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Modelling the risks of extreme weather events for Australasian hospital infrastructure using rich picture diagrams

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Anticipated increases in the frequency of extreme weather events in the future are likely to expose hospital infrastructure to new risks which are poorly understood. Traditional approaches to risk identification and analysis produce linear, narrow and static risk profiles which fail to consider complex sub-system interdependencies that may assist or hinder healthcare delivery during an extreme weather event. The ability to create resilient hospitals depends on new risk management methodologies which provide an understanding of these complex relationships. Focus groups with key stakeholders in three hospitals in Australia are used to construct rich picture diagrams (RPDs) of hospital infrastructure interdependencies under different extreme weather event scenarios. They show that the risks posed to hospitals by extreme weather events cannot be considered in isolation from the surrounding infrastructure, emergency management systems, health systems and communities in which they are imbedded. The new insights provided have major governance and policy implications for agencies responsible for ensuring that hospital infrastructure can continue to support the delivery of effective health services during extreme weather events.

Keywords: Extreme weather, hospitals, risk, stakeholders.

Introduction

It is now widely accepted that over the next 50 years, we are likely to experience more frequent extreme weather events which will test the resilience of national critical infrastructure and services (Secretary of State for Environment, Food and Rural Affairs, 2011, p. 5). Hospitals represent an important element of national critical infrastructure, particularly during an extreme weather event. Research has shown that extreme weather events such as floods, storms and heatwaves have a significant effect on community health, particularly among the most vulnerable in our communities such as the disabled, aged and obese (McMichael and Woodruff, 2008). Furthermore, it has shown that many hospitals are vulnerable, unprepared and unable to adapt effectively to the new patterns of care which such events will suddenly require (Loosemore *et al.*, 2011). The inability of healthcare to respond to these new physical and health-related risks is clearly evident in the many recorded instances of hospitals failing to support effective healthcare delivery during such events. For example, in 2005, the Sydney heatwaves highlighted insufficient surge capacity in hospitals to cope with increased demand and changed admission profiles. In 2006, Tropical Cyclone Larry forced the closure of numerous hospitals in Queensland (Queensland Government, 2006) and in 2007, floods in New South Wales cut off hospital power supplies and access to surrounding roads for almost two days (Hunter New England, 2007). More recently, in 2011, the evacuation of both Cairns Base and Cairns Private Hospitals in the face of Cyclone Yasi is a further graphic example of the inability of hospital facilities to cope with the risks posed by extreme weather events (Miles, 2011).

Given the implications of extreme weather events for human health, it is widely acknowledged that there is a need to better understand how to protect and improve the resilience of public health systems to

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such events (Department of the Environment and Water Resources, 2007; Productivity Commission, 2011). While many aspects of healthcare delivery are being researched in the context of extreme weather events (McCaughrin and Mattammal, 2003; Bonnett *et al.*, 2007; Lalonde, 2007), research into healthcare infrastructure has been relatively neglected. This is an important deficiency which needs to be addressed as acknowledged by the Australian Science, Engineering and Innovation Council and by the Council of Australian Governments, which recommended that Australian governments should give priority to developing adaptation strategies for Australia's health infrastructure (Council of Australian Governments, 2007; Prime Minister's Science, Engineering and Innovation Council, 2007). To address this challenge, the aim of this paper is to explore the risk exposure of Australasian hospitals to extreme weather events. More specifically, by exploring the complex system interdependencies which exist in the healthcare sector, this paper challenges traditional approaches to risk management which produce linear, narrow and static insights into hospital resilience. It argues that the ability to create resilient hospitals depends on new risk management methodologies such as rich picture diagrams which provide an understanding of complex sub-system interdependencies that may assist or hinder healthcare delivery during an extreme weather event.

Understanding hospitals as complex systems

In understanding the risk exposure of hospitals to extreme weather events, it is important to point to Becker and Carthey's description of the healthcare systems as a 'tangled web of interdependencies' (2007, p. 2). Becker and Carthey make the point that the many problems experienced in healthcare systems around the world are systemic, rather than being caused by any single factor. This means that there is rarely a simple and single solution to any challenge faced. Furthermore, if one is to understand how the health system works in response to an extreme weather event, one must understand the interdependent sub-systems that need to interact to enable a hospital to respond effectively. This in turn requires not only an appreciation of specific hospital infrastructures but also an appreciation of the interaction between a hospital system, its users and the wider socio-political and emergency management environment in which it is imbedded. A hospital is a complex organization with many diverse internal and external stakeholders and functions which combine to deliver appropriate health services to a community. Responses to extreme weather events are similarly complex and involve the interplay of many economic, social, organizational, political and cultural considerations.

Although it is widely acknowledged that health infrastructure systems are complex, we have a poor understanding of the interdependencies between critical health infrastructure sub-systems and of the cascading uncertainties which they can produce (Arboleda *et al.*, 2009; Productivity Commission, 2011). For example, power outages caused by a heat-wave can affect heating and cooling systems, waste treatment, sterilization and telecommunications, making treatment of patients impossible precisely at the time when admissions are likely to increase. These interdependencies are likely to increase as hospital technologies become more complex through the use of smart grids, virtual power plants, decentralized power production, the integration of fluctuating renewables and the break-up of previously vertically integrated electricity utility companies (Hiete *et al.*, 2011). Unfortunately, as Koubatis and Schonberger (2005) point out, traditional approaches to risk identification and analysis are unable to help us understand these types of complex and dynamic interdependencies. These approaches were developed for simple linear systems in relatively stable environments which in turn means that current hospital policies and response strategies to such events are also likely to be linear in nature.

A useful starting point in understanding these interdependencies is Markus *et al.*'s (1972, p. 1) systems-based conceptual model which encapsulates the interrelationships between built infrastructure and the wider systems in which it exists (see Figure 1). Despite being over four decades old, the basic construct of Markus's model remains relevant today since it views a building facility and its stakeholders as an 'adaptive system' which comprises five key elements (sub-systems): the building system; the environmental system; the activity system; the objectives system; and the resources system. These systems are in a dynamic relationship and are conceived not as silos but as discrete yet interactive components.

In Markus's model the *building system* comprises three interdependent sub-systems: construction (the external envelope, the structure, the division of internal spaces: i.e. the building fabric); services (mechanical and electrical services providing air conditioning, lighting and power); and contents (furniture and fittings—in a hospital context this would include surgical equipment, beds, diagnostic equipment). The *environmental system* refers to the internal building environment created by the building system which comprises two sub-systems: spatial (the layout of the facilities, the relationship of one space to another), and

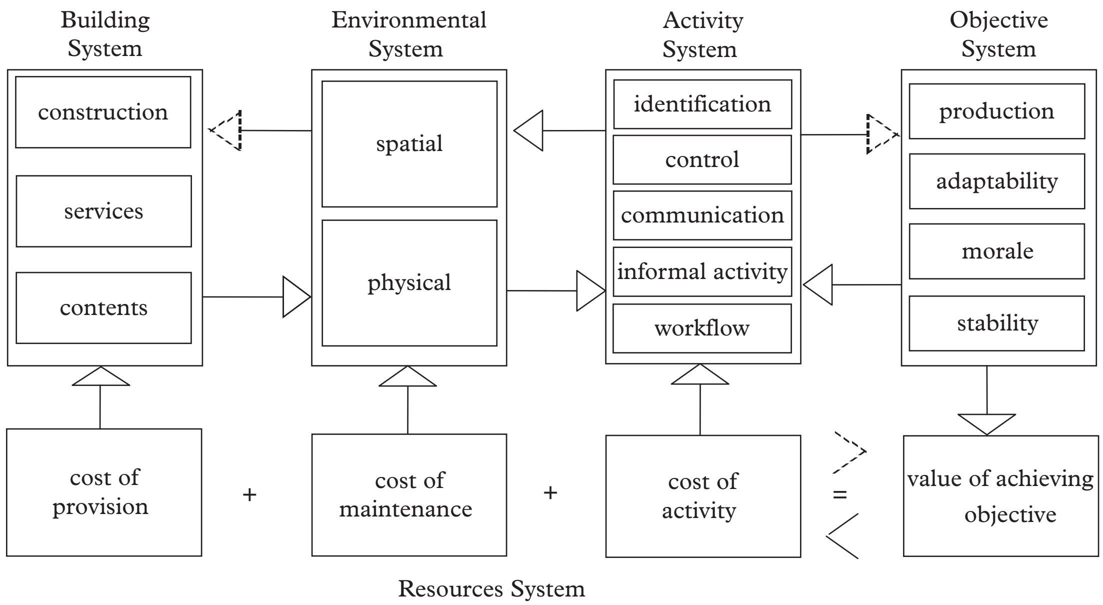

Figure 1 Markus's conceptual building sub-systems model (Markus, 1971, p. 1)

physical (the air quality, internal air temperatures, infection control). The *activity system* represents what happens within the facility and comprises several 'organizational' sub-systems which control the way people interact and work together to enable the *objectives system* to function, which in a hospital context involves the continuity of healthcare delivery to the community during an extreme weather event. Finally, the *resources system* represents the external 'environment' from which the other sub-systems draw to enable them to function effectively. This includes the supply of physical, financial and human resources. It also includes critical services such as electricity, gas and water.

Using Markus's model, Figure 2 shows how an extreme weather event might impact on the environmental, activity, objectives and resource systems of a hospital. In this example, which reflects a number of examples that have occurred in reality, a heatwave

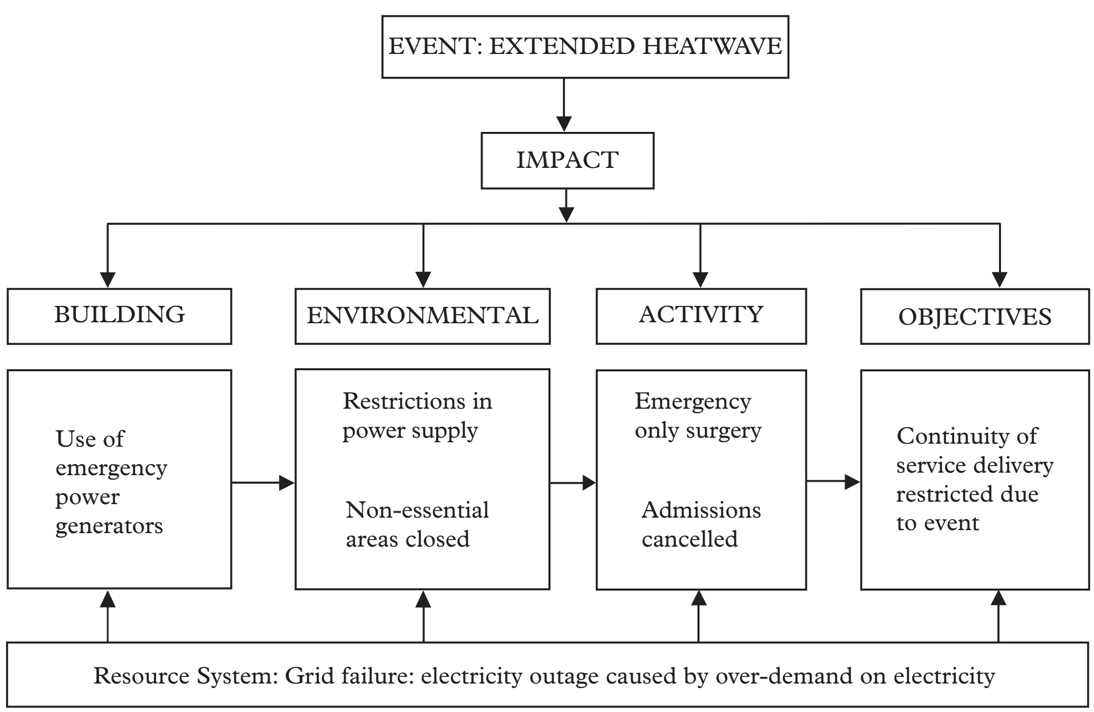

Figure 2 Possible effects of heatwave on a hospital explored using Markus's model

causes an electricity supply outage because of excess demand on the national electricity supply system. This in turn causes the hospital to use emergency generators which in turn restricts power supplies internally to essential services such as life-support systems, which in turn causes the cancellation of elective surgery and reduced admissions, which in turn affects the continuity of healthcare delivery into the community.

While Markus's model is useful in representing hospital sub-system interdependencies, the limitation of this model is its inherent linearity. An alternative technique to illustrate and conceptualize the healthcare system's interdependencies is the use of rich picture diagrams (RPDs). RPDs developed out of soft systems methodology which distinguishes between hard systems and soft systems as described in Table 1.

It is important to appreciate that the system characteristics in Table 1 represent two extreme ends of a spectrum. There is also the emerging system dynamics approach founded by Jay Wright Forrester in the mid-1950's and used by Koubatis and Schonberger (2005) in the health sector, addressing the time dimension of systems which is missing in the above approaches. Considering this caveat and given the attributes of soft systems described in Table 1, soft systems methodologies are likely to be a useful way to understand the complex interdependencies within the healthcare system during an extreme weather event. The RPD technique is one such technique and has been defined as a pictorial summary of the actual situation in the systems world based on enquiries or observations of the 'real world' (Patching, 1990). In essence, a RPD is a pictorial multi-layered representation of the real world using symbols to represent sub-systems and their relationships (of different types—communications, dependencies) within a defined system boundary. A typical rich picture diagram from a hospital (our first case study) is depicted in Figure 3. This diagram represents pictorially the various components of the system affected by a flooding event which are dependent on each other to respond effectively. The effectiveness of the whole system in responding is therefore also determined by how well these interdependencies are recognized and enabled through the various interacting management systems and through the informal actions of human actors who might be forced to move outside those systems (the invisible informal organization). Physically the system depicted in Figure 3 encompasses a large area with some components of the systems being widely dispersed. For example, one component of the system (hospital stores) is at a physical distance of over 400 kilometres from the base hospital. In a rich picture diagram the nodes are simply pictorial representations of 'critical assets' which have been identified as risks with connecting lines which represent dependencies (flows of 'resources') between them. For example, in Figure 3, the availability of key maintenance staff (a key risk) depends on the roads being open (another key risk) to get to hospital. The arrow represents the direction of an interdependency and a flow of resources between these two critical asset risks.

In our RPDs there are three types of critical assets:

1. Organizations—suppliers, external service providers, external authorities.
2. People—staff, patients, public.
3. Physical—buildings, plant, machinery, infrastructure.

And there are five types of resource dependencies between the critical assets:

1. Information—X needs information from Y to respond effectively.
2. Financial—X needs money from Y to respond effectively.
3. Power—X needs permission from Y to respond effectively.
4. Material—X needs materials, water, energy from Y to respond effectively.
5. Human—X needs staff, people, emotional support from Y to respond effectively.

Methodology

The complex interdependent nature of hospitals and the large number of diverse stakeholders affected by

Table 1 Characteristics of hard and soft systems (Agnew, 1984, p. 168)

Hard system characteristics	Soft system characteristics
Well-defined goals	Objectives frequently poorly defined
Clearly established boundaries	Decision taking procedures vague
Quantifiable performances	Difficult to quantify
Clearly structured	Poorly structured
Physical systems	Human activity systems

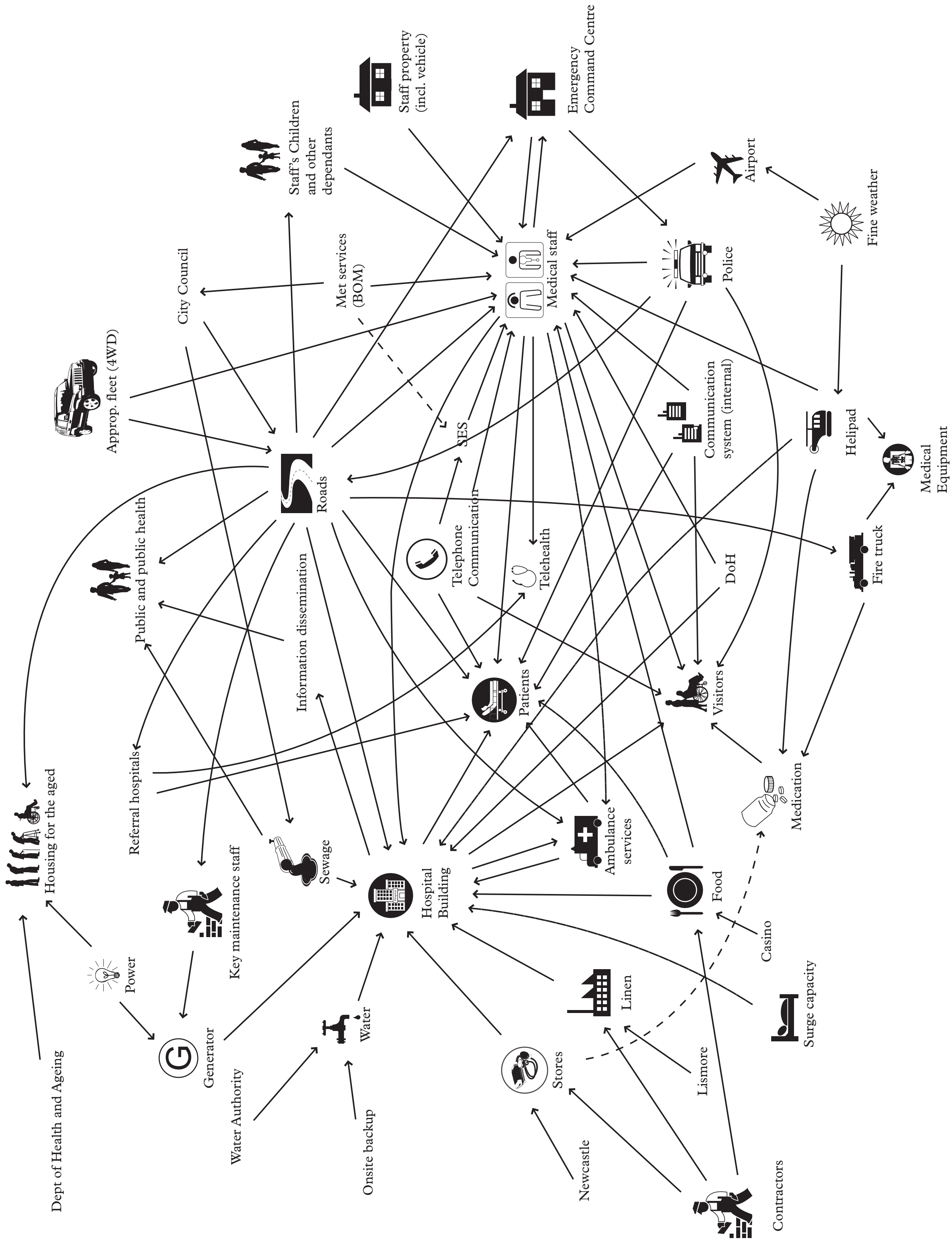

Figure 3 Rich picture diagram of Case Study 1 during and after an extreme weather event

Table 2 Methodological paradigms (Heng, 2010)

	Paradigms		
Item	Positivism	Realism	Constructivism
Ontology	Naive realism; reality is real and apprehensible	Critical realism; reality is real but imperfect and probabilistically apprehensible. Therefore triangulation from different sources is permitted	Relativism; local and specific constructed realities
Epistemology	Dualist/objectivist; findings are true and value free	Modified objectivist; findings are probably true, value aware	Transactional/ subjectivistic; created findings
Methods	Experiments/survey; verifications of hypotheses; mainly quantitative method	Case studies; convergent interviewing; interpretation of research issues by qualitative and quantitative methods; multi-methods	In-depth interviews; participant observation

extreme weather events raise some interesting and challenging methodological issues in undertaking risk-related research in this area. As we have pointed out above, traditional methodologies for understanding risk have been highly linear in nature and the result has been that management strategies have followed suit. Using Heng's (2010) model of methodological spectrums in Table 2, it is clear that this historical approach reflects a positivist paradigm which is not suited to the nature of the system that it purports to understand and explain. While this also reflects a general lack of methodological pluralism in the wider field of construction management research (Dainty, 2008), our research was driven by a realism paradigm. The critical realism position is a shift beyond the positivistic (scientific) paradigm—in rejecting the idea that the social world can be examined and studied in an objective and value-free way. In short, the ontological position of critical realism claims that critical realism is a specific form of realism in that it recognizes the reality of the natural order and the events and discourses of the social world and holds that we will only be able to understand the social world if we identify the structures at work that generate those events and discourses. These structures are not spontaneously apparent in the observable pattern of events and can only be identified through the practical and theoretical works of social science (Bhaskar, 1989). Accordingly, critical realism straddles the objective and subjective worlds, and is considered as a *modified objectivist* position because of its acceptance of the existence of reality that is independent of the mind but also a socially and culturally constructed reality within it (Sayer, 2000). Put simply, a critical realist attempts to maintain a 'scientific' attitude towards social analysis while simultaneously recognizing the importance of actors' meanings and in some way incorporating them in research.

Method

A multiple case study approach was adopted for our research. In adopting this approach, we concur with Barrett and Sutrisna's (2009) critical analysis of research methodologies in complex organizations which also employed a critical realism paradigm and used RPD techniques. Like us, Barrett and Sutrisna (2009) argue that a case study approach is an appropriate framework to undertake research within this context because it enables investigators to capture rich information from a variety of stakeholders, providing a holistic understanding of real-life, interdependent and complex events. Drawing on grounded theory research, they argue that such insights using a more conventional positivist paradigm are not possible. The development of RPDs also aligns with a critical realism paradigm since they are able to represent the holistic and multidimensional complexity of the hospitals we investigated. Like Barrett and Sutrisna, we intended the development of our rich picture diagrams 'to provide a new "lens" to see the data in a more holistic way'. Similarly, the use of multiple case studies enables valuable new insights by 'revealing informal aspects and stimulating the emergence of a fresh understanding of the processes and interactions among different stakeholders' (p. 937).

Our case studies (see Table 3) were chosen in close consultation with partner health services in Australia and New Zealand. Selected based on their size and age, population dependency, historical climatic records and future climatic predictions, the three case studies comprised Coffs Harbour Base Hospital, Ceduna District Health Services and Whangarei Hospital. These facilities had previously been subjected to flash floods, heatwaves, and floods caused by storm surges respectively.

Table 3 Case studies

Case study	Description
1. Coffs Harbour Base Hospital	Coffs Harbour Base Hospital is the largest hospital on the North Coast of NSW and is the area's major referral hospital. Many other health facilities rely on this hospital in the case of a major disaster. The hospital serves a population of about 100 000. Coffs Harbour is classified as a sub-tropical area with warm to hot summers and mild winters and, due to its geographical location, flooding and storms are relatively common. In May 2009 floods resulted in the evacuation of 148 residents from local aged care facilities and in November 2009, Coffs Harbour was again declared a natural disaster zone following flooding which caused damage to local infrastructure.
2. Ceduna District Health Services	Ceduna District Health Services provides the primary healthcare to the residents of Ceduna and surrounds, along the far west coast of South Australia. Ceduna has a population of 3500 people and 24% of the population are Aboriginal and Torres Strait Islanders. Ceduna is an arid zone with hot dry summers and very high temperatures. Although extreme heat is common in Ceduna, periods of prolonged temperatures in the mid 40 degrees Celsius range have increased in frequency and intensity in recent years.
3. Whangarei Hospital	The city of Whangarei is located 160km from Auckland, New Zealand and is the largest urban centre in the Northland region, serving a population of about 75 000. The Northland region has a sub-tropical climate with warm humid summers and mild winters. In summer and autumn, storms of tropical origin may bring high winds and heavy rainfall from the east or northeast. In 2007, Whangarei had its wettest winter since 1973 producing widespread severe flooding and landslips throughout much of Northland. Many buildings were washed away, homes flooded, and many motorists were stranded on flooded roads. Whangarei Hospital was forced to use emergency generators, water supplies were affected and thousands of residents were left without phones and electricity.

Case study data were collected using a proprietary system called 'Risk and Opportunity Management System' (ROMS) (Cell-Media, 2011). Using ROMS, a series of independent focus group sessions were conducted in each case study hospital with key stakeholders who would be involved in the response to an extreme weather event scenario. This scenario was different for each hospital and to ensure it was relevant, was developed in consultation with UNSW's internationally recognized Climate Change Research Centre. The stakeholders involved in the ROMS workshops included facility managers, business managers, emergency staff, nurses, clinicians, hospital administrators, community health specialists. They were selected through a standard stakeholder analysis framework developed by Freeman (1984) which classifies stakeholders into three categories according to their importance to the problem being explored. Our focus group participants included only 'key' stakeholders who were critical in terms of their ability to influence and be influenced by an extreme weather event. In the ROMS workshops key stakeholders are required through a structured brainstorming exercise to first agree key objectives in responding to an extreme weather event, then to identify and assess the risks and opportunities that may affect the attainment of those objectives, and finally to minimize identified risks and maximize opportunities. ROMS (Cell-Media, 2011) manages this process in a systematic and consistent way and records the results in a multimedia format. Transcripts of the workshops were then analysed using content analysis to map the interplay of the many interdependent sub-systems identified in each case study workshop.

The strength of the ROMS focus-groups was their ability to provide insights into the participants' knowledge, largely based on past experience. The structured approach of ROMS ensured uniformity of discussions in each case study, thus reducing potential bias and facilitating easier cross-case study analysis. Within the detailed discussions that occurred in these intensive one-day workshops, many references were made to other actors and resource flows and it is these references which underpinned the construction of the RPDs.

In order to identify system interdependencies from the ROMS focus groups, we analysed co-occurrences of comments from our focus group participants using a pattern recognition technique recommended by Guest and McLennan (2003). By cross-referencing these multi-stakeholder accounts, we were able to construct a more accurate picture of what these dependencies and relationships were in practice. Table 4 shows an example of transcript data relating

Table 4 Coding of interdependencies

Just-in-time models for logistics resulting in reduced on-site stock levels	Depends on …	
1.44.10 *PARTICIPANT 1*—[with staffing], you're talking about getting local people into the hospital, whereas your food comes from Casino, your linen comes from Lismore and your stores from Newcastle. So you are talking about a delay of say, a few hours.	Hospital building	Food
	Hospital building	Linen
	Hospital building	Stores/ supplies
1.45.20 *PARTICIPANT 2*—Again, [we] need to define what the essential supplies are first then we have a better chance of making them available for the period needed.	Food	Contractor
FACILITATOR—Can we put a clause in contractor's contracts so that they must provide during an emergency?	Linen	Contractor
PARTICIPANT 2—[we are] already doing that.	Stores/ supplies	Contractor

to the risks of not having enough essential supplies on site due to the just-in-time delivery model for logistics in one case study hospital. Thematic nodes from the passage were identified, such as 'hospital building', 'food', 'linen', 'stores/supplies' and 'contractors', and how one item depends on another was established at this stage. This process requires a level of judgement from the researcher but the risk of subjectivity in analysis was minimized by constant comparison of one link against another.

In terms of the mechanics of the production of RPDs, Sutrisna and Barrett note that there are no universal standards or formal techniques (Sutrisna and Barrett, 2007). Our use of RPDs was to some extent similar to Sutrisna and Barretts' cross-case study comparisons and, like them, we found it useful to standardize the RPD symbols across all three case studies to represent the components of the system in order to achieve a degree of consistency. Sutrisna and Barrett cite the caveat from Checkland and Scholes that RPDs have to be considered idiosyncratic in that they show the preoccupations of their compilers to express relationships and value judgements by finding/using certain symbols to convey the correct 'feel' of the situations (Checkland and Scholes, 2005).

Results and discussion of findings

Before progressing to an analysis of the RPDs it is important to point out that the RPDs illustrated below were used to complement linear lists of risks which were generated by using traditional risk analysis methods in the first stage of the research. We have reported these in previous papers (Carthey *et al.*, 2010; Loosemore *et al.*, 2010, 2011). The advantage of the RPDs over the traditional 'laundry list' approach is that the interdependency between different elements of the system can be better understood. The RPDs for each case study system under stress (subject to a relevant extreme weather event scenario) are illustrated in Figures 3, 4, 5.

The advantage of the RPDs depicted in Figure 3, Figure 4, Figure 5 is that they can be analysed visually to reveal information about risk in the system in question. What is initially apparent is that many of these RPD elements were not evident before the extreme weather event happened (see Figure 6) indicating that the boundary of the hospital system expands beyond the 'normal steady state' in these situations, as do connections between different elements of the system. Extra elements at risk introduced by the onset of an extreme weather event include aged care facilities, emergency command centres, telecommunications services, external emergency services, staff property management, accommodation for staff dependants, transport fleets, backup power and water supplies. It is also evident that in the stressed system medical staff and roads become much more important parts of the system (as evidenced by the increase in dependencies around them).

It is also evident that the hospital system during an extreme weather event is part of a much larger system over which hospital facility managers are likely to have limited control. This raises numerous governance issues for hospitals in managing the impacts of extreme weather events. For example in an emergency situation the residents of an aged care facility may have to be evacuated to the acute hospital (see Figure 3). The fact that an aged care facility may be privately owned and would not normally come under the control of hospital management is overridden by the need to provide healthcare in time of stress. Other facilities such as emergency command centres, outsourced material supplies and staff property also introduce components which are additional

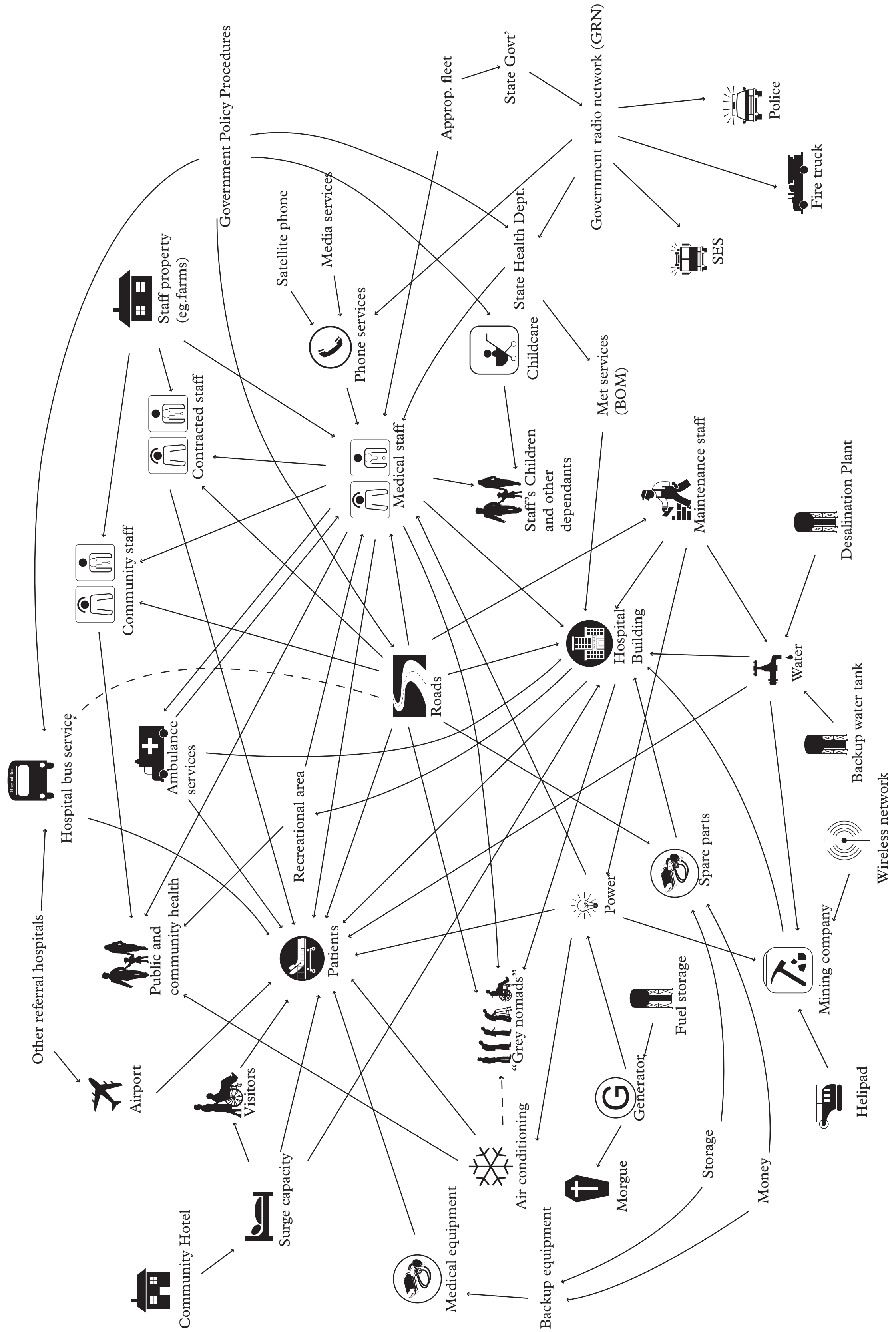

Figure 4 Rich picture diagram of Case Study 2 during and after an extreme weather event

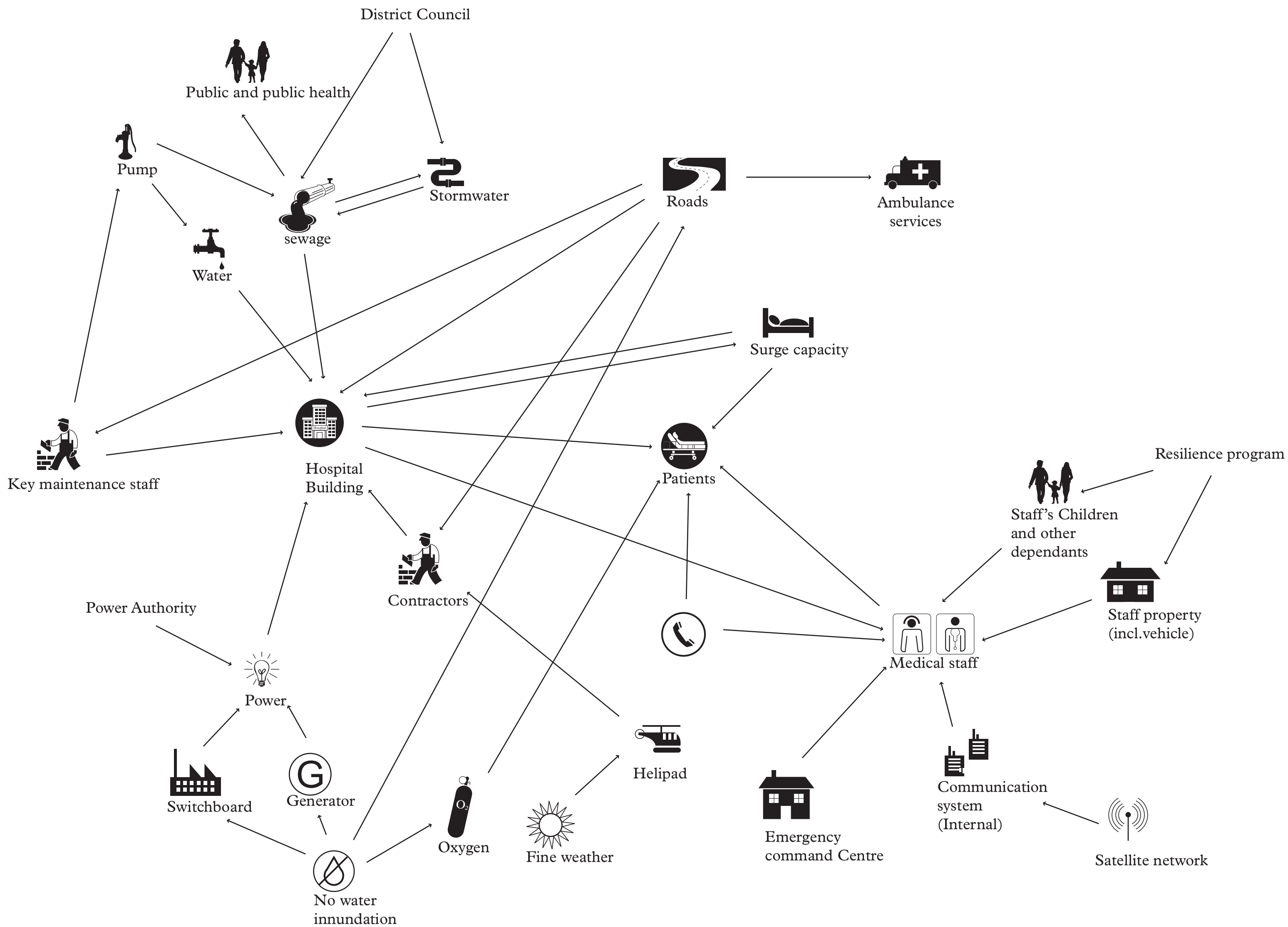

Figure 5 Rich picture diagram of Case Study 3 during and after an extreme weather event

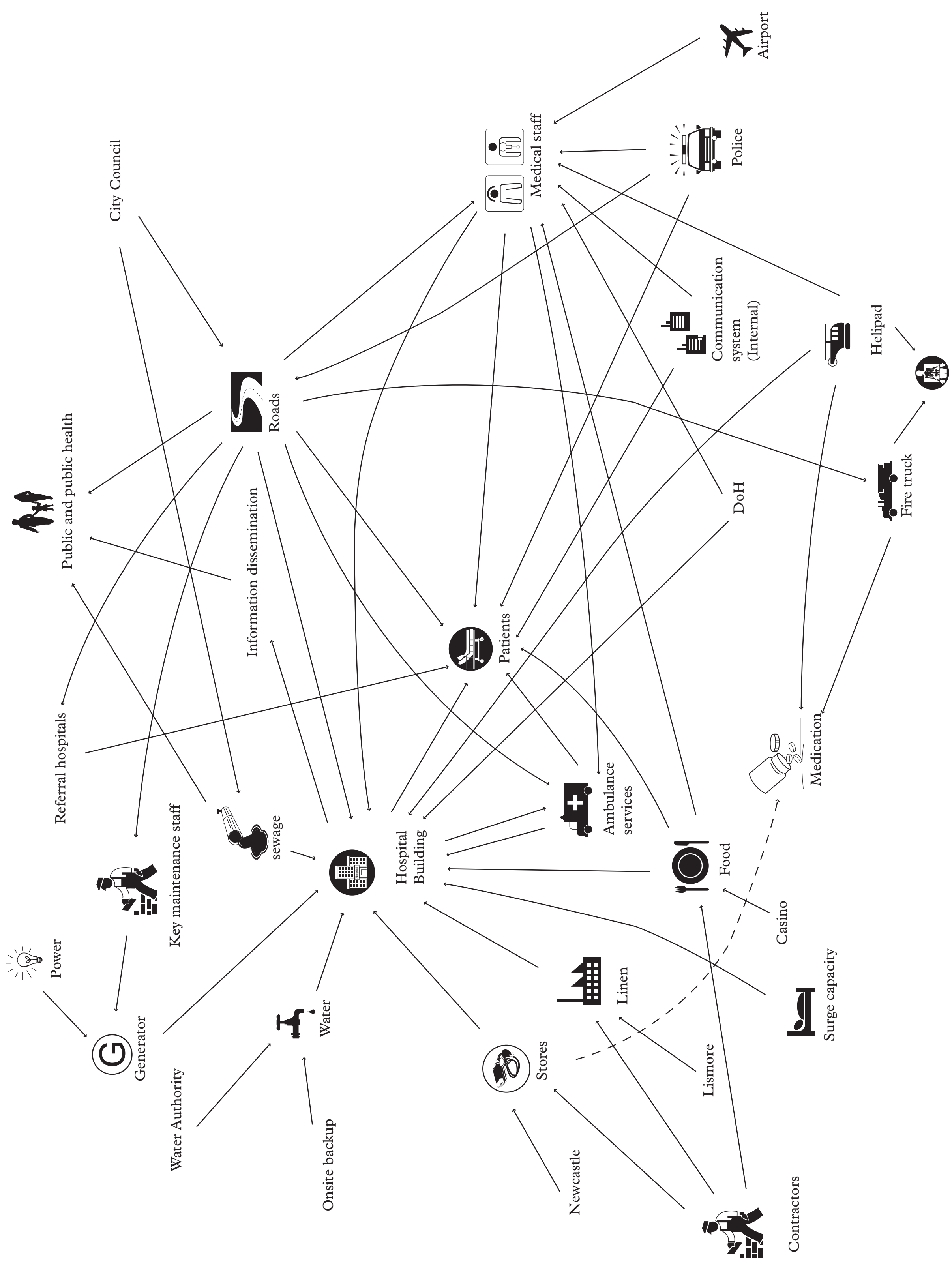

Figure 6 Rich picture diagram of Case Study 1 during normal weather conditions

to the norm in terms of governance arrangements. As the name implies emergency command centres only come into play during an extreme weather event or similar crisis situation. Staff property in Case Study 1 refers to the loss of 90 cars which were inundated in a staff car park which had been inadvertently designed as a water retention area.

While the arrows on the RPD do not represent the strength of dependency between different system elements (as they may do in a social network analysis—see for example Heng and Loosemore, 2011), it is possible to reach some conclusions from the patterns of interdependencies which emerge. For instance, using long-established and widely tested measures of social structure from the field of social network analysis it is possible to identify three types of assets in terms of their centrality to the system: those with high 'in-degree' centrality; those with high 'out-degree' centrality; and those with high 'betweenness' centrality (Scott, 1991). All of these critical assets are high risks but in different ways.

In-degree centrality

A node with a high in-degree centrality has high numbers of incoming arrows and depends heavily on resources from other critical assets. These are therefore highly central but also highly vulnerable points within the system during an extreme weather event since they have a high dependency on other nodes within the system. For example, across all three of our case studies, it is apparent that the 'patients' and the 'staff' nodes depend on a large range of resources. Patients require available and suitable staff to deliver care to the patients, a functional road infrastructure to provide access to and from the hospital, and a functional hospital building from which treatment could be received. Staff require adequate communication channels, safe access to the hospital, and peace of mind that their dependants (e.g. children; property) are out of harm's way. Other nodes with a high in-degree centrality include the visitors (Figure 3) and the public (Figure 4), which in an extreme weather event scenario may depend on the healthcare system to provide communication, medical advice or treatment, and shelter in the form of the hospital building. The high dependency of these parts of the system on other parts of the system implies that they need protecting with built-in redundancy or alternative backup supplies, since their functionality is dependent on the functionality of others.

Out-degree centrality

In contrast to those nodes with a high in-degree centrality, nodes with a high out-degree centrality are critical assets with many outgoing arrows. These drive the system and must be maintained to keep the system operating. In reality these nodes may be leaders in the system or communication technologies which are designed to send out instructions. For example, in all three rich picture diagrams the road network is a node with a very high out-centrality. This highlights the importance of being able to gain access to the hospital during a crisis, not only for the patients, but also for external contractors delivering medical and other supplies, for staff and ambulance services, and for transferring patients to other referral hospitals. It is interesting to note that the ROMS results have identified road access as a high risk regardless of the nature of the event, which in our case studies range from a short event typically lasting up to 48 hours (flash flooding) to a prolonged event lasting more than two weeks (heatwave). In building system resilience, the high dependency of other parts of the system on these elements requires that they are resourced appropriately and ring-fenced during an extreme weather event to ensure that they can remain functioning.

Betweenness centrality

Those assets with high betweenness centrality sit 'between' other assets or groups of assets and control the flow of resources between them. These nodes act as 'valves' in systems and represent high risk points in the network because if they break down or malfunction the whole system splits into independent silos. There are several examples of betweenness centrality observable in the three RPDs. For example, in Case Study 2 (described by Figure 4), the government radio network and the phone services control the flow of information between the state government and the emergency services such as the State Emergency Services (SES), the police and the fire brigade. These parts of the systems act as brokers, connecting otherwise disparate parts of the system which need to interact during an extreme weather event. To protect the whole system from the potential vulnerabilities they present, it is useful to have alternative routes through which information can flow in the case of such an event.

Clusters

It is also evident in many RPDs that there are clusters of assets that tend to have higher levels of interdependency than others. For example, in Figure 7 there seem to be three main clusters joined by three main nodes (roads, patients and ambulance). The danger in this type of network is that the system can break into separate parts and become dysfunctional if the connecting nodes are not maintained effectively. These

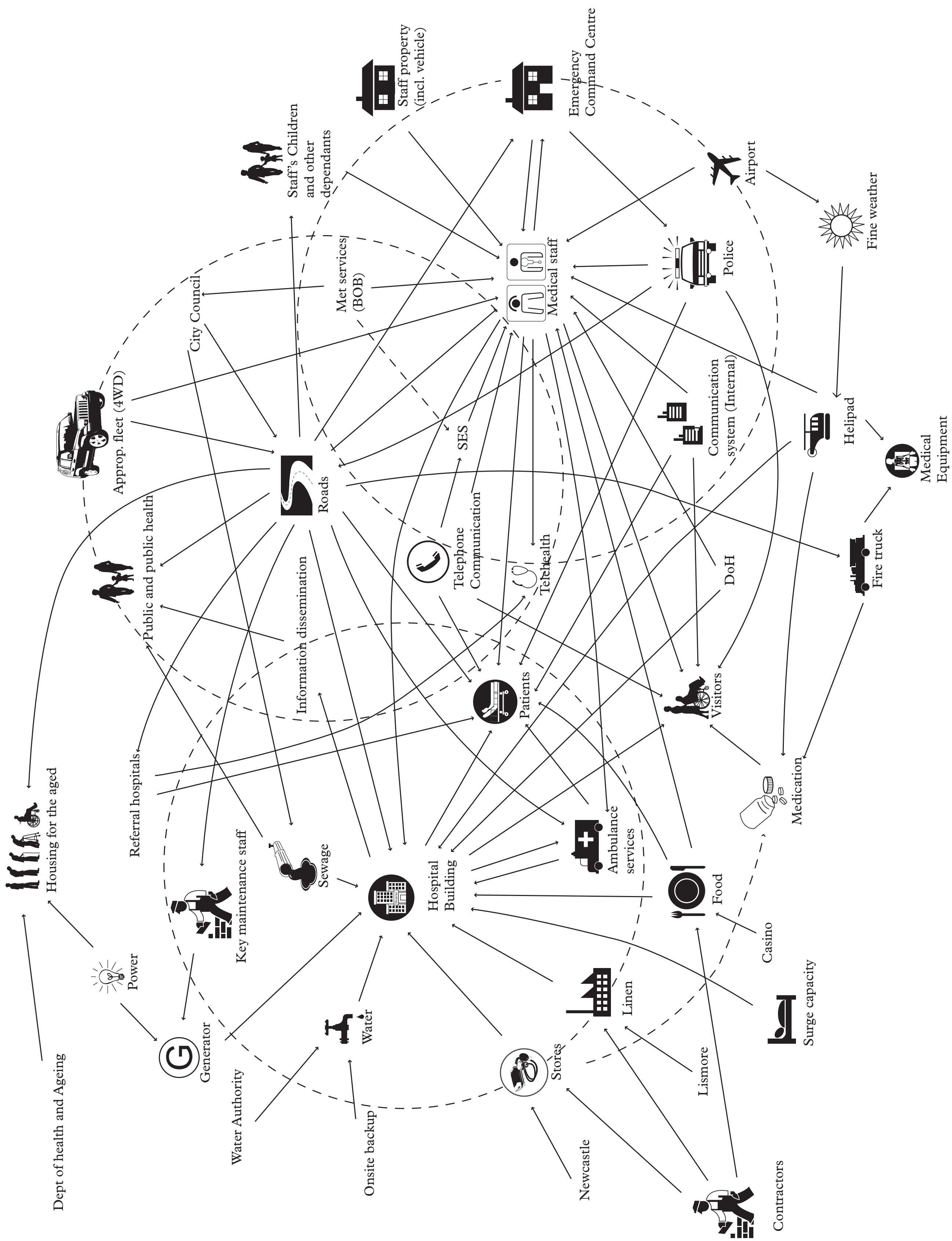

Figure 7 Clusters in Case Study 1

connecting nodes therefore represent high risk points in maintaining the integration of the whole network.

One of the advantages of presenting the system in this visual manner is the ability to gain an immediate and visceral appreciation of how items seemingly unrelated to the core objective of delivering healthcare are in fact highly interconnected. The three case studies yielded very different RPDs although there were common patterns and linkages to each. For example, all three cases showed a heavy dependence on road access, regardless of the geophysical distinction of each hospital and the type of scenario under discussion. All three cases identified contracted non-core staff (other than essential clinical staff) to be of significance in maintaining functionality of the hospital building, whether it be providing maintenance support for the generator, or delivery of goods and stores to the hospital. All three cases also identified the important role of staff dependants and property, especially the safety of the children of staff, on staff attendance at the hospital. By understanding the key drivers that may assist or hinder how each of the objectives is being met, any proposed strategy can be viewed with a clearer understanding as to how it may affect the whole system, not just the item at which it is originally targeted.

Conclusion

The aim of this paper was to explore the risk exposure of Australasian hospitals to extreme weather events by better understanding the complex system interdependencies within and around them. The theoretical contribution of this work is to challenge traditional linear methodologies which produce 'laundry lists' of risks which fail to consider the important interdependencies which exist within hospital organizations. Using a soft systems approach, our rich picture diagrams were able to illustrate for the first time that the boundaries of hospital systems expand during an extreme weather event, increasing the complexity of management in two main ways. First, in the increased number of stakeholders that need to be considered and second, in the increased interdependencies which are introduced. We also discovered that there are certain elements of this hospital system that become of central importance during an extreme weather event, whether it be a storm, flood or heatwave. These are the medical staff, the roads and the hospital building itself. What is clear from our research is that hospital buildings cannot be treated in isolation from the wider systems in which they exist. To understand the impact of an external extreme weather event on a hospital, they must be seen in this system entirety. The practical implication of our research for facility managers in considering how to respond to extreme weather events, is its revelation that it is not enough to focus on the physical aspects of healthcare infrastructure alone. Our results show that there is a whole collection of stakeholders whose interdependent interests and needs need to be considered in building adaptive capacity. This raises many interesting governance issues which we continue to explore in ongoing research.

It is clear from this research that an understanding of how to create and manage resilient healthcare infrastructure depends, in part, on developing a conceptual understanding of the complex relationships between the various components of a healthcare system which includes emergency services and command centres; off-campus hospital supplies; polyclinics; and aged care facilities. Methodologically we have shown how a critical realism paradigm and RPD approach can provide useful insight into these highly complex and dynamic system relationships, and as such, bring a fresh perspective to the design, construction and management of healthcare facilities, particularly in terms of the new challenges being imposed on both buildings and people by extreme weather events.

However, we finish with two qualifications. First, since our RPD data were collected by facilitated focus groups (and not in-depth interviews), there was a limit to the richness that could be captured and therefore included in the diagrams. While identifying co-occurrences is an acceptable way to understand the dataset, the conceptualization and understanding of the dataset in performing analysis could also be broadened in future research to form a more detailed understanding of the matter. Furthermore, although useful for representing interdependencies, RPDs remain a static representation of the systems our respondents discussed in our focus group sessions. There is no doubt that the system adapts and changes over time in response to these events, sometimes rapidly in response to a sudden crisis and sometimes slowly in response to a creeping crisis. The ability to assess the behaviour of the system over time would provide an even better understanding of the risks posed to healthcare systems by these events.

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