by the number of relationships in the network.

The following hypothesises proposed by Hossain et al. (2012) are possible for the performance of the ED coordination;

Hypotheses 1: Performance of coordination in the emergency department is influenced by the social network (Hossain et al., 2012).
Hypothesis 1a: Performance of coordination in the emergency department is influenced by the centrality of the network (Hossain et al., 2012).

Hypothesis 1b: Performance of coordination in the emergency department is influenced by the density of the network (Hossain et al., 2012).
Hypothesis 1c: Performance of coordination in the emergency department is influenced by the degree of connections in the network (Hossain et al., 2012).

Quality of coordination in the social network

The quality of coordination within an emergency department focuses on measuring the processes or what is done to patients and outcomes or how patients do after health care interventions. To measure the quality of coordination, we are focused mainly on the outcomes and how the outcomes may be influenced by network interactions.

The measures of quality are the same for Performance of coordination in the social network; 'patients revisited within 72 hours', 'deaths within the emergency department' and 'patients vacated prior to being seen by physician'. Centrality and density can also be assumed to influence the quality of care provided by the individual actors. The connections between actors affect the quality of coordination, by increasing the connections between actors a higher degree of communication and thus quality of coordination may be achieved. However it has been suggested by Coiera and Tombs (1998) that increased communication beyond a certain point may negatively affect the performance of individual's (Coiera et al., 1998).

The following hypothesises proposed by Hossain et al. (2012) are possible for the Quality of coordination in the social network;

Hypotheses 2: Quality of coordination in the emergency department is influenced by the social network (Hossain et al., 2012).
Hypothesis 2a: Quality of coordination in the emergency department is influenced by the centrality of the network (Hossain et al., 2012).
Hypothesis 2b: Quality of coordination in the emergency department is influenced by the density of the network (Hossain et al., 2012).
Hypothesis 2c: Quality of coordination in the emergency department is influenced by the degree of connections within the network (Hossain. et al., 2012).

Appendix G: Organizational model of a hospital system, Cimellaro et al. (2010)

This thesis describes a model to quantify resilience of hospital networks that include both technical and organizational aspects as well as the impact of the damage of the roadway system. Each hospital in the network is modeled using a meta-model (Cimellaro et al., 2008) that is able to estimate the hospital resilience and incorporate the influence of the structural damage in the organizational model. The damage of the road network is evaluated in increments of the travel time (Werner et al., 2006)

Cimellaro et al., (2010) defines a method for calculating the functionality of individual hospitals by using waiting time (WT) in an Emergency Department (ED) as a key parameter in the quantification of the quality of service (QS). WT is defined by the time taken between the request for care by the patient and the provision of the care by the hospital, it is determined by the number of; staff on duty, labs, beds (B) and operating rooms (OR). The outcome of the model is the qualitative functionality (Qqs), which is calculated using the outcomes of the quality of service (QS). And the quantitative functionality (Qls) related to the losses in the healthy population calculated with the variables mentioned above (Cimellaro et al., 2010).

The required data is as follows:

- (Wt) waiting time in emergency department (saturated or unsaturated)
- (B) Number of spare beds
- (OR) Operating rooms
- (WT0) Waiting time during normal unsaturated conditions
- (WT(t)) Waiting time during saturated conditions
- (NTR) Number of patients treated under saturated conditions (indicator of functionality)
- (Ntot) Total number of patients requiring treatment
- (NNTR) Total number of patients not treated

The first Qualitative functionality (1) is a linear combination of the two functions, Qqs,1(t)and Qqs,2(t), expressed in equations 2 and 3. Alpha (α) is a weight factor that combines the two functions describing the behavior in non saturated and saturated conditions. In non saturated conditions the patient arrival rate is below the rate of treatment, $\lambda \leq \lambda U$, where λU is the patient arrival rate in saturated conditions, the quality of care is expressed by the function Q qs 1(t). The loss of the healthy population is related to the patients that are not treated, so in saturated conditions when $\lambda > \lambda U$, the function Qqs,2(t) will be derived from equation (3).

Where WT_{crit} is the critical waiting time of the hospital in saturated conditions, U; WT_0 is the waiting time in normal operative conditions when = 0 and WT(t) when = (t).When the hospital operates in saturated conditions, it is not able to guarantee the normal level of QS, because the main goal is to provide treatment to the most number of patients. In this case the number of patients treated (N_{TR}) is the indicator of functionality (Q). The quantitative functionality (Qls(t)) is then defined as a function of the loss (L(t)), which are defined as the total number of patients not treated (N_{NTR}) versus the total number of patients requiring treatment (N_{tot}). In this case, the functionality is defined in equation (4)

3. $QQS(t) = (1-a)QQS,1(t) + aQQS,2(t)$
4. $QQS(t) = [\max(WTcrit - WT(t)),0)]/WTcrit$ if $\lambda \leq \lambda u$
5. $QQS(t) = WTcrit/[\max(WTcrit, WT(t))]$ $\lambda \leq \lambda u$
6. $QLS(t) = 1-L(t) = 1-[NNTR(t)]/[Ntot(t)] = [NTR(t)]/[Ntot(t)]$

The total number of patients requiring care (Ntot) and the NNTR are given by the formulas;

7. $Ntot(t) = \int_{to}^{t0+t} \lambda(\tau) \cdot d\tau$;
8. $N_{NTR}(t) = 1 - NTR(t) = 1 - \int_{to}^{t0+t} \min(\lambda(t), \lambda u) \cdot d\tau$

The total functionality (Q(t)) of the hospital is then shown as:

9. $Q(t) = QQS(t) \cdot QLS(t)$

(Cimellaro 2010)

Appendix H: Vulnerability assessment and seismic risk reduction strategies of hospitals in Basilicata region (Italy) (Masi et al., 2012).

Masi et al., (2012) defined the “Vulnerability assessment and seismic risk reduction strategy” In order to mitigate the risk of earthquake induced damage to the health care network in Basilicata Italy.

The methodology consists of;

7 The extensive analysis of current seismic vulnerability in hospital facilities.
8 The financial estimation of seismic strengthening methods and the level of risk deemed tolerable.
9 The calculation of “time-risk” curves showing the continuous reduction of seismic risk for the whole building considering strengthening options and their financial availability.
10 The analysis of the results achieved by the strengthening strategies in order to define the most affective risk reduction strategy.
11 The prioritisation of a seismic vulnerability intervention timescale.

(Masi et al., 2012).

The seismic vulnerability of buildings is calculated as a ratio of the buildings capacity to withstand PGA and the demand of the building to withstand PGA. Masi et al. (2012) defines the demand period as100 years with an exceedance probability of 10% for SLV and 63% for SLD. The seismic risk indexes for Life Safety (SLV) and Damage Limitation (SLD) limit states are calculated with the following equations:

Life Safety (SLV) $\alpha_{SLV} = \frac{PGA_{SLV}}{PGA_{950y}}$ Damage Control (SLD) $\alpha_{SLD} = \frac{PGA_{SLD}}{PGA_{101y}}$

(Masi et al., 2012).

Where; (PGA_{SLV}) equals the Peak Ground Acceleration value causing severe structural damage, (PGA_{SLD}) equals the value causing nonstructural damage, αSLV is the seismic risk index related to the structural safety, αSLD is the capability of the building avoiding unacceptable nonstructural damage. Masi, G et al (2012) states values close to 1.0 are acceptable according to seismic code requirements for new buildings, values lower than 1.0 are deemed to have excessive seismic risk levels (Masi et al., 2012).

Four models between current αSLV values and estimated costs have been proposed considering different buildings (Table 3.3). Table 3.3 reflects that in 1972 a new structural code came into force in Italy determining remarkable changes to design and construction activities of RC structures (Masi 2003).

Table H.1: Summary of provided cost models (Masi et al., 2012).

Cost model	Model Criteria of Strategic
N1	Full retrofit of all buildings achieving α_{SLV}=1
N2	Full retrofit α_{SLV}=1 of all post-1972 building and pre-1972 buildings with α_{SLV} <0.8
N3	Full retrofit achieving α_{SLV}=1 of all buildings with α_{SLV} <0.8
N4	Upgrading of buildings having 0.2<α_{SLV} <0.8 achieving α_{SLV} <0.7

The time risk curves outlined in this method depend on the strengthening strategy and the ratio between the available and the required financial resources. An index has been defined by Masi et al., (2012) in order to generate the risk curves. The outputs are constrained to the seismic hazard and vulnerability of the buildings, the number of people at risk (exposure) is not included. The number of individuals in the hospital can be assumed to be proportional to the net floor area. Also, the intervention costs are assumed to be proportional to the floor area. An index (ā) is used to quantify the life safety risk posed by the hospital starting from each buildings αSLV value. The ā index value is calculated using the following equation;

$$\bar{\alpha}(t) = \frac{\sum \alpha_i(t) \cdot S_i}{\sum S_i}$$

Where;

- αi (t); is the risk index αSLV of the "i-th building" at the time (*t*).
- Si; is the total floor area of the "i-th building".

αSLV and ā(t) have an inverse proportional relationship with the risk level, thus, the following equation can be used as a global risk index:

$$IR(t) = 1 - \overline{\alpha}(t)$$

Appendix I: Post Disaster Needs Assessments (PDNA)

The Health sector assessment and analysis frame work method is comprised of an assessment and analysis matrix that outlines a structure for the evaluations of; the changes in the epidemiology of the burden of disease (BoD), the physical damage, the performance of the hospitals organizational structure and the performance of six interdependent "building blocks" (service delivery, health workforce, information, medical products, financing and leadership). The methodology incorporates the influence of the assets, stakeholders, and hospital processes' and how a disaster may affect them.

The assessment is not limited to health sector buildings but also encompasses the recovery and emergency preparedness plans. A range of the required budgets for the implementation of the national safe and prepared hospital programme (not including implementation of extensive structural or nonstructural measures) are also included in the methodology.

The WHO defined a number of subsectors for the health services building blocks (PDNA 2010). The following minimum services need to be available during the recovery phase in order for the hospital to maintain operational continuity. The essential minimum services have to be assessed with respect to the regional and national epidemiological profile including the change in epidemiological requirements during the response phase of a disaster.

- Child Health, Nutrition,
- Communicable diseases,
- General clinical services,
- Non Communicable Diseases (including injuries and Mental Health), and Environmental Health,
- Sexual and reproductive health (including STI, HIV/AIDS, Maternal and Newborn Health, and clinical management of sexual violence).

The sub-sectors also guide the assessment of the pre-existing BoD related to each subsector and whether it was affected directly or indirectly. By assessing the changes in subsectors, the morbidity attributed to the disaster may be calculated. The performance and capacity of the hospitals health programmes to address the morbidity are also assessed.

3.3.3.1 Health sector assessment and analysis matrix

The analytical matrix (Table 3.4) provides a structure for the estimation of damage and losses in the health sector. The matrix aims to identify the critical problems (headings on the top row and left column) that impede the health system's ability to respond and define strategies to address the issues. The cost of damages and losses calculation is defined in the ECLAC (2003). ECLAC

Table I.1: Analytical matrix for the health sector PDNA and RF (PDNA 2010)

Health Programmes and health system functions	Pre-crisis challenges baseline indicators	Impact of the crisis, key challenges for early recovery	Humanitarian response	Response for recovery, Strategy for reconstruction	Products & expected results for recovery, short and medium term	Activities and resources for the short and medium term	Key indicators for monitoring	Estimated costs for the RF
1a Service delivery; health programmes								
1b service delivery; organization and management of services, including. The health network (infrastructure, equipment, transport)								
2. leadership and governance								
3. Human resources for health								
4. Health information system								
5. Health financing								
6. Medical products vaccines and technology								

By adding key indicators and examples of minimal qualitative data requirements in the analytical matrix, it becomes a standardized protocol for assessment data collection and analysis, guided by the headings and the indicators in the template. The methodology also includes a table for examples of key indicators for the assessment of the pre-disaster baseline within each health subsector and for the health system building blocks. The choice of indicators are reviewed by age and sex and adapted based on the nation's epidemiological characteristics. The table also provides examples of typical impacts and issues for the emergency and recovery phases.

The methodology doesn't fully assess the disaster preparedness and risk reduction plans; however the method defines gaps that need to be addressed and a constrained budget to accomplish the risk reduction. Estimates are included in the methodology for the additional costs of making facilities risk resilient. The cost of constructing new resilient buildings is stated at 4-8% of the original cost, whereas retrofitting an existing building to be resilient is estimated to cost 20-25% of the original cost.

Appendix J: Methodology for rapid seismic risk assessment of health structures: Case study of the hospital system Florence, Italy (Miniati et al., 2012)

The aim of Miniati et al. (2012) is to build on prior reliability analysis methodology, flow modelling methodology, dynamic simulation methodology and numerical seismic analysis methodology in order to develop a rapid risk assessment method for health structures. Some prior holistic healthcare methods are affective at taking into account the complexity of the organization, but they are not robust enough when real data is used. Others methods work better when real data is used, but gaps are apparent in the outputs (Miniati et al., 2012).

Miniati et al. (2012) is a proposed integrated method, designed to find weaknesses in hospital networks using a holistic approach which goes beyond the structural components. The method is based on the combination of the two following research concepts: the theory of complex systems analysis using the Leontief input–output inoperability model, and the rapid WHO seismic vulnerability assessment. The method was implemented within Florence’s (Italy) hospital network which consists of five main hospitals. The rapid spatial and temporal seismic exposure analysis is for two situations: during the day, as well as during holidays or the night-time. (Miniati et al., 2012).

Appendix K: The calculation of travel time by road for transfers from Christchurch hospital to other hospitals (Rhise network)

Hospital	Possible Route	Distance (m)	Speed	Speed (m/s)	Time (s)	Total Distance (km) by road Between Christchurch Hospital and receiving facility under normal conditions	Total Time (min)	Number of patient transfers received	Mode of transfer
Southern Cross	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	5.3	13	-	Road
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	450	20-30km/h use 25 km/h	6.944	64.8				
	Holy Rd	650	20-30km/h use 25 km/h	6.944	93.6				
	Springfield	270	20-30km/h use 25 km/h	6.944	38.88				
	Durham St	300	20-30km/h use 25 km/h	6.944	43.2				
	Sum of remaining distance small roads and roundabouts	680	Use 25km/h	6.944	97.92				
Hillmorton	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	4.5	13	**4**	Road
	Riccarton Ave	600	<20km/h use 15km/h	4.167	144				
	Mandeville St	850	use 15km/h	4.167	204				
	Blenheim Rd	260	<20km/h use 15km/h	4.167	62.4				
	Whitleigh Ave	900	use 25 km/h	6.944	129.6				
	Sum of remaining distance small roads and roundabouts	590	use 25 km/h	6.944	84.96				
St Georges	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	5.3	13	**1**	Road
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	1400	20-30km/h use 25 km/h	6.944	201.6				

	Sum of remaining distance small roads and roundabouts	950	use 25 km/h	6.944	136.8				
Parklands hospital	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	6.1	15	**1**	Road
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	2500	20-30km/h use 25 km/h	6.944	360				
	Sum of remaining distance small roads and roundabouts	650	use 25 km/h	6.944	93.6				
Princess Margaret's	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	8.3	19	**41**	Road
	Deans Ave	1200	<20km/h use 15km/h	4.167	288				
	Moorhouse	450	<20km/h use 15km/h	4.167	108				
	Lincoln	1000	Use 25km/h	6.944	144				
	Barrington	3000	Use 35km/h	9.722	308.6				
	Cashmere	900	Use 35km/h	9.722	92.57				
	Sum of remaining distance small roads and roundabouts	450	use 25 km/h	6.944	64.8				
Rosewood rest home	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	12	29	**1**	Road
	Deans Ave	1200	<20km/h use 15km/h	4.167	288				
	Moorhouse	450	<20km/h use 15km/h	4.167	108				
	Lincoln	1000	Use 25km/h	6.944	144				
	Brougham st.	4000	1/2 b/w 20-30km/h and 1/2 b/w 30-40km/h so use 30km/h	8.333	480				
	Ensors	1100	30-40km/h use 35km/h	9.722	113.1				
	Aldwin	1000	30-40km/h use 35km/h	9.722	102.9				
	Buckleys	1000	<20km/h use 15km/h	4.167	240				

	Sum of remaining distance small roads and roundabouts	950	use 25 km/h	6.944	136.8				
Burwood Hospital	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	16	27	**41**	Road
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	1500	20-30km/h use 25 km/h	6.944	216				
	Innes Road	1300	35km/h	9.722	133.7				
	Cranford St.	2200	40-50km/h use 45km/h	12.5	176				
	Queen Elizabeth	5600	50+km/h use 55	15.28	366.5				
	Burwood Rd	1100	use 35km/h	9.722	113.1				
	Mairehau rd	500	use 35km/h	9.722	51.43				
	Sum of remaining distance small roads and roundabouts	850	use 25 km/h	6.944	122.4				
Lincoln	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	20.3	38	**24**	Road
	Riccarton Ave	3300	<20km/h use 15km/h	4.167	792				
	Main South Rd	2500	use 20km/h	5.556	450				
	Springs Rd	12600	use 55 km/h	15.28	824.7				
	Sum of remaining distance small roads and roundabouts	600	use 25 km/h	6.944	86.4				
Rangiora	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	32.2	49	**29**	Road
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	3100	20-30km/h use 25 km/h	6.944	446.4				
	Main North Rd	1200	<20km/h use 15km/h	4.167	288				
	Main North Rd	6000	40-50km/h use 45km/h	12.5	480				
	Rest of the way to Rangiora	18400	use 55km/h (average from google maps)	15.28	1204				

	Sum of remaining distance small roads and roundabouts	550	use 25 km/h	6.944	79.2				
Ellesmere	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	40.8	58	**0**	Road
	Riccarton Ave	3300	<20km/h use 15km/h	4.167	792				
	Main South Rd	2500	use 20km/h	5.556	450				
	Rest of the Way to Ellesmere	33200	use 58km/h (average from google maps)	16.11	2061				
	Sum of remaining distance small roads and roundabouts	500	use 25 km/h	6.944	72				
Darfield	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	44	52	**2**	Road
	Riccarton Ave	3300	<20km/h use 15km/h	4.167	792				
	Yaldhurst Rd	5400	50+km/h so use 55km/h	15.28	353.5				
	Rest of the way to Darfield	33600	use 67km/h (average from google maps)	18.61	1805				
	Sum of remaining distance small roads and roundabouts	400	use 25 km/h	6.944	57.6				
Oxford	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	57.3	61	**29**	Road
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	3100	20-30km/h use 25 km/h	6.944	446.4				
	Main North Rd	1200	<20km/h use 15km/h	4.167	288				
	Main North Rd	6000	40-50km/h use 45km/h	12.5	480				
	Rest of the way to Oxford	43300	use 81km/h (average from google maps)	22.5	1924				

	Sum of remaining distance small roads and roundabouts	750	use 25 km/h	6.944	108				
Waikari Hospital	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	78.9	82	**3**	Road
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	3100	20-30km/h use 25 km/h	6.944	446.4				
	Main North Rd	1200	<20km/h use 15km/h	4.167	288				
	Main North Rd	6000	40-50km/h use 45km/h	12.5	480				
	Rest of the way to Waikari	65000	use 74km/h (average from google maps)	20.56	3162				
	Sum of remaining distance small roads and roundabouts	650	use 25 km/h	6.944	93.6				
Akaroa Hospital	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	83.7	83	**4**	Road
	Deans Ave	1200	<20km/h use 15km/h	4.167	288				
	Moorhouse	450	<20km/h use 15km/h	4.167	108				
	Lincoln	2400	Use 25km/h	6.944	345.6				
	Rest of the way to Akaroa	77700	use 70km/h (Average from google maps)	19.44	3996				
	Sum of remaining distance small roads and roundabouts	650	use 25 km/h	6.944	93.6				
Ashburton Hospital	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	85.2	87	**20**	Road/helicopter
	Riccarton Ave	3300	<20km/h use 15km/h	4.167	792				
	Main South Rd	1600	<20km/h use 15km/h	4.167	384				
	Main South Rd	2500	20-30km/h use 25 km/h	6.944	360				
	Main South Rd	1400	30-40km/h use 35km/h	9.722	144				
	Rest of the Way to Ashburton	74600	use 80km/h (average from google maps)	22.22	3357				

	Sum of remaining distance small roads and roundabouts	500	use 25 km/h	6.944	72				
Timaru	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	163	150	**14**	Road/helicopter
	Riccarton Ave	3300	<20km/h use 15km/h	4.167	792				
	Main South Rd	1600	<20km/h use 15km/h	4.167	384				
	Main South Rd	2500	20-30km/h use 25 km/h	6.944	360				
	Main South Rd	1400	30-40km/h use 35km/h	9.722	144				
	Rest of the Way to Timaru	153000	use 76.5km/h (average from google maps(	21.25	7200				
	Sum of remaining distance small roads and roundabouts	-100	use 25 km/h	6.944	-14.4				
Kaikoura Hospital	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	182	151	**0**	Road/helicopter
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	3100	20-30km/h use 25 km/h	6.944	446.4				
	Main North Rd	1200	<20km/h use 15km/h	4.167	288				
	Main North Rd	6000	40-50km/h use 45km/h	12.5	480				
	Rest of the way to Waikari	168000	use 82.5km/h (Average from google maps)	22.92	7331				
	Sum of remaining distance small roads and roundabouts	750	use 25 km/h	6.944	108				
Grey Base	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	238	190	**3**	Road/helicopter
	Riccarton Ave	3300	<20km/h use 15km/h	4.167	792				
	Yaldhurst Rd	5400	50+km/h so use 55km/h	15.28	353.5				
	Rest of the way to Grey Base	228000	use 81km/h (Average from google maps	22.5	10133				

	Sum of remaining distance small roads and roundabouts	0	use 25 km/h	6.944	0				
Wairau	Riccarton Ave	1300	30-40km/h use 35km/h	9.722	133.7	313	247	**1**	Road/he licopter
	Deans Ave	550	<20km/h use 15km/h	4.167	132				
	Harper Ave	1100	20-30km/h use 25 km/h	6.944	158.4				
	Papanui Rd	3100	20-30km/h use 25 km/h	6.944	446.4				
	Main North Rd	1200	<20km/h use 15km/h	4.167	288				
	Main North Rd	6000	40-50km/h use 45km/h	12.5	480				
	Rest of the way to Wairau	299000	use 82.5km/h (Average from google maps)	22.92	13047				
	Sum of remaining distance small roads and roundabouts	750	use 25 km/h	6.944	108				

Appendix L: ALOS (days) for all patients in the Christchurch Hospital (non-earthquake and earthquake related patients) following the Christchurch earthquake

	Date																
Admit Ward	22/02/2011	23/02/2011	24/02/2011	25/02/2011	26/02/2011	27/02/2011	28/02/2011	1/03/2011	2/03/2011	3/03/2011	4/03/2011	5/03/2011	6/03/2011	7/03/2011	8/03/2011	9/03/2011	Daily Average
ADC - Acute Dialysis Centre	0	-	0	0	-	-	0.5	-	0	0	0	-	-	0	0	0	0.05
AMAU - Acute Medical Assessment Unit	0.73	2.04	4.92	3.64	1.75	2.93	2.93	3.52	3.65	3.46	3.29	5.47	4.16	2.96	3.9	3.64	3.31
BMTU - Bone Marrow Transplant Unit	1	0	4.5	-	0	6	1	8.5	0.2	0	4	0.5	-	1	9	6	2.98
CAA - Child Acute Assessment	2.45	1.14	0.77	1.07	1.33	1.33	0.7	0.6	2.11	4.67	1.58	1.22	0.43	1	0.73	0.91	1.38
CATH - Cardiology Day Unit	0.14	-	-	-	-	3	-	1	0	-	0	-	-	0.5	0.71	0.5	0.73
CCU - Coronary Care Unit	2.4	2.17	-	1	-	-	5.25	-	2	-	-	18	-	-	2.5	4.5	4.73
CHOC - Childrens Haem/Onc Centre	0	5	6	0	3	4	12.8	7	-	-	0	-	-	2	0	2.67	3.54
CICU - Cardiac Intensive Care Unit	5	-	13	-	3	25	-	-		-	-	-	-	4	-	5	9.17
CTW - Cardiothoracic Ward	-	1	-	0	-	-	-	-	-	-	-	-	-	11.3	-	6	4.58
DOSA - Day of Surgery Admissions	2.36	-	-	-	-	-	-	-	-	-	-	-	-	0.8	1.25	1.67	1.52
DSU - Day Surgery Unit	0.57	-	-	-	-	-	-	0.08	0	0.1	0	-	-	0.06	0.3	0.11	0.15
EO - Emergency Observation Unit	1	0.83	0.39	0.3	1	0.29	0.67	0.25	1.69	1	0.38	1.15	0.67	1.75	0.4	0.43	0.76
GAU - Gynae Assess Unit	0	0.25	0	1.29	0.33	-	0	1	0	0	0.4	1.5	0.75	0.88	0	0.3	0.45
GLM - Gynae Lynd Med	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3
GLS - Gynae Lynd Surg	0	-	-	-	-	-	0	0	-	0	-	-	-	0	0	-	0
GSD - Gastro Day Ward	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2
GYU - Gynaecology Ward, Level 2	1	3.5	-	-	0	-	7	1	-	0	-	-	-	8	-	0.5	2.62
HDTC - Home Dialysis Training Centre	0	-	-	0	-	-	-	-	-	-	-	-	-	-	-	-	0
HDW - Haematology Day Ward	0	-	-	-	-	-	-	0	0	0	0	-	-	0	0	0	0
ICU - Intensive Care Unit	2.43	-	4	2.5	5	3.67	23	-	-	14	-	9	12	1	-	-	7.66
MDU - Medical Day Unit	1.06	0	0	0	-	-	0	0	0.45	0	0	-	-	0	0	0	0.13

NED - CWH Labout Ward	8.15	1.2	2.12	2.65	3.73	0.89	5.67	2	1.5	2.83	3.25	4.38	1.43	1.95	1.9	2.07	2.86
NIC - Neonatel Intensive Care	3	-	-	-	-	1	-	-		-	-	-	-	-	-	2	2
NIM - Neonatal Unit Mothers	4	-	1	0.5	6	2	-	-	3	-	2	-	-	-	-	-	2.64
OBD - CWH Labour Ward	0.87	0.93	1.61	2.04	1.33	0.86	1.47	1.73	1.57	1.55	1.32	1.94	2.33	1.29	1.7	1.58	1.5
OBM - Maternity Ward	-	-	-	-	-	-	-	-	-	-	4	-	-	2.5	5	-	3.83
ODA - Obsetric Day Assessment Unit	-	-	-	-	-	-	-	-	0	-	-	-	-	0	-	-	0
OPAES - Outpatient Extended Stay	-	-	-	-	-	-	-	-		-	-	-	-	0	-	-	0
OTU - Orthopaedic Trauma Unit	9	-	-	-	25	-	5	-	-	7	-	-	-	-	7	-	10.6
PDP - Paediatric Day Patients	0	-	-	-	-	-	-	-	0	-	0	-	-	1	0	0	0.17
PHDU - Paediatric Hdu	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-	-	5
PM3B - General Medicine	-	-	-	-	-	-	-	-	-	-	-	-	-	3.5	-	-	3.5
SARA - Surgical Assess Review Area	4.35	0.63	1.5	2	2.8	3.42	3.56	2.71	4	1.92	1.7	3.75	1.6	2.22	0.8	3.07	2.5
SPCU - Surgical Progressive Care Unit	6	-	-	-	-	4.5	-	4	-	-	-	-	-	31	-	9	10.9
UU - Urology Unit	1	3	-	0	-	0	0	-	-	-	-	-	-	0	-	-	0.67
WD12 - Ward 12 Cardiology	4.86	1.75	1.75	2.2	1.71	1.88	1.7	2.67	1.29	0.75	-	-	-	-	3.5	3.14	2.27
WD14 - Ward 14 Cardio/Nephro	2.63	2	1.44	1.8	1	1.75	1.38	3	0.86	0.5	1.38	5.2	1	2.07	3.71	5.67	2.21
WD15 - Ward 15 General Surgery	6	-	-	-	5	-	2	-	3	12	-	5	2.5	4.5	-	18	6.44
WD16 - Ward 16 General Surgery	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
WD17 - Ward 17	1.5	2	-	-	1	-	7	-	-	-	-	-	2	3.67	3	-	2.88
WD18 - Ward 18 Orthopaedics	4.21	9.15	4.29	3.5	2.8	4.25	1.5	3.25	3.09	4	6	3.33	-	7.25	4.17	5.2	4.4
WD19 - Ward 19 Orthopaedics	12.1	2.47	8.5	6.17	2.25	-	2	2	6.75	4.2	4.25	4	-	3	0	5.4	4.5
WD20 - Ward 20 Plastic Surgery	6.71	1.36	2.33	2.71	1.75	4.8	1.56	1	1.6	3.13	2.63	2.7	2.25	3	4	0.33	2.62
WD21 - Ward 21 Paediatrics	1	-	0.67	0.5	3.5	5	-	4.67	1	2.5	2.5	-	0.5	0.33	2	0.67	1.91
WD22 - Ward 22 Paediatrics	-	0	-	-	-	-	-	8	-	4	1	-	-	1	1.67	-	2.61
WD23 - Ward 23 General Medicine	-	2	-	-	-	-	-	-	-	-	-	-	-	8	-	-	5
WD25 - Ward 25 Gen Medicine/Resps.	9	2	3	7	4	3.25	11	3.8	4.75	2.71	3.5	10	3.33	8.75	1.5	4.67	5.14

WD26 - Ward 26 General Medicine	-	-	5.67	2.5	-	1	3	1.67	-	-	4	1	-	3	1	8	3.09
WD27 - Ward 27 Oncology	3.33	-	3	2.5	-	9	-	4.5	2.5	2.25	3.75	-	3.5	3.38	4.8	3.25	3.81
WD28 - Ward 28 Neurology/Neurosurgery	0	0	14	4.5	4.25	-	2.5	3.33	2.5	3	7	5	3	2.43	0	1	3.5
WD29 - Ward 29 Gen Med/Gastro/Derm	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2
WD31 - Ward 31 Gen Medical Ward	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
WD32 - Ward 32 Eyes/Ent	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5
Grand Total	3.02	2.87	2.46	2.26	2.29	2.63	2.53	2.36	2.02	2.23	1.91	3.42	2.28	2.3	1.79	2.19	2.41

Appendix M: ALOS (days) for earthquake causalities in the Christchurch Hospital following the Christchurch earthquake

	Date																											
	22/02/2011		23/02/2011		24/02/2011		25/02/2011		26/02/2011		27/02/2011		28/02/2011		1/03/2011		2/03/2011		3/03/2011		4/03/2011		5/03/2011		6/03/2011		7/03/2011	
Admit Ward	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers	ALOS	Transfers
AMAU	3	0	2	1	1	0		0		1	1	0	4	0	2	1	5	0		0		0	2	0		0		0
CICU	1	0		1	13	0		0		0		0		0		0		0		0		0		0		0		0
CTW		0	1	0		1		1		0		0		0		1		0		0		0		0		0		0
EO	2	0	1	0	1	0		1		0		0		0		0		0	1	1	1	0	0	1		0		0
GSD		0	2	0		0		1		0		0		0		0		0		0		0		0		0		0
ICU	3	0		13		0		1		0		0		0		0		0		0		0		0		0		0
MDU	4	2	0	14		0		5		0		0		0		0		0		0		0		0		0		0
OBD	0	2		1		6		2	1	5		4		0		1		4		0		3		3		0		4
OTU	9	-		-		-		-		-		-		-		-		-		-		-		-		-		-
SARA	9	0		0	1	1		0	1	0		1		0		0	0	0		0		0		0		0		0
SPCU	6	0		2		0		1		0		0		0		1		0		0		0		0		0		0
UU	1	0		0		1	0	0		0	0	0		0		0		0		0		0		0		0		0
WD12		0		2	1	0		3		0		0		0		1		1		0		0		0		0		0
WD14	3	0		2		0		0		0		0		0		1		0		1		0		0		0		0
WD17		0	3	2		4		0		1		0		0		0		0		0		0		0		1		1
WD18	5	1	11	7	7	1	1	6	4	7	2	2		0	0	1	3	1		1		1		0	4	1	4	1

WD19	17	1	3	3	1	2	6	6	2	2		0	2	2	2	0	7	2		5		0		0		0	5	3
WD20	8	0	1	1	4	3	2	2	1	1	4	1		0		0		0		0	2	0		0	9	0		0
WD21		0		0		0		0		0		0		0		0	0	0		0		0		0		0		0
WD28		1	0	6		1		4		1		0		0	3	2	1	2		2		0		0		0		0
Grand Total	5.07	0.37	2.4	2.89	3.63	1.05	2.25	1.74	1.8	0.95	1.75	0.42	3	0.11	1.75	0.47	2.67	0.53	1	0.53	1.5	0.21	1	0.21	6.5	0.11	4.5	0.47

Appendix N: Table 5.6: The distances, mode and time for transfers out of Christchurch Hospital to other Hospitals following the Christchurch earthquake (Rhise network)

Hospital	**Distance (km) by road** Between Christchurch Hospital and receiving facility under normal conditions	**Time (min) on road** From Christchurch hospital to receiving facility under normal conditions	**Distance (km) by road** Between Christchurch Hospital and Christchurch Airport	**Time (min) on road** From Christchurch hospital to Christchurch Airport	**Distance (km) by fixed wing** Between Christchurch Airport to nearest airport of receiving facility	**Time (min) by fixed wing** From Christchurch Airport to nearest airport of receiving facility	**Distance (km) by road** Between nearest airport and receiving facility	**Time (min) on road** From nearest airport to receiving facility	**Total Time (min)** for transfer by fixed wing	**Total Time (min)** for transfer by road	**Total Time (min)** for transfer Helicopter	**Total estimated transfer time (min)**	***Number of patient transfers received in the weeks following the Christchurch earthquake***	**Mode of transfer**
Southern Cross	4.1	13	10	18	-	-	-	-	-	**13**	-	**13**	-	Road
Hillmorton	3.3	13	10	18	-	-	-	-	-	**13**	-	**13**	***4***	Road
St Georges	4.9	13	10	18	-	-	-	-	-	**13**	-	**13**	***1***	Road
Parklands hospital	6.1	15	10	18	-	-	-	-	-	**15**	-	**15**	***1***	Road
PMH	5.2	19	10	18	-	-	-	-	-	**19**	-	**19**	***41***	Road
Rosewood rest home	7.2	29	10	18	-	-	-	-	-	**29**	-	**29**	***1***	Road
Burwood Hospital	15.7	27	10	18	-	-	-	-	-	**27**	-	**27**	***41***	Road
Lincoln	19.8	38	10	18	-	-	-	-	-	**38**	-	**38**	***24***	Road

Rangiora	32.6	49	10	18	-	-	-	-	-	**49**	-	**49**	***29***	Road
Ellesmere	40.3	58	10	18	-	-	-	-	-	**58**	-	**58**	***0***	Road
Darfield	44	52	10	18	-	-	-	-	-	**52**	-	**52**	***2***	Road
Oxford	57.9	61	10	18	-	-	-	-	-	**61**	-	**61**	***1***	Road
Waikari Hospital	73.9	82	10	18	-	-	-	-	-	**82**	-	**82**	***3***	Road
Akaroa Hospital	81.4	83	10	18	-	-	-	-	-	**83**	-	**83**	***4***	Road
Ashburton Hospital	84.7	87	10	18	75.36	-	-	-	-	**87**	28	**87**	***20***	Road
Timaru	163	150	10	18	139.54	45	14.6	19	64	150	**48**	**48**	***14***	Road/helicopter
Kaikoura Hospital	182	151	10	18	146.37	100	2.8	6	106	151	**46**	**46**	***0***	Road/helicopter
Grey Base	238	190	10	18	158.49	100	1	4	104	190	**53**	**53**	***3***	Road/helicopter
Wairau	313	247	10	18	244.77	50	9.5	13	63	247	**71**	**71**	***1***	Helicopter/Fixed wing
Buller	333	253	10	18	209.26	65	8.3	15	80	-	-	**-**	***1***	Helicopter
Dunedin	357	286	10	18	328.17	65	29.3	36	101	-	**92**	**92**	***11***	Helicopter
Southland	565	453	10	18	465.92	100	4.9	8	108	-	**69**	**69**	***2***	Road/helicopter
Nelson	415	308	10	18	248.76	50	5.8	11	79	-	**71**	**71**	***7***	Helicopter/Fixed wing
Auckland city	-	-	10	18	746.33	80	18.6	25	**123**	-	-	**123**	***2***	Fixed wing
HAS	-	-	10	18	-	-	-	-	**-**	-	-	**-**	***1***	-
Hawke’s Bay (Royston)	-	-	10	18	552.72	90	22.5	25	**133**	-	-	**133**	***1***	Fixed wing
Middlemore	-	-	10	18	746.33	80	10.1	16	**114**	-	-	**114**	***2***	Fixed wing
Napier (Atawhai)	-	-	10	18	575.24	90	10.8	13	**121**	-	-	**121**	***1***	Fixed wing
North Shore	-	-	10	18	746.33	80	30.6	36	**134**	-	-	**134**	***2***	Fixed wing
Tauranga	-	-	10	18	715.9	115	8.7	15	**148**	-	-	**148**	***2***	Fixed wing
Waikato	-	-	10	18	666.92	100	13.2	17	**135**	-	-	**135**	***2***	Fixed wing
Wellington	-	-	10	18	304.42	55	4.9	9	**82**	-	92	**82**	***13***	Helicopter/Fixed wing
Average	132.8	116.39	10	18	415.93	79.06	12.23	16.75	**105.93**	72.47	71.25	**69.3**	***7.64***	