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TOWARDS CREATING RESILIENT CITIES: A CASE STUDY OF HAMILTON, NEW ZEALAND

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Abstract

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Hamilton, the fourth largest city in New Zealand, has a population of 140,000 people covering an area of 110km^2. While Hamilton has not experienced significant earthquakes in recorded history, recent geological surveys have discovered multiple fault lines running in a northeastern direction throughout the city. These fault lines run under critical infrastructure, including a wastewater treatment plant, water and sewer lines, and three main roads. They also run under the local university, one of the main industrial subdivisions, and an important bridge over the Waikato River. The Waikato region is largely a drained peat swamp with significant regions vulnerable to liquefaction and land movement. An earthquake hazard map identifies five key regions in Hamilton most vulnerable to damage from earthquakes, including the Waikato Hospital, the central business district, an industrial subdivision along Kahikatea Drive, and some residential areas. Main power lines also cross the fault lines. This study examined the effect of a combined moderate earthquake and extended power outage on Hamilton's lifelines, including storm, waste, and potable water networks, communication networks, emergency services, and transportation. Soil maps, ground movement estimates, and fragility curves for buildings and utilities were used to assess the risk of damage to each network. The resilience of Hamilton's utilities was assessed using a rating matrix that evaluated robustness, redundancies, resourcefulness, and rapidity. The rating matrix considered policies, documentation, training, availability of personnel, and service culture. Infrastructure interdependence was assessed using a Pugh selection matrix to identify key linkages, priority areas for repair, and critical connections that require strengthening. Finally, a strategy was proposed for strengthening key infrastructure components to improve the overall resilience and robustness of Hamilton's infrastructure for the scenario described.

During a moderate earthquake event in Hamilton, several disruptions are expected in key areas of the city. These include increased traffic congestion, communication outages, and damage to Fairfield Bridge, one of only six bridges linking the two sides of the city across the Waikato River. With limited road capacity, emergency services vehicles are expected to experience significant delay. On the other hand, bandwidth overloading and interoperability remain the two major challenges to maintaining communications. Further, water pipelines crossing the fault line are expected to be damaged. The pipe materials and routing for these pipe networks were not designed for seismic resilience, and there is only one potable water treatment plant. Finally, the main challenge for emergency services is two-fold—ensuring facilities remain structurally sound and functional and allowing for interagency operability. It has been observed across all four lifelines that there is a lack of collaboration between agencies in planning and training, which results in a significant disconnect in major response operations. Although individual plans may be sound, the lack of an integrative strategy often results in inefficient ad hoc response and increased risk.

1. Introduction

New Zealand is a land of diversity. Located about 1600 km southeast of Australia, and its southern tip only about 4100 km away from Antarctica, the country's climate ranges from subtropical in the far north to a cooler, temperate climate in the south [1-3]. A chain of mountains extends throughout the length of the country further introducing dramatic differences in climate between different regions [3]. The Waikato region, in particular, experiences a mild, humid climate due to its proximity to the coast. The region's terrain consists of large sections of farmland, suburban areas, the largest collection of peat lakes in the country, and the Waikato River [4]. Its largest city, Hamilton, covers 110 km^2 with a population of 140,000 [5]. Hamilton continues to develop and is one of the safest cities in New Zealand in terms of susceptibility to natural disasters. However, recent studies by Waikato scientists challenge this claim. In 2015, discoveries of historic liquefaction and underground cracks have led scientists to identify a previously unknown fault running through the northwestern side of the city [6]. New Zealand is no stranger to seismic activity. On February 22, 2011, a 6.3-magnitude earthquake shook the city of Christchurch, resulting in 185 deaths, 164 injured, and rebuilding costs amounting to 10% of the country's GDP [7]. The event was a wakeup call for the country to pay greater attention to the hazards it is exposed to and the resilience of its cities. The Department of Building and Housing recently updated New Zealand's earthquake hazard zones, dividing the country into three areas based on z-factors (a value used in the New Zealand building Standards to determine seismic risk of an area), which correspond to a level of risk as specified in Table 1 [8].

Table 1—Seismic risk classification according to z-values

Seismic risk area	Z factor
High	$Z \geq 0.3$
Medium	$0.15 \leq Z < 0.3$
Low	$Z < 0.15$

These z-values are specified in New Zealand Standard 1170.5:2004. The old seismic risk map puts Christchurch in a lower risk zone, as opposed to its updated classification as a high-risk area. Hamilton was initially classified as a low-risk zone, but its updated z-value of 0.16 puts the city in a medium-risk zone[8].

This paper defines resilience as the ability of a system to maintain critical functionality in the midst of sudden change and uncertainty. Resilience can be assessed against four dimensions—robustness, rapidity, redundancy, and resourcefulness. Robustness is the ability of a system to withstand stress [9]. Redundancy is the availability of alternate pathways or options that can be taken to allow the system to continue critical functions. Rapidity is a measure of how quickly a system can adapt and recover to prevent further damage [9]. Finally, resourcefulness is the ability to recruit the necessary equipment and resources to aid in recovery. This paper investigates Hamilton's current level of resilience based on four lifelines—transportation, communication, water (potable, waste, and storm), and emergency services. This study uses a broad, high-level perspective to qualitatively assess resilience. Individual systems can be assessed further in detail, just as service providers assess their systems in isolation, but in-depth assessments like this are out of this paper's scope. Moreover, this study incorporates the influence of organizational resilience and interdependencies between the four lifelines in addition to technical resilience. This study is based on the scenario of a moderate earthquake accompanied by an extended power outage. Resilience is measured for each lifeline using qualitative models, and suggestions for improvement are presented.

2. Assessment Methodology

Previous studies conducted by GNS Science and local government provided the necessary information to conduct a hazard analysis, and therefore, set a basis for the resilience assessment. Representatives from key agencies and organizations also participated in interviews to supplement and support this information. Hamilton is susceptible to a number of hazards, but according to a risk assessment by Hamilton City Council (HCC) and the Waikato Regional Council (WRC), the city is most susceptible to earthquakes, with possibly four active faults running through it [10]. The Kerepehi fault, an active normal fault running through the Waikato region and capacble of a M_w 5.5-7.0 single segment rupture event, also lies close to the city[11]. GNS Science and WRC worked together to identify different hazard zones throughout the Waikato region and produced a hazard map (Fig.1). Four different zones were identified ranging from “least hazardous” to “most hazardous”.

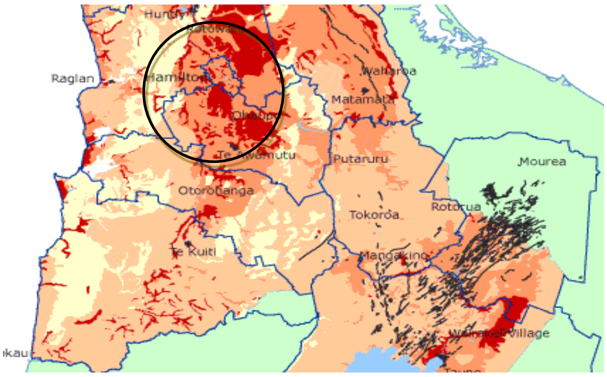

Fig.1 – Ground shaking hazard map produced by Waikato Regional Council and GNS Science, colours indicate level of hazard ranging from least hazardous (light tan) to most hazardous (dark red) and is based on the age and make up of the ground soil [10]

Critical assets within hazard zones are identified by overlaying this hazard map onto the map of Hamilton. Further, the probabilistic GNS seismic hazard model predicts a reasonable expectation of peak ground acceleration (PGA) values ranging from 0.13 g to 0.2 g with a 10% probability of occurring within a 50-year time period [12]. For the purpose of this investigation it was assumed that the “most hazardous” zones on the map corresponded to a PGA of 0.2g, and those in the “quite hazardous” zones corresponded to a PGA of 0.165g. Thus, the study is based on these values with an accompanying power outage lasting over 8 hours, assuming that most backup batteries last for only 8 hours.

Assessing each lifeline means assessing individual components and how these work together within that system. The next step was to compile a list of components and narrow these down to the critical ones using systems tools like causal loop diagrams and fault tree analysis. A damage assessment of each component was conducted based on fragility curves and historical data. This not only included the estimation of physical robustness, but also recovery time. However, robustness and recovery time also depend on redundancies, resourcefulness, and organizational resilience. To take these factors into account and do it systematically, a model was designed for each lifeline. These models assigned scores to individual components within each lifeline, and these scores were based on robustness, redundancy, rapidity, and resourcefulness. Previous models, such as the New Zealand Transport Agency (NZTA) Resilience Assessment Framework and the World Health Organization’s Hospital Safety Index, served as the skeleton for the resulting models. It was appropriate to modify the model to be specific to each lifeline, because the types of information available and the measure of resilience were different for each one. These models highlighted weaknesses and certain components that deserved higher prioritization in terms of implementing improvements and mitigations. An example component assessment is shown in Table 2.

The transportation, communication, and emergency services models also produced a score that proved helpful in showing how improvements can increase overall resilience. Note that these models are qualitative and serve only as a representation of the resilience of components relative to one another, as well as the overall system before and after implementing improvements. Detailed discussion on the individual models are beyond the scope of this paper.

Table 2—Sample assessment of an individual item from transportation

Item	Measure	Measurement Scale	Score
Diversion plans	Existence of robust, tested plans to establish diversions to alternate routes or control traffic when failure of critical link occurs	4 - Plans are well specified for different assets. Systems are available, tested, and ready for failure due to certain hazard. 3 - Plans are well specified but not enacted 2 - Ad hoc approach 1 - No plan/requirements	3

3. Transportation

During a disaster situation clear routes and knowledge of detours and road closures are especially important to allow civilians to evacuate, if needed, and for emergency services and essential contractors to get to their destinations as quickly as possible. Earthquakes can damage transportation networks in a number of ways. Landslides near roads and bridges can completely halt traffic flow. Intense ground vibrations can lead to faulting and the collapse of bridges and other structures [13]. Furthermore, liquefaction, a situation when the soil behaves more like a liquid than a solid, can cause the surface above the soil to tilt and sink [14, 15]. Couple these with an extended power outage, and the traffic lights will eventually lose function, causing increased traffic congestion and risk of traffic accidents.

3.1 Organizational resilience

3.1.1. Road closure warnings

It is not a stretch to expect road closures in the event of an earthquake, and it is ideal for travelers to be redirected early to reduce traffic congestion. Announcements are currently made via radio and HCC's website. Six popular radio stations, including The Hits (98.6FM), The Breeze (99.4FM), and MORE FM (92.2FM), are used for these [16]. However, it is an unreasonable assumption that most drivers listen to the radio, let alone tune in to the correct station to receive these warnings. A more effective and efficient way of issuing emergency warnings is needed. The local Civil Defence Emergency Management (CDEM) group has the authority to issue emergency mobile alerts [17]. The alerts come in the form of push notifications, which can be a more effective way to issue road closure warnings. With the system already in place, extending this for traffic updates is a low-cost alternative that can prove to be more effective. Additionally, NZTA, HCC, and CDEM must all follow a uniform protocol to implement this without causing interoperability issues.

3.1.2. Staff and resource availability

According to an HCC manager, in the event of a major disaster, it is unlikely that there will be enough staff and resources for Hamilton to cope. There is no plan in place to compensate for such a shortage; instead, HCC depends on the availability of contractors around the city. A more concrete protocol is needed to replace this ad hoc approach. To ensure enough resources are available, each lifeline can be assigned a disaster preparedness inventory list that compiles the resources that the city would need on-hand for different scenarios such as earthquakes, floods, etc. For staffing, memoranda of understanding (MOU) should be established with contractors within and outside of Hamilton to bring awareness of what is expected and required in the event of an emergency. Enough staff should be brought in to enable a healthy turnover, while ensuring they have enough resources for themselves and their families while on duty. Interagency collaboration is required to establish effective handover protocols to ensure everyone understands their role and the demands of that role.

3.2 Technical resilience

3.2.1. Prioritizing emergency vehicles

When traffic becomes more frenzied and congestion increases it can be difficult for emergency vehicles such as ambulances to reach their destination. Most Hamilton roads have insufficient space to allow emergency vehicles to overtake general traffic. This space, or capacity, is defined as the number of vehicles passing a point on a road per lane per hour [18]. According to NZTA standards, the ideal spare capacity is 50% or more [18]. In total, only 42.8% of critical assets examined in this study meets the standard. Cobham Bridge, which links State Highway 1 (SH1) from the south through to the city, and is also one of the three bridges that can carry the heaviest loads, has the lowest spare capacity at 1.06% [18]. In the event of an earthquake, with traffic fluctuations and increased demand, this will not be enough. Widening shoulder lanes is a reasonable way to alleviate capacity problems. Most shoulder lanes within Hamilton are less than 1 m wide, which is not wide enough to accommodate an average vehicle, let alone an emergency vehicle. It would therefore be beneficial to widen shoulder lanes leading to critical facilities, such as the Waikato Hospital and water treatment plant, to allow easy passage of emergency vehicles. In particular, the near-complete Hamilton Ring Road, which links Wairere Drive with Cobham Drive and SH1, has enough land to accommodate a wider shoulder, and it would be worthwhile for the HCC and NZTA to investigate if it is possible to implement this before opening the new major route. There is a larger cost associated with this solution, but this should be compared to the cost of being unprepared, before dismissing it completely. The benefit of widening shoulder lanes, however, depends on the relative lane width [19] and must be kept in mind when designing for optimal safety for both business as usual and disaster scenarios.

3.2.2. Backup power for traffic lights

Hamilton traffic lights are not equipped with automatic backup power. During a power outage, HCC needs to manually deploy generators—an inefficient process, especially because transporting those generators to their destination will be a challenge given traffic congestion, available capacity and non-functioning traffic lights.. HCC is currently investigating automatic backup power supplies and critical sites to install these in, but there is plan for implementation at this time. An uninterruptible power supply (UPS) battery system would be ideal for traffic lights at key intersections [20]. Generators are suitable for higher power applications, while a UPS, on the other hand, is less expensive and does not carry the noise, smell, and environmental impact that comes with using generators. A UPS that can provide power for a minimum of four hours is recommended. This allows enough time to implement alternative solutions such as temporary roundabouts and traffic wardens.

4. Communication

Without communication, coordination of emergency responses suffers significantly, and lack of awareness about developing or existing situations can lead to chaos that can otherwise be avoided. For information and communication technologies (ICTs), resilience is the ability of the network to continue to function despite attacks or disruptions. In a disaster event it is not only the robustness of individual communication technologies that defines resilience, but also how these adapt to sudden changes and are used together by different groups of people. Hamilton has access to six methods of communication: cellphones, landline, internet, radio, satellite, and face-to-face (FTF). This study focuses on the cellular network, radio, satellite, and FTF as power outages limits internet availability to mobile data and most landline users own wireless handsets, which also require mains power.

4.1 Organizational resilience

4.1.1. Interoperability

External service providers like Vodafone and Spark are also involved in disaster response and recovery. In Christchurch, lack of communication between contractors and local government almost resulted in major damage to the telecommunications network. Early demolitions were cancelled just in time, saving critical telecommunications equipment in one of those buildings [21]. These ad hoc operations may have been successful, but had these been planned for in advance, risk and recovery time could have been minimized. Thus, it is important to not only emphasize interagency collaboration in emergency planning and training, but to also coordinate with external service providers. These service providers are experts in their field and can contribute valuable insight to disaster response, however, security and commercial sensitivity are hurdles that need to be overcome.

4.1.2. Strategic placement of resources

Disaster response times are extended when resources are not readily available. To ensure that critical resources are available within eight hours of a disaster occurring, these resources must be strategically placed within the city to ensure easy access. Past events indicate that external resources can take well over 24 hours to acquire [21]. Thus, enough resources to last at least 48 to 72 hours should be available within the city and controlled by the HCC. The HCC should have control, with access to external contractors, because in some cases, local contractors may not be available, due to concerns about their family and property in a disaster event.

4.1.3. Door-to-door notification

When all communications equipment fail, responders must use FTF communication. Although the Civil Defence and other agencies deploy staff on the ground, there is no indication of formal procedures for door-to-door notification in any of the training manuals. This FTF communication is also important for people without access to ICTs. Procedures should include details of when to activate this procedure and at what scale.

4.2 Technical resilience

4.2.1. Bandwidth overloading and alternative communication

Emergencies almost always increase demand for telecommunications, with civilians and first responders all needing to communicate with each other. To control bandwidth overloading of the telecommunications network, Civil Defence issues a text announcement instructing people in affected zones to restrict communication to texting/SMS only unless calling emergency services [22]. Bandwidth overloading has been observed to be almost inevitable, especially during and after an extended power outage, warranting a more reliable solution. A potential solution is through the imminent roll-out of 5G in New Zealand. 5G has the potential to allow for virtual networks to be created and assigned priorities [23]. This ensures that high priority calls such as emergency services are connected in times of peak demand. Another solution is establishing a two-way texting service via the Civil Defence as an alternate form of communication. This can be set up as an SMS short-code, similar to the existing 111 short-code. People could text their first and last name and date of birth to the Civil Defence to mark themselves "SAFE" and also text the first and last name and date of birth of a person they are looking for. If two people get matched up, they both get a notification. This would help minimize both demand on the network and panic.

Internet of Things (IoT) devices, such as smart watches, can communicate with each other via Bluetooth, independent of the cell network and internet. With a software-defined network (SDN) protocol in place, IoT devices can be enabled to send small "tweets" to each other and even form a local mesh network, effectively providing another alternate form of communication [24]. It is worth looking into how this can be implemented since it can be an effective but low-cost solution.

Finally, there are central meeting points for the public, such as the cricket and rugby stadiums where information can be displayed [25]. Event sites, public noticeboards, and even parking space information boards can be repurposed to display updates for people who have no access to their own ICTs.

4.2.2. Fibre optic cables

The fibre optic network is vulnerable to major landslips and localized breaks, such as the Aqualink cable breakage along the east coast of the South Island following the Kaikoura earthquake [26]. However, the percentage loss of functionality of the cell network is difficult to estimate without expert knowledge and a map of fibre optical cable routes. However, service providers do conduct their own resilience assessments, which further emphasizes the importance of getting these providers involved in planning.

5. Three Waters

Three Waters refers to the waste, potable, and storm water networks. Hospitals, fire fighters, and the general public all require safe drinking water, and storm water networks are vital to prevent flooding. Waste water must be kept well-contained and managed since leakage can result in increased health risks.

5.1 Organizational resilience

5.1.1 Emergency response

In an earthquake scenario, the HCC assumes regular water sources are contaminated by wastewater leakages [27], boil water notices are issued, and alternative water sources made available for distribution to the community. However, poor coordination of responders from the HCC, Civil Defence, the community, and other parties, communication outages, and traffic congestion can slow response time. It is therefore important to establish alternatives such as ensuring house-holds and businesses have sufficient water reserves, and the community is educated in and have available alternative methods of water treatment (e.g. chlorination, filtration, UV treatment) in the case of water outages or water contamination.

5.2 Technical Resilience

5.2.1. Pipe network

Pipe reticulation damage has been identified as the main cause of service disruption for both potable water and wastewater networks. Pipelines are especially prone to damage in liquefaction zones due to settlement or lateral spreading [28]. Pipe material, location, and age all influence how robust these pipelines are. In particular, pipes consisting of asbestos cement and cast iron are more prone to damage. In Hamilton, wastewater pipes are typically made of reinforced concrete, PVC, and fiberglass, which float in liquefaction zones, making these more prone to damage. Lifting of dry well lift stations and pump stations can also occur due to liquefaction. For wastewater pump stations, this is especially concerning since wastewater overflow and backup can cause contamination and raise health risks.

A simple improvement would be to strategically install alternate pipelines around hazard zones. Older pipes that are nearing their end of life can also be replaced with seismic resilient material, such as steel with welded joints, ductile iron with seismic joints, and molecularly oriented PVC with restrained joints [29]. Pipes located in areas prone to liquefaction especially need to be prioritized. The main pipelines can be redesigned to include enough redundancies, special points of distribution, and other mitigations to ensure uninterrupted service to critical facilities, like the Waikato Hospital.

For the wastewater network, upgrades could include interceptor pipe extensions, pump upgrades, and duplicate sewers to ease overflows. Connections to pumping stations could also be replaced with flexible piping and joints. Pipe anchoring and addition of concrete to manholes, dry-lift wells and pump stations can also reduce the risk of sewers and manholes floating in areas prone to liquefaction. Pump stations also depend on electricity, which could become another cause of failure in an extended power outage. After the Christchurch earthquake, it took two to three days to restore 75% of the power to the community [30]. This puts pump stations in the priority list for backup power supply retrofitting or emergency distribution.

5.2.2. Reservoirs

Depending on the method of construction, excessive shaking and ground displacement can cause reservoirs to fail in a variety of modes, including settling of foundations, cracking or shearing of walls, roof-wall foundation sliding, and elephant buckling [31]. The Ruakiwi and Hamilton South reservoirs were found to be especially vulnerable due to their proximity to hazard zones. Since there are only eight reservoirs in Hamilton, it becomes a priority to either reinforce or relocate these or acquire additional reserviors. Seismic retrofitting of water tanks can include anchoring foundations, strengthening concrete tank walls, replacing rigid pipe connections with flexible couplings, and improving roof structures [31].

5.2.3. Treatment plants

In addition to settling, clarifiers in treatment plants can sustain damage from sloshing wastewater [32]. Debris and sand can also infiltrate the wastewater network and increase loading at the wastewater treatment plant [32]. In Hamilton, there is only one potable water treatment plant and one wastewater treatment plant, which makes them single points of failure. Both the water treatment plant and waste water treatment plant have onsite generators in the case of an extended power outage.

6. Emergency Services

97% of earthquake-related injuries occur within the first 30 minutes following the main earthquake [33]. This emphasizes the importance of efficient response from emergency services agencies. Resilience is demonstrated in emergency services and healthcare sectors when disruptions, especially those outside of planned events, are recognized, adapted for, and absorbed [34]. In this study, three agencies are assessed specifically for Hamilton, and these are the New Zealand Police, Fire and Emergency New Zealand (FENZ), and the Waikato Hospital.

6.1 Organizational resilience

6.1.1. Integrating Coordinate Incident Management System into FENZ response

A 2015 report states that emergency services representatives believe that FENZ does not follow Coordinate Incident Management System (CIMS) in the same way that the NZ Police and St John's are expected to [35]. This lack of coherence can lead to slower response, duplicated actions, and waste of resources. Evidence of this can be seen in Christchurch, where there was lack of control at major rescue sites such as the CTV building [36]. Adherence to CIMS can be reinforced through interagency exercises involving the NZ Police, St. John's, and other agencies, such as the New Zealand Defence Force and Urban Search And Rescue.

6.1.2. Reduce the average length of stay (ALOS) at Waikato Hospital

The ALOS at Waikato Hospital is one of the highest in the country—3.5 days, according to the 2019 resource review [37, 38]. Major delays result from a lengthy discharge process that can take a full day to complete. A recent recommendation to create a criterion-led discharge process gives authority to the charge nurse to discharge patients. This was tested in the cardiology ward, but a lack of commitment led to failure [37]. A Patient Flow Manager (PFM) was also implemented in nine departments but excluded the emergency department [37]. Since the emergency room (ER) is the most frequented department, ER implementation should be reconsidered.

6.1.3. Emergency packs for patients and staff

In the 2011 Christchurch earthquake, 500 emergency packs with assessment, radiology, and laboratory request forms were distributed to patients, giving each one a unique identifier number and disaster number [39]. This was a means of identification, as well as, keeping count of patients. There is no record of Waikato Hospital having a tracking system like this. A suggestion is to have 600 packs on site, readily available for distribution, since the hospital uses 600 beds on average [37]. This needs to be coordinated with the kits provided by the ambulance to avoid tracking mistakes. Packs can also be made for doctors, nurses, and other staff containing a disposable jacket and name tags that indicate what services they can provide. Following the example of Christchurch Hospital, the system should use international disaster color triage differentiation .

6.2 Technical resilience

6.2.1. Diesel tank filters for generators

During the Christchurch earthquake, vibration caused settled diesel sludge to be suspended that led to generator failure [40]. A simple solution to this was to install a filter and diesel cleaner. The same should be implemented in all buildings classified as Importance Level 4 (IL4). IL4 buildings are required to continue function even after a disaster, and must have a permanent generator on site [41]. The diesel filter and cleaner are especially important for facilities with only one generator, such as the Police and FENZ stations.

6.2.2. Communication redundancy specific to Waikato Hospital

Waikato Hospital continues to depend primarily on telecommunications, intranet, and email even during a disaster [42]. As discussed in Section 4, this depends on the robustness of the telecommunications infrastructure. Thus, establishing an alternate method of communication specifically for the hospital is imperative. The National Library of Medicine recently developed a communications system that enables the creation of an email service via amateur radio. This system, known as BHEPP Military Emergency Radio Systems (BMERS), combines Wi-Fi, specialized software, and amateur radio to enable the email service by using the internet outside of telecommunications blackout zones [43]. This does not require roof-mounted equipment and is more affordable than acquiring satellite phones [43].

6.2.3. Improve passive fire protection systems

The Waikato Hospital conducts regular maintenance on their fire protection systems and runs regular drills. However, gaps have been identified in their firewall protection. The presence of these holes means that fire cells are no longer separated, allowing fire to spread more quickly across different sections. These were also found in Police facilities. Fixing this issue is a top priority. The Waikato Hospital has its own natural gas reticulation system which increases their risk, thus justifying an investment in fire protection system upgrades, such as fire doors, fire walls, and fire protection coatings.

7. Overall

It is easy to imagine the immediate physical consequences of a catastrophic event such as an earthquake. Thus, disaster planning largely focuses on reinforcing physical structures and local organizational resilience. It is apparent that resilience is often overlooked in the larger scheme, as is the case for the city of Hamilton. A city is a complex system of systems, comprised of elements whose individual properties and interactions dictate the behavior of the whole. It is, therefore, necessary to examine the common issues and interdependencies between Hamilton's four lifelines to obtain an accurate representation of the city's resilience as a whole.

7.1 Common vulnerabilities

The first issue that encompasses all four lifelines is a lack of collaboration. Although the local Civil Defence group in Hamilton has a group plan set in place and regular training activities with the local police, FENZ, and HCC, there is still a significant disconnect with emergency services agencies outside of Hamilton. With 16 Civil Defence groups each preparing their own group plan, interoperability issues will arise. Each Emergency Operations Centre (EOC) has their own responsibilities and terminology, creating a barrier for other agencies to help efficiently. Different regional councils also prepare their own standard operating procedures (SOPs), vulnerability assessments, and communications plans. Other agencies like New Zealand Search and Rescue (NZSAR), are often left out [44]. When a major disaster occurs, it is reasonable to expect these external agencies to be involved in the response, and this response relies heavily on coordinated actions. The establishment of the new National Emergency Management Agency (NEMA) may be a solution to this problem. $4.5 million has been allocated to funding the establishment of NEMA [45]. However, there is no mention of how this will involve external suppliers, contractors, and service providers in joint planning and training. As evident from the Christchurch earthquake, involving these external groups in planning and training is necessary.

Several improvements can be implemented to avoid interoperability issues. Firstly, all Civil Defence Groups should set up the same sub-functions according to the current New Zealand Coordinate Incident Management System (CIMS 3). Having the same sub-functions allows for easier integration and handover. Further, it would be beneficial to create a platform, overseen by the Ministry of Civil Defence Emergency Management (MCDEM), for Coordinating Executive Groups (CEGS) of different Civil Defence Groups where reports, preand post-mortem analyses, and plans can be securely shared. This platform can help speed up learning and planning and also improve understanding between these different divisions. Instead of duplicating what has already been researched, different agencies can instead build upon each other to avoid wasting time and resources. Additionally, having a forum, such as the Local Resilience Forums in the UK, can contribute to this goal [35]. Another vulnerability is lack of public engagement. Civil Defence does take steps to involve and educate the public, but these efforts are inadequate. The public remains unaware of how communications work in disaster events and what they can and should not do to help. Advertisements, like the famous NZ Police anti-drink driving ads, can be a vehicle to educate the public about disaster procedures.

7.2 Interdependencies

It is already apparent from the previous sections that there are interdependencies between these lifelines, such as the dependency of emergency services on communications, transportation, and water services. These interdependencies influence decisions on which assets to prioritize in terms of implementing improvements and response planning. To see these interactions more clearly, an influence matrix was used (Table 3). The matrix scores the degree of dependence of the column elements on the row elements from 0 to 3 (0 corresponding to no dependency and 3 to a strong dependency).

Column number	1	2	3	4	5	6	7	8	9	10	11	12
	Roads	Tele. Com.	VHF/UHF radio	Broadcasting	Potable water	Storm water	Waste water	Fire department	Police	Hospital	Score	Percentage Score
Roads	0	3	3	3	3	3	3	3	3	3	27	**100.00%**
Tele. Com.	3	0	2	3	3	3	3	3	3	3	26	**96.30%**
VHF/UHF radio	2	2	0	2	2	2	2	3	3	3	21	**77.78%**
Broadcasting	1	1	1	0	1	1	1	2	2	2	12	**44.44%**
Potable water	1	0	0	0	0	0	0	3	3	3	10	**37.04%**
Storm water	0	0	0	0	0	0	0	2	0	1	3	**11.11%**
Waste water	0	0	0	0	0	0	0	2	2	3	7	**25.93%**
Fire department	0	0	0	0	0	0	0	0	3	3	6	**22.22%**
Police	0	0	0	0	0	0	0	3	0	3	6	**22.22%**
Hospital	0	0	0	0	0	0	0	3	3	0	6	**22.22%**

Fig. 2—Interdependency Matrix (0 corresponding to no dependency and 3 to a strong dependency)

Column 11 shows how many other elements depend on the element in each row. It is a clear conclusion that transportation and communication are the two lifelines that are most in demand. Emergency services, on the other hand, depends the most on all other elements. These interdependencies are reflected in the individual models. For example, increasing the robustness of the telecommunications network also increases the resilience score for emergency services, and that increase in scores within each of those lifelines increases overall rapidity. The differences in models, including the different scoring criteria and rating scales, made it difficult to integrate all four models into an overarching resilience model for the whole city. Those individual models can be modified and further refined to allow for integration and produce a better picture of the system as a whole. It should also be taken into consideration that a resilience strategy for an earthquake may potentially be harmful if another type of disaster was to occur. That being said, this research can potentially be expanded to include other likely hazards that may occur in Hamilton.

8. Conclusion

The purpose of this research project was to investigate the resilience of the four lifelines of Hamilton, New Zealand in the event of an earthquake with a peak ground acceleration of 0.2 g and a 475-year return period. Both technical and organizational resilience were assessed by looking at individual components of each lifeline, evaluating their vulnerabilities, and examining how these elements interact. Resilience models were created for each lifeline to quantify resilience before and after implementing suggested solutions. One common weakness was found across all four lifelines—poor interoperability. External contractors are not involved in resilience assessments and disaster planning, even though their perspective and expertise are incredibly valuable. Individual Civil Defence groups create plans in isolation without a working platform to collaborate effectively and efficiently with other groups and agencies. This study was limited by the information that was publicly available, and it hinges on the accuracy of the hazard analyses done by WRC, HCC, and GNS Science. Additionally, further research can be conducted to extend this study to a resilience assessment based on other hazards that Hamilton is susceptible to. Implementing suggestions made in this report to improve resilience comes with a price, but the question is whether this cost outweighs the economic and social costs of remaining unprepared.

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