University of Southern Queensland

Faculty of Health, Engineering, and Sciences

AN ASSESSMENT OF RURAL ROAD NETWORK RESILIENCE AS CRITICAL INFRASTRUCTURE FOR COAL SEAM GAS DEVELOPMENT IN REGIONAL QUEENSLAND

A dissertation submitted by

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ABSTRACT

The Coal Seam Gas (CSG) and Liquefied Natural Gas (LNG) extraction and export industry forms a large part of the Australian Resource Sector, a driving force in the national economy. Given the nature of these industries, the vast majority of the development associated is located in rural and regional Australia. With these developments comes a significant increase in the volume of traffic, and the percentage of commercial vehicles expected to utilise the local road networks.

The local infrastructure networks in these areas have often been designed and constructed to cater to low volumes of traffic and as such will usually consist of a pavement and formation only, with little in the way of drainage infrastructure. This existing asset class leaves these roads and associated road networks vulnerable to heavy rainfall events and flood events, with these roads often suffering significant damage and requiring a substantial amount of repair work be undertaken before the road is returned to the regular level of service. As a result these networks are extremely susceptible to damage and disruption during flood events.

Following the significant damage caused to infrastructure networks in Queensland during the major Flood events of Tropical cyclones Tasha and Anthony in 2011, and Ostwald in 2013, the resilience of transportation networks during and after major flood events has come into consideration. Many communities were isolated during the flood events and many assets were not returned to full service for periods of up to 2 years following the initial event. This disruption of the transportation network not only caused physical damage to the network, but is estimated to have cost the Queensland economy in excess of $15.7Billion. (Easdown, 2011).

This research project aims to investigate the resilience to flooding of the local road network in the Wandoan Region of Queensland, Australia and the expected economic impacts on local CSG developments as a result of this level of resilience.

To meet the research objectives of this project, a literature review was undertaken to determine existing frameworks for the quantification of network resilience. From this study the Networked Infrastructure Resilience Assessment (NIRA) Framework developed by (Omer, et al., 2013) was selected as the most appropriate and suitable method of analysis.

The NIRA framework was applied to model the resilience of the Western Downs Regional Council’s (WDRC) Wandoan West Road Network during a flood event of 2011 event magnitude, and assess the financial implications of this resilience on local Coal Seam Gas (CSG) Development in the area. This was undertaken by the application of forecast traffic data provided by CSG Developers, and historic damage information collected by WDRC in delivery of the 2011 flood damage recovery program.

This initial analysis provided a benchmark level of performance against which the impact of proposed upgrades would be measured. This initial analysis identified three major links in the network as having the most potential for financial loss due to decreased level of performance following a flood event, with a cumulative cost per day to developers of $4,913.16.

Using this analysis as a benchmark of existing network performance, a series of proposed upgrades were modelled by reducing the impact of recorded defects on the network in accordance with the proposed upgrade type. The impact of these upgrades was shown in a decreased cumulative cost per day of $1,985.43. This relatively minor saving per day has the potential to save CSG developers millions of dollars in lost production and increased travel costs over the extended period to full network recovery.

From the comparison of these analyses, a number of conclusions regarding factors which may influence link resilience were drawn, and potential improvements and further work to the analysis were discussed. The analysis performed was determined to be a useful tool for identifying and quantifying vulnerable links in a road network, but collection of more detailed data would be required to have full confidence in the financial impacts calculated.

This research project is supported by the University of Southern Queensland and the project supervisor, Trevor Drysdale.

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Limitations of Use

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Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Samuel Jesse Fitzgerald

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Signature:______________________

Date:__________________________

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INTRODUCTION

BACKGROUND HISTORY

Resilience in regards to infrastructure networks refers to the response of the network to severe and catastrophic shock, such as natural disasters and flood events, and the network's ability to continue to meet an acceptable level of service during and after these events (Omer, et al., 2013). Such events have become more common recently as demonstrated by the significant flood events caused by Tropical Cyclones Tasha and Anthony in 2011, and Tropical Cyclone Ostwald in 2013. Both of these events resulted in significant flooding across the state of Queensland, and resulted in restoration and upgrade works to government infrastructure networks in excess of $13 Billion (Queensland Reconstruction Authority, 2014).

As a result of this and other international events, much attention has been given to the investigation of resilience in infrastructure and how relevant techniques can be implemented at all stages of the asset life cycle to increase the network resilience to shocks and disruptions. In order to accomplish this, an understanding of the current level of resilience held by a network is necessary.

There are currently a number of frameworks which aim to assess the level of resilience of a transport network. These include the Networked Infrastructure Resiliency Assessment (NIRA) frame work (Omer, et al., 2013), the framework proposed by (Bruneau, et al., 2003) for the quantitative assessment of the seismic resilience of communities, and the Three-Stage Resilience Analysis Framework developed by (Ouyang, et al., 2012).

In addition to the level of service provided by transport networks, it is also important to consider the many underlying economic factors which may indicate the priority of a particular road asset. These may include industries supplied by or dependant on the network, access of landowners to health and other services, and in the case of local government the asset owner's responsibility to landowners and the public.

As with any government organisation, intense scrutiny is placed upon local government when assessing and funding any capital works project. The use of public money and the constant consideration of political agenda requires all financial decisions be thoroughly evaluated and the most cost effective solution chosen. This constant review, coupled with a vested public and economic interest in a fully functional transportation network means that while upgrades to the road network are essential, all options must be fully evaluated in order to ensure best value in the use of public funds.

The Western Downs Regional Council's (WDRC) local road network was severely affected by the 2011 and 2013 flood events. These events resulted in extensive damage to the unsealed roads portion of the network, as well as significantly damaging much of the drainage infrastructure in the region. This damage resulted in isolation of remote rural communities and severe restriction of local primary industries.

The failure of these rural road networks during these flood events has highlighted the need for significant network upgrades in order to improve flood immunity and increase network flood resilience. However to accomplish this with the limited budget available to most rural Councils a thorough and detailed analysis of the current resilience of the network is required. From this the best value for money options can be selected for further investigation and possible inclusion in future capital works budgets.

In addition to funding of upgrades with the use of Local Government's capital works budget, significant external funding is available to Council in areas with a high amount of Coal Seam Gas development activity, such as the Wandoan region of the Western Downs Regional Council. This funding is provided by the resource company developing the area as a means of offsetting the impact that construction and operation traffic caused by the development would have on the existing road network. However, to gain access to this funding Council must be able to identify the benefits to the Resource Company provided by the proposed upgrades. An analysis of road network resilience, and the potential loss savings to the resource company in a flood event, would provide a clear justification for the full or partial funding of proposed road upgrades.

RESEARCH OBJECTIVES

This project proposes to undertake an analysis of the WDRC Local Road Network in the Western Wandoan region, which is currently being developed by both QGC and Origin Energy for the extraction, compression, and transport of liquefied natural gas. As a direct result of this development, traffic volumes in this remote rural area have increased dramatically. Due to this increase WDRC has put conditions on both companies to significantly upgrade Bundi Road, which connects the surrounding region to the Jackson-Wandoan Road and through this the Warrego highway which links southeast Queensland to Brisbane.

It is proposed through the analysis of the existing network, to determine the resilience of Bundi Road and surrounding roads to flood events, and through this the financial implications a disruption to this network would have on the CSG industry development in the area. From this analysis a series of recommended road upgrades would be modelled, and the network reanalysed with these proposed upgrades in place. This will provide a difference in expected financial loss during a flood event, which may then be compared to the estimated cost of the proposed upgrades in order to determine the value for money posed by construction of these flood mitigation measures.

Overview of Dissertation

This paper contains six chapters which broadly define the different section of this research project. A summary of these is given below.

Introduction A brief introduction to the consideration of infrastructure resilience, a summary of recent flood events and the need to consider resilience to flooding developed from this, and the specific considerations relating to infrastructure resilience in the West Wandoan region of the Western Downs Regional Council area.

Literature Review A review of the existing literature regarding the study and evaluation of a network's resilience to disruptions, an overview of the existing condition of the West Wandoan road network, and an overview of the impacts of recent flood events on this network.

Methodology A detailed investigation into the methodology required to meet the report objectives, including data collection and review techniques, boundary conditions for selection of data, an assessment of project risks, identification of required resources, and the project schedule.

Network Analysis The development of the network model from the collected asset data, and analysis of this network using historic flood recovery data collected. A second iteration will then be completed to analyse potential benefits and savings due to a series of proposed upgrades.

Discussion Comparison of the network analysis results to identify trends in the data, and draw conclusions based on correlations between the virtual network and the physical network.

Conclusions Review of the results if the network analysis as well as the proposed upgrades will identify areas of concern in the existing network which may benefit the network as a whole by upgrade.

1 LITERATURE REVIEW

1.1 INTRODUCTION

Resilience in regards to infrastructure networks refers to the response of the network to severe and catastrophic shock, such as natural disasters and flood events, and the network's ability to continue to meet an acceptable level of service during and after these events (Omer, et al., 2013). Such events have become more common recently as demonstrated by the significant flood events caused by Tropical Cyclone Anthony and Tasha in October 2010 and February 2011, and Tropical Cyclone Ostwald in 2013. Both of these events resulted in significant flooding across the state of Queensland, and resulted in restoration and upgrade works to government infrastructure networks in excess of $13 Billion (Queensland Reconstruction Authority, 2014).

As a result of this and other international events, much attention has been given to the investigation of resilience in infrastructure and how relevant techniques can be implemented at all stages of the asset life cycle to increase the network resilience to shocks and disruptions. In order to accomplish this, an understanding of the current level of resilience held by a network is necessary.

1.2 RESILIENCE AND THE RELEVANCE TO THE MODERN WORLD

Due to the significant network disruption and cost associated with recovery caused by natural disasters and acts of terrorism in the modern world, much focus has been given to enhancing the ability of these networks to function adequately and recovery quickly from these disruptions.

(Bruneau, et al., 2003) defines community seismic resilience as "the ability of social units (e.g. organisations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimise social disruption and mitigate the effects of future earthquakes. While (Ouyang, et al., 2012) defines resilience as the joint ability of infrastructure systems to resists (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation. For the purposes of this paper, resilience in regards to regional transportation networks will be defined as the ability of the network to reduce the occurrence of disruptive events, minimise the network disruption due to these events, and recover to an adequate level of service in a reasonable and effective timeframe following these event.

Resiliency in urban areas may mean a disruption in the level of service provided to road users, while in a regional or remote area, a disruption may mean isolation from necessary services for short or long periods of time. The primary reason for this is the lower class of asset commonly found in these regional areas. The lower class of asset is justified due to the cost of construction compared to the number of expected users. The compromise in this reduced minimum level of service is the increased vulnerability of these roads to flood and heavy rainfall events.

With Construction traffic for Phase 2 QGC developments in the Wandoan Area expected to be greatly in access of the low traffic volumes the roads usually cater too, the potential for loss due to a flood event is substantially higher, drawing attention to the resiliency or lack there of, of this network to flood events.

1.3 The Wandoan West Road Network

This section of the literature review is intended to give a brief overview of the Wandoan West Road Network, particularly the area in the region of the proposed and existing CSG developments. This summary will provide an understanding of the current state of the road network in this area, the current level of service offered, and the susceptibility of the network to flood events.

1.3.1 Network Overview and Boundary

The Wandoan Local Road Network consists of approximately 518.1km of road, of which 199.8km is sealed and 318.3km unsealed (Moloney Systems, 2011). Due to the scarcity of quality granular pavement materials in the local area, this proportion of sealed to unsealed roads is higher than would be expected in most regional areas, as the cost to supply pavement material often means that sealing a road provided lower whole of life costs than gravel resheeting.

For the purpose of this paper, the network to the west of Wandoan, north of Bundi Road, and east of the Roma-Taroom Road will be considered. This portion of the road network will be referred to as the Wandoan West Road Network (WWRN). This portion of the network can be seen in figure 1.1 below. This image is extracted from Appendix A – Wandoan Rural Surface Type.

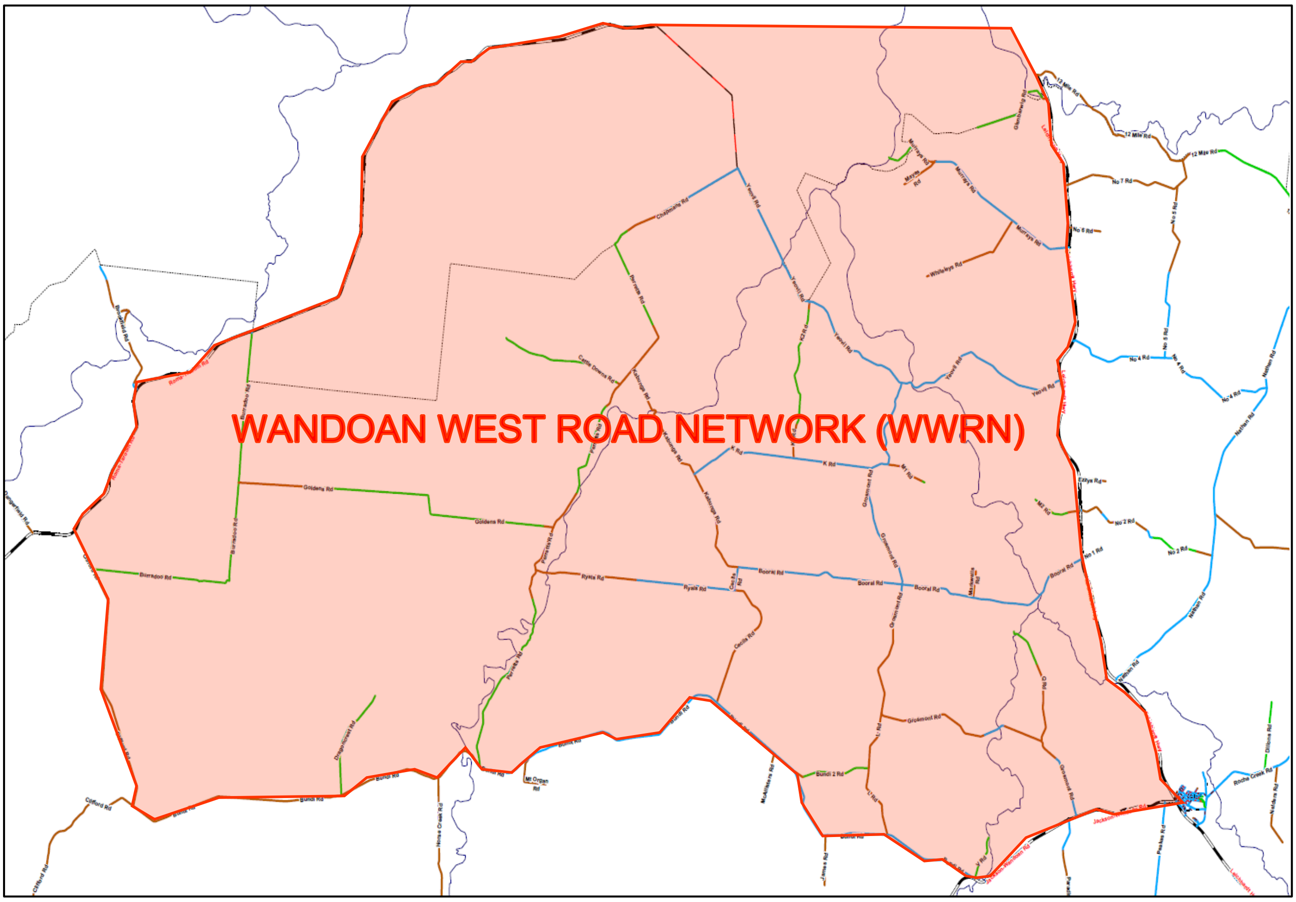


Figure 1.1 - Wandoan West Road Network extents

These network extents were chosen for the primary reason being that this area, specifically the south-western section, is the major centre for CSG development in the Wandoan Area and because of this is the area planned for major upgrades of the road network. This provided the motive for selecting the region, while the network boundary was chosen as it encompasses the area between three major arterial roads, being Roma-Taroom Road to the west, Jackson-Wandoan Road to the south, and the Leichardt Highway to the east. These three roads link the major population centres of the region, as well as linking the region to the Warrego Highway which provides access to south-east Queensland, and the cities of Toowoomba and Brisbane. Due to this the majority of labour, plant, and materials to be used in all development in the area will use one of these roads to access the region. Effectively, the WWRN shown encompasses a subsection of the network with these three arterial roads providing access to the larger network.

1.3.2 Current Network Conditions

As shown in Appendix A – Wandoan Rural Surface Type, and the extra figure 1.1, much of the key sections of the WWRN are sealed bitumen surfaces (shown in blue), with links between these sealed roads often being unsealed (shown in brown), or formation only (shown in green) meaning the road is formed of insitu material only.

1.3.2.1 Existing Road Surface Types

Of the sealed sections of road, the bitumen seal width ranges between 4 and 8 meters, depending on the traffic volume and composition, and road hierarchy. A seal width of 4 meters is suitable for use by a single vehicle at a time only, with approaching traffic being forced to partially leave the sealed surface in order to pass safely. This causes wearing of the road shoulder, and in wet weather conditions can prove hazardous to traffic, particularly heavy commercial vehicles which can cause severe deformation of the road shoulder under these conditions. Figure 1.2 below illustrates well typical shoulder damage to a sealed road due to trafficking of unsealed shoulders during wet weather.

Figure 1.2 – Example of a typical rural road with sealed surface of 6 meter width (Bungaban Road, Wandoan)

The unsealed roads in the Wandoan Road Network typically have a pavement width of 5 to 6 meters. The pavement is constructed of a crushed granular material, typical to the region is crushed laterite, and is intended to provide a high strength trafficable surface without the additional construction cost of a bitumen seal. These roads typically experience only local traffic of low volume, such as that shown of the rural feeder in WDRC Standard Drawing for Roads in Appendix E, and are often capable of an operating speed of between 80 and 100km/h dependant on road geometry. An extract of this is shown below. These unsealed roads require more frequent maintenance than sealed roads, often requiring grading annually or bi-annually, and requiring a resheet of gravel material every 15 years (Moloney Systems, 2011). These roads will be trafficable to a reasonable extent in periods of wet weather, though may become slippery requiring a reduction in operating speed. Often heavy vehicles will be unable to traffic these roads during extended periods of wet weather, or if trafficking these roads, will often cause significant damage to the road due to deformation and rutting of the pavement.

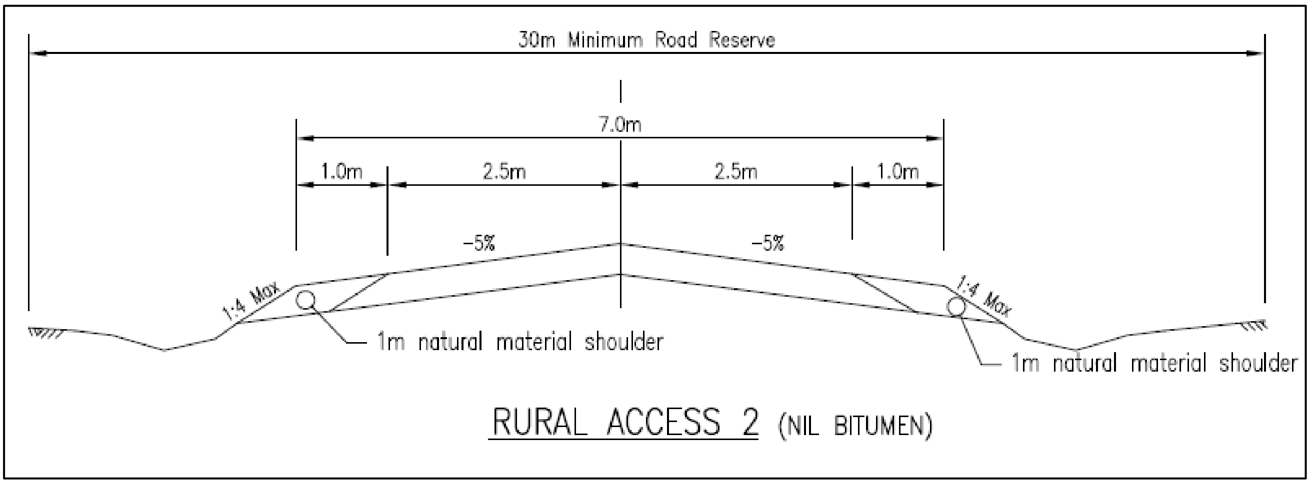


Figure 1.3 - Extract Appendix E, Typical Road Cross Sections (WDRC)

The figure 1.4 below is an excellent illustration of the potential vulnerabilities of a pavement only road. This photo of Old Chinchilla Road was taken during delivery of 2013 Flood Damage restoration works. Note the road surface seems to be in good condition and suitable for the traffic volume of the road, however in the invert shown approximately half way along this section, moisture has penetrated and weakened the pavement resulting in failure. The darker material would indicate that the insitu subgrade has been forced though the pavement contaminating the pavement material, and as such the entire damage section will require pavement replacement with new material.

Figure 1.4 - Example of Typical Unsealed pavement only road for the Wandoan Region (Old Chinchilla Rd, Guluguba)

Formation only roads are typically minor roads which provide access only to local landowners, of which there are few. For example, Burradoo Road to the west of the WWRN recorded a total AADT of 6 vehicles per day at last count in 2005 (Western Downs Regional Council, 2009). These formation only roads often don't service enough of the community to warrant the expenditure of a gravel pavement, and as such provide only an absolute minimum level of service. These roads often require minimal maintenance due to the low traffic volumes experienced, but are often untrafficable under wet conditions.

Figure 1.5 – Example of typical formation only road, Wandoan (Perretts Rd, Bundi)

Figure 1.5 shows a typical formation only road operating well under dry conditions. Evidence of wheel rutting indicates the low tolerance of these formation only roads to traffic during wet weather events.

1.3.2.2 Existing Drainage Structures

Of the existing drainage structures in the Wandoan Road Network, Bridges constitute approximately half of all major flow crossings. Of the existing bridges in the Wandoan Region, the majority are timber pile and girder bridges. These bridges prove common due to the relative low cost to construct at the time of construction. Constructed in the 1960’s or 1970’s, labour and hardwood timber were both inexpensive and plentiful resources in the region, and because of this and the relative unavailability of concrete, the majority of the drainage structures in the area were constructed in this manner. These bridges were often constructed to a for a T44 maximum design vehicle, indicating a maximum load of 44 tonnes. As such these bridges are unideal for use by the modern road trains. There are a number of timber bridges in the WWRN, located on Bundi, Yeovil, Booral, and Grosmont Roads.

Figure 1.6 - Timber Bridge – Bundi Road, Wandoan

The alternative to timber bridges at major creek crossings in the Wandoan Area are large Reinforce Concrete Box Culverts (RCBC). The majority of these units were constructed of cast insitu reinforced concrete and prove more durable and suitable to modern vehicles than the timber bridges of the region. However, due to their nature, these culverts are constructed at low level crossings only, meaning that these structures are often inundated and submerged during large flows. During minor to moderate flows however these structures provide a safe and trafficable means of crossing for traffic.

Figure 1.7 - Large Cast Insitu Cuvlert

At minor crossings or areas where water will frequently cross a road, the most common treatments are small culverts, similar to the above but of hydraulic area ≤3m², or concrete floodways. Concrete floodways are often used in areas where fast moving flows will cross a road, or where slow flows will inundate the road for extended periods of time. These floodways essentially do not provide any flood immunity to a road during the time of the event, but provide a much more durable asset which is less prone to the failures that would be experienced if a sealed or unsealed granular pavement road was constructed in the same area.

Figure 1.8 - Concrete Floodway – Bundi Road, Wandoan

1.3.2.3 Existing Traffic Volume

As shown by Appendix 2 – Historic Traffic Volumes Wandoan Rural, the historic traffic volumes for Bundi Road was 117 vehicles per day, with 36% Heavy Vehicles in January 2009. Considering the road Hierarchy in the network, as shown in Appendix 3 – Wandoan Rural Road Hierarchy, this count is modest. The road status as a Rural Collector refers to its role in the network of collecting all traffic in the Eastern Wandoan Area and transporting this to the Rural Arterial roads of Jackson-Wandoan road and the Leichardt Highway, which run between major population centres.

1.3.3 Forecast Network Conditions

The major impact to WWRN road conditions due to CSG developments in the region is a significant increase in traffic volume on these local roads. Data provided to the Snowy

Mountains Engineering Corporation (SMEC) by QGC indicate and expected construction traffic of 433 vehicles per day on average, for a period of 1.5 years (SMEC, 2014). This means an increase in AADT of 370% during this construction period, and an increase of 45.2% due to operational traffic over the following 8 years. This traffic data is shown below in figure 2.1.

Item	Road	Adopted Values	
		Short Term (Construction) (Data from Schedule P6 Project ID:QP2T1EX Oct 2013 report)	Long term (operation traffic + background traffic)
AADT	Bundi Rd "A" (between Cecils Rd and Jacksons Rd)	433 (for 1.5 years)	150 +20 =170 (for 8.5 years)
	Bundi Rd "B" (between Cameron Access and Cecils Rd)	394 (for 1 year)	100 +20 =120 (for 9 years)
	Bundi Rd "C" (between Perretts Rd and Cameron Access)	388 (for 1year)	100 +20 =120 (for 9 years)
	Bundi Rd "D" (between Dragoncrest Rd and Perretts Rd)	259 (for 1 year)	100 +20 =120 (for 9 years)
	Dragoncrest Rd (between Arthur Access and Bundi Rd)	259 (for 1 year)	100 +20 =120 (for 9 years)
%HV	All Roads	Assumed: 25%	Assumed: 15%
R	All Roads	Nil growth over short term	Adopt 3% annual growth
LDF	All Roads	1.0 for design lane	
DF	All Roads	0.5	
ESA/HV	All Roads	2.5 (Austroads 2008, Table 7.8)	
Design Life	All Roads	10 years	

Notes: AADT = Annual Average Daily Traffic; DF = Direction Factor; %HV = Average percentage of heavy vehicles; LDF = Lane Distribution Factor, R = Annual Growth Rate; ESA/HV = Average number of Equivalent Standard Axles per Heavy Vehicle.

Figure 1.9 - Design Traffic Summary

While this increase in traffic does not directly affect the resiliency of the Wandoan West Road Network, it does dramatically increase the commercial and community dependency on the network, as well as substantially increasing the repercussions of a network failure. This concept is expressed in figure 1.2, using the principles proposed by (Omer, et al., 2013) as detailed in section 11 of this chapter in terms of travel time for road users.

Scenario 1		Scenario 2	
Traffic Volume = 117 vpd		Traffic Volume = 433 vpd	
V =	117	*V* =	433
t_1 =	2	t_1 =	2
D =	1	*D* =	1
R =	0.6	*R* =	0.6

Calculate travel time after disruption using: $t_2 = \frac{t_1}{R}$

t_2 =	3.333333	t_2 =	3.333333

Calulate cumulative additional travel time due to disruption to express reduced network performance using:

$$P = V(t_2 - t_1) * D$$

Cumulative Extra Travel Time (hours):

P =	**156**	*P* =	**577.3**

Definition of variables:

V =	Traffic Volume (vehicles per day)
t_2 =	Travel Time post-Disruption (hours)
t_1 =	Travel Time pre-Disruption (hours)
D =	Duration of Network Disruption (days)
P =	Measurement of Reduced Network Performance (additional travel hours)
R =	Reduction in Network Capacity (expressed as a fraction)

Figure 1.10 Increased consequences of network failure due to increased traffic volume

As shown above, an increase in traffic volume is directly proportional to increases in the measures of reduced network performance. To analyse this further, assuming an hourly rate per road user of $35/hr, this decrease in network performance could be expressed as an additional cost to the local community of $14,745.50. In order to reduce the impact of this disruption, additional measures would be required which either reduce the severity of the disruption (R value), or reduce the duration of the disruption (D value).

Though a gross oversimplification of the NIRA Framework developed by (Omer, et al., 2013), figure 1.2 illustrates well the concept of increased potential for loss, or increased consequence of road network failure due to increased traffic volume.

This increased potential for loss is a currently developing issue in the Wandoan West Road Network. This paper aims to investigate this increased potential for loss due to network resilience, and the financial implications this would have for all road users, particularly road traffic involved in the development of CSG facilities in the area.

To offset the dramatic increases in traffic volume, QGC and Origin Energy are in the process of constructing a number of upgrades to the WWRN. These proposed and in process upgrades will be detailed and analysed in the Analysis chapter of this report.

1.4 Impacts of Significant Flood Events

1.4.1 Past Flood Events

WDRC experienced significant network damage and disruption in the years 2010-11, and 2013 due to Tropical Cyclones Tasha and Anthony from November 20 to February 2011, and Tropical Cyclone Ostwald in 2013. These events can be identified in the chart below created from BOM historic rainfall data for station 35014 located at the Wandoan Post Office (Australian Government Bureau of Meteorology, 2015).

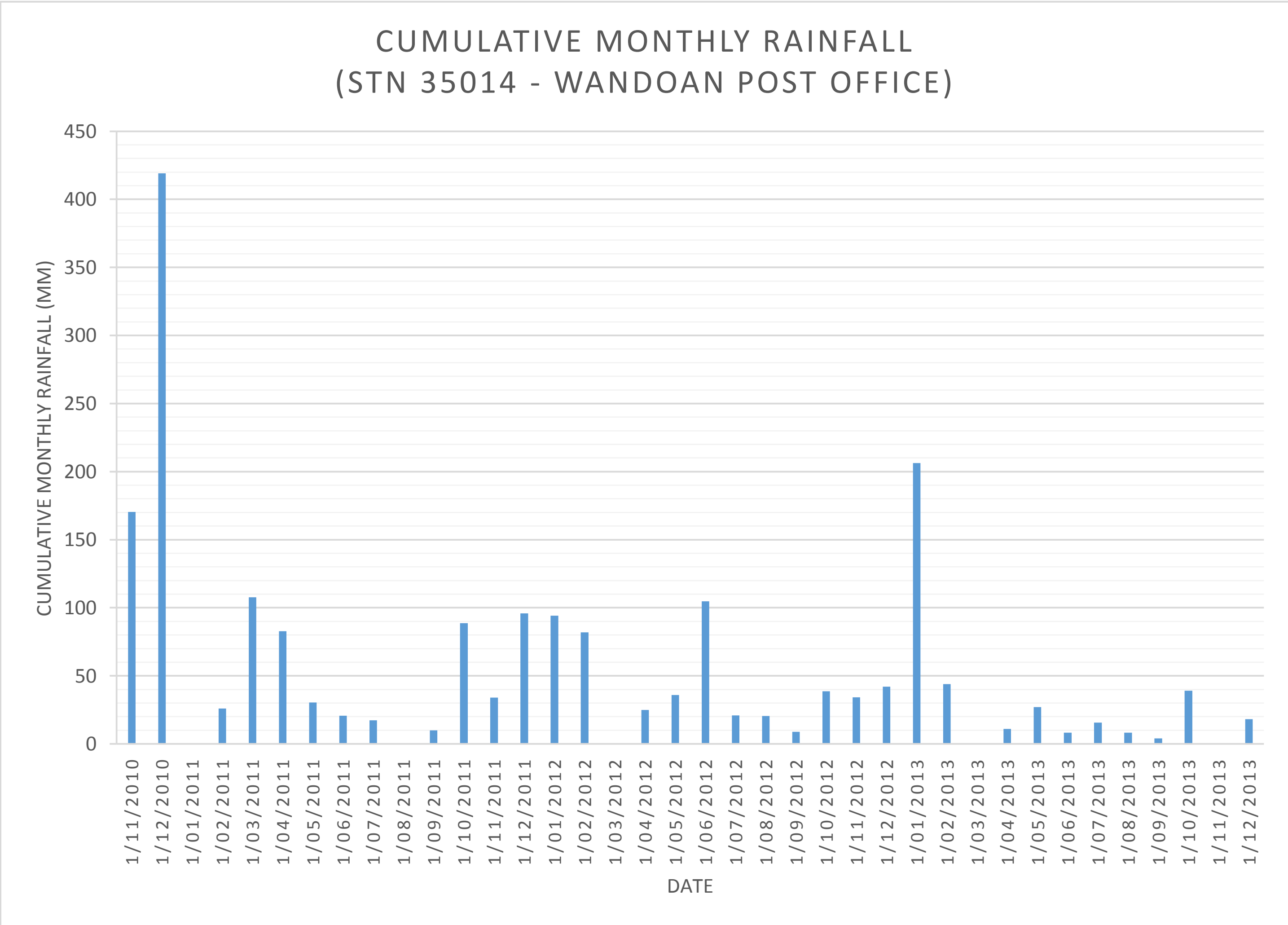


Figure 1.11 - Cumulative monthly Rainfall Data (Wandoan Post Office) 2010-2014 (Australian Government Bureau of Meteorology, 2015)

Note that due to a lack of records regarding road closure durations and extents during both of these events, durations for road closures have been determined by interview with WDRC Staff present in the area during the time of the events, and involved in the subsequent emergent and restoration works.

1.4.1.1 2011 Event – Tropical Cyclones Tasha and Anthony November 2010 – February 2011

Due to widespread torrential rain caused by Category 1 Cyclone Tasha in December 2010, and Category 2 Cyclone Anthony in January 2011, large swathes of the Western Downs Regional Council road network were inundated as tributaries of the Fitzroy River Basin reached and exceeded their natural capacity. This flooding of the Fitzroy Basin was determined to be a 1% AEP Event, meaning that the probability of a rainfall event of this magnitude is approximately an average of once every 100 years.

This widespread flooding caused massive disruption to the Wandoan Road Network, with all bridges in the region being submerged for a period of 2 days, with some low lying bridges remaining submerged for up to 2 weeks. Following floodwaters receding these roads became trafficable, though many were significantly damaged due to flow across the road way, or damage to drainage structures. Further to this, many of the roads that weren't damaged outright by inundation were weakened due to moisture penetration and saturation of the granular pavement. This weakening of the road resulted in damage once exposed to traffic loads, resulting in potholes, pavement deformation, and damage to the bitumen seal, and rutting.

The rectification of this work was undertaken in two distinct stages. The emergency restoration work, referred to as emergent work, and the restoration of non-hazardous defects. The emergent work period takes place immediately following the flood event, with works identified as dangerous and in need of emergency repair by WDRC staff, and being immediately repaired dependant on resources. The restoration work period can occur much later, due the time taken for the asset owner (WDRC) to gather data and submit claims to the QRA, and the time taken for the QRA to assess the claim to determine eligibility. Many local councils will not proceed with restoration work until given approval for the eligibility of the work by QRA. This is to minimise the risk to council of additional expenditure, should the work be completed and then determined to be non-eligible.

The figure 1.12 demonstrates the extent of the flooding due to the 1% AEP event associated with Cyclones Tasha and Anthony.

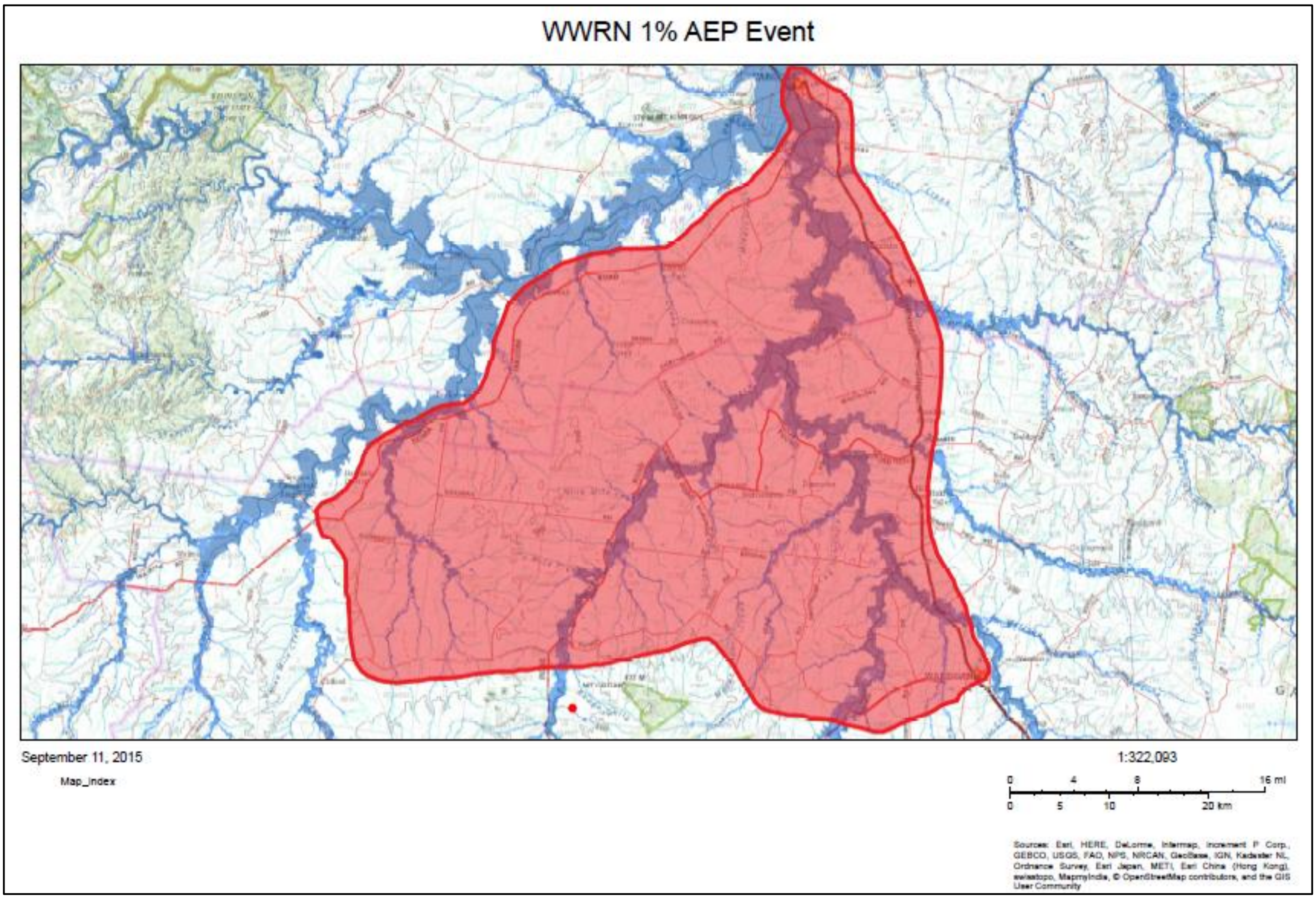


Figure 1.12 - 1% AEP Event footprint - Fitzroy Basin (Department of Natural Resources and Mines, 2015)

The estimated cost to repair this damage in the WWRN alone was $1,817,000. $9,492,000 for the entire Wandoan Region, and $67,183,000 for the entire Western Downs Regional Council Area (Western Downs Regional Council, 2011).

In addition to the enormous financial cost of reconstructing the damaged network, there were unestimated losses to the community due to the network operating at sub-optimal performance for the duration of restoration works. As discussed earlier, the emergent works phase restored the network to a minimum acceptable level of safety in a matter of weeks, however the restoration phase of this reconstruction was in operation until June of 2013, meaning the network was operating below the regular performance level for a period of 2.5 years.

1.4.1.2 2013 Event – Tropical Cyclone Ostwald 2013

In similar circumstance to the widespread flooding of 2011 caused by tropical cyclones Tasha and Anthony, major flooding to the Wandoan Road Network was caused in January

2013 by torrential rain accompanying the landfall of Category 1 Tropical Cyclone Ostwald. This event was less severe than the preceding 2011 event as shown in figure 1.11, however this event still caused significant and widespread damage and disruption to the Wandoan Road Network.

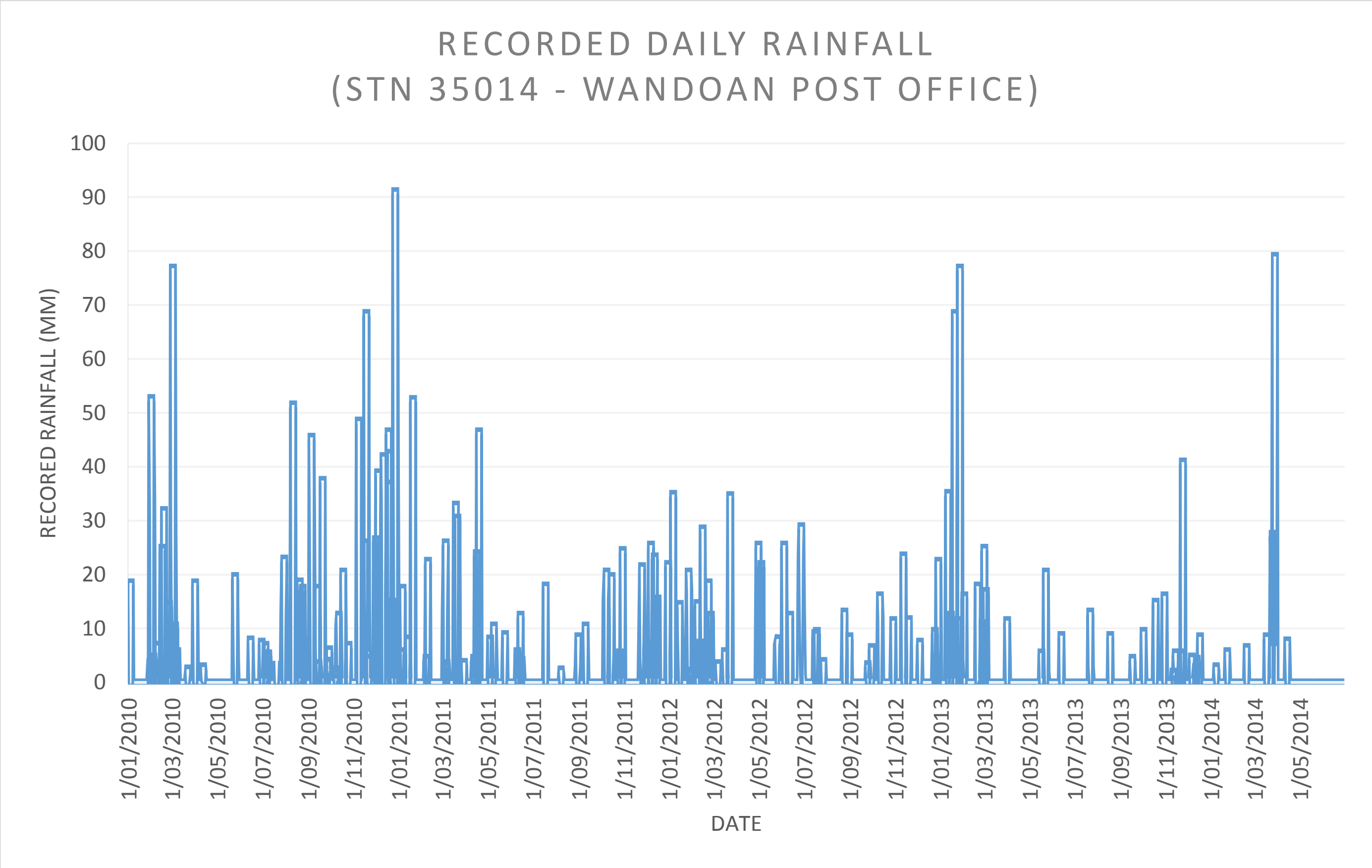


Figure 1.13 - Historic Daily Rainfall (2010-2014) Wandoan Post Office (Australian Government Bureau of Meteorology, 2015)

Figure 1.13 better illustrates the intensity of the 2013 TC Ostwald Flood Event in the Wandoan Region. While the total cumulative value for the month is not as high as the 2011 event as indicated by figure 1.11, the peak daily rainfall is 87% of the 2011 peak daily rainfall, and this rainfall was consistent over two consecutive days during the 2013 Event. The result is a flood event of similar severity, but of shorter duration and equally as capable of causing widespread damage to the local infrastructure networks.

The total cost for reconstruction and recovery of the network in the Wandoan Area was estimated at $3,352,000 for reconstruction works, and $513,000 for emergent works. This amounted to a total estimated recovery cost of $3,865,000.

The restoration works for this event were delivered in a similar manner to the 2011 flood damage event, in two distinct phases: the emergent works phase, and the restoration phase. The result of this is the most dangerous or disruptive defects to the network were restored to a minimum level of service in a short timeframe following the event, but the bulk of the defects (86.7% as a proportion of value of work) were delivered gradually over a 2.5 year period.

1.4.2 Consequences and reduced level of service

1.4.2.1 Short Term Network Disruption

Short Term Network Disruption in regards to the 2010-11 and 2013 Flood Events detailed, refers to disruptions to the network during the flood event itself. These short term disruptions were manifested primarily in the inundation and untraffickibility of key bridges for extended periods of time due to abnormally high flood water levels.

A number of bridges were inundated during the 2011 Flood Event for a period of 48 hours (Chown & Harth, 2015) including structures on all major creeks in the area, including: Horse Creek, Juandah Creek, Wooleebee Creek, Roche Creek, Eurombah Creek, and Bungaban Creek. The location of these structure is shown below in figure 1.14. The importance of these structures to maintaining network function is clearly shown, with the entire WWRN and surrounding area isolated should these bridges not be functional. These images are generated using Google Earth and the Queensland Globe (Queensland Government, 2015).

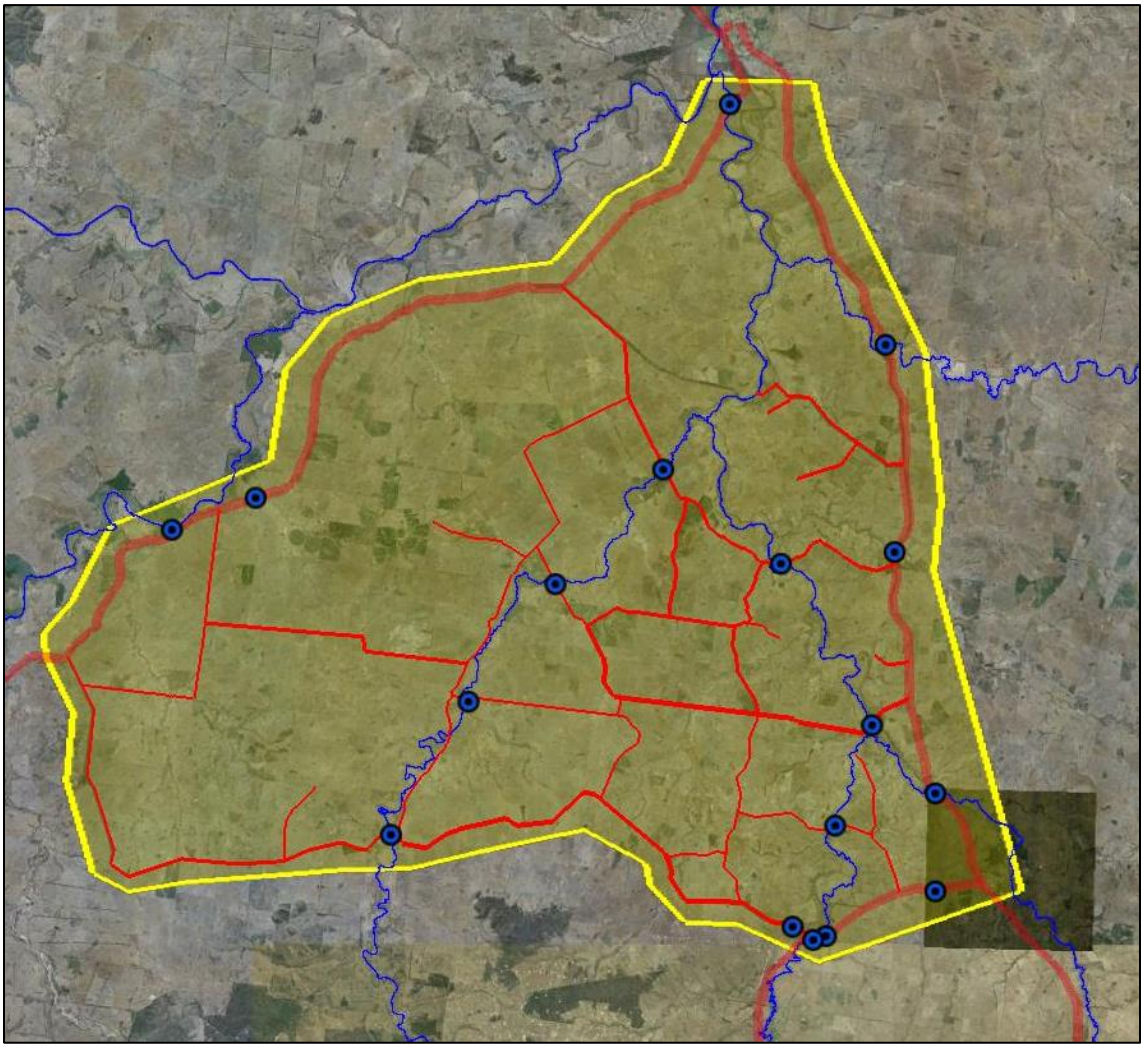


Figure 1.14 - Bridge Locations - WWRN (Google Earth, 2015)

These disruptions will be restored to service naturally with the receding of floodwaters to allow trafficability of these structures. Further to this most structures will be inspected to ensure no compromising damage to the structure has occurred prior to allowing traffic to use the structure.

1.4.2.2 Long Term Network Disruption

Long Term Network Disruptions refers to the damage to the network which reduces the level of network performance until the defect is repaired. These disruptions become apparent following the flood event and the natural restoration of the short term disruptions (bridges). These disruptions are the result of various types of damage to road pavement, surfacing, or drainage structures.

Damages to sealed pavements constituted approximately $2,976,000 worth of the restoration cost of the 2011 Floods to the Wandoan Region. This is 31% of the total reconstruction value. The most common of these defects can be broadly defined as damage to sealed pavement, damage to bitumen seal, and damage to unsealed shoulder. This is a very vague and broad generalisation of defects to a sealed road, but will prove sufficient for description of flood damage to sealed roads in the WWRN. Examples of these defects are shown below in figure 1.15. These defects are most commonly repaired by reconstruction of the damaged pavement and application of a new bitumen seal to the reconstructed pavement.

Figure 1.15 - Examples of Pavement deformation due to moisture ingress including damage to bitumen seal (right) and damage to the unsealed shoulder (Left)

Damages to Unsealed Pavement constituted 38% of the overall cost of reconstruction of the 2011 Flood Event in the Wandoan region, with an estimated repair cost of $3,645,000. Damage to unsealed roads was most commonly experienced as deformation of saturated pavement material, and loss or scouring of pavement material due to overland flow or inundation. The repair treatment in both cases usually constitutes resheeting of the gravel pavement with new pavement material, or compaction and profiling of the existing material to restore to geometry and crossfall. These defects are illustrated in figure 1.16.

Figure 1.16 - Deformation of Saturated Pavement (left) and scouring and loss of pavement materials due to overland flow (right)

Damage to formation only roads is also common not only after major flood events, but any form of significant rainfall. Being a lower class of asset, these roads are more easily damaged by wet weather, but are also more easily restored, usually requiring only regrading of the road to restore to the previous level of service. A significant amount of formation grading was required to restore formation only roads to service following both

flood events. In particular, the lower order roads to the west of the Wandoan District.

Figure 1.17 - Damage to Formation Only road - Perretts Road Wandoan

As expected in flood events of significantly high magnitude, drainage structures are required to accommodate weather flows far greater than their design capacity, and as a result of this often sustain damage. This damage can take the form of undermining or scouring on the downstream side of the structure due to high velocity flow, separation of reinforced concrete pipe (RCP) components, build-up of silt or debris, or inundation or damage to the surrounding road.

Figure 1.18 - Scouring on downstream side of concrete floodway due to high velocity flow, severe damage to RCP units due to hydraulic pressure build-up caused by insufficient capacity

Each of these defects will affect the performance of a road network differently according to location, severity, and road hierarchy and usage. All defects as documented in the recovery of the 2011 Flood Event in the WWRN will be considered individually in order to determine the impact that defect would have on the capacity of the particular road segment or network link. From this the reduction in network capacity and performance may be determined, and the network resilience to a flood event of Q100 magnitude, as experienced as a result of TC Tasha and Anthony, calculated and quantified.

1.5 Existing Frameworks and Procedures for the Analysis of Network Resilience

There are currently a number of frameworks which aim to assess the level of resilience of a transport network. These include the Networked Infrastructure Resiliency Assessment (NIRA) frame work (Omer, et al., 2013), the framework proposed by (Bruneau, et al., 2003) for the quantitative assessment of the seismic resilience of communities, a risk based approach to resilience calculation as provided by (Zoubir, 2013), and the Three-Stage Resilience Analysis Framework developed by (Ouyang, et al., 2012).

In addition to the level of service provided by transport networks, it is also important to consider the many underlying economic factors which may indicate the priority of a particular road asset. These may include industries supplied or dependant on the network, access of landowners to health and other services, and in the case of local government, the asset owner's responsibility to landowners and the public. An example of the importance of this; the estimated economic losses caused due to the 2011 flood event are estimated to be between $5bn and $6bn (Uren, 2011).

There are a number of frameworks which have been developed and proposed as means of quantifying and assessing the level of resilience of an infrastructure network. Though not all of these frameworks apply directly to transport infrastructure networks, the general principles of most can be applied to such. A number of these frameworks will be investigated below with the aim of determining the framework most suited to the network being analysed, and the framework which will produce the most relevant and meaningful results.

1.5.1 A framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities

A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities was authored by (Bruneau, et al., 2003) and published in Volume 19, No. 4 of the Journal; Earthquake Spectra.

This paper presents a conceptual framework to be used in analysing the current resilience of communities to seismic disruptions, and developing quantitative measures of resilience that may then be used to identify possible methods or practises for enhancing this resilience. At the time of publishing there had been many previous investigations into seismic resilience. However, the majority of this research has been focused on developing new technologies or knowledge to increase seismic resilience, being a qualitative assessment of the concept. Due to this there was little understanding of the factors contributing to resilience, or the systematic process required to assess a community's current level of resilience. This quantitative approach is necessary to better implement and identify the need for those technologies and knowledge discussed earlier.

1.5.1.1 General Measures of Resilience

(Bruneau, et al., 2003) defines community seismic resilience as "the ability of social units (e.g. organisations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimise social disruption and mitigate the effects of future earthquakes. This definition provides clear objectives for the framework, being that any actions to enhance the resilience of the community should increase the probability of core services functioning during a disruption. Core services would include infrastructure, such as water supply or electricity, or community services such as health care. If these services are able to function during disruptions, the severity and duration of the consequences of this disruption is likely to be significantly reduced.

1.5.1.2 Concept and Quantification of Resilience

(Bruneau, et al., 2003) states that a resilient system is one which reduces the chances of a disruption or shock, has increased capacity to absorb the shock without diminishing performance to an unacceptable level, and has the ability to recover quickly after a shock. To summarise, a resilient system shows:

1. Reduced failure probabilities
2. Reduced consequences from failures
3. Reduced Time to Recovery

These concepts are illustrated in the below figure from (Bruneau, et al., 2003);

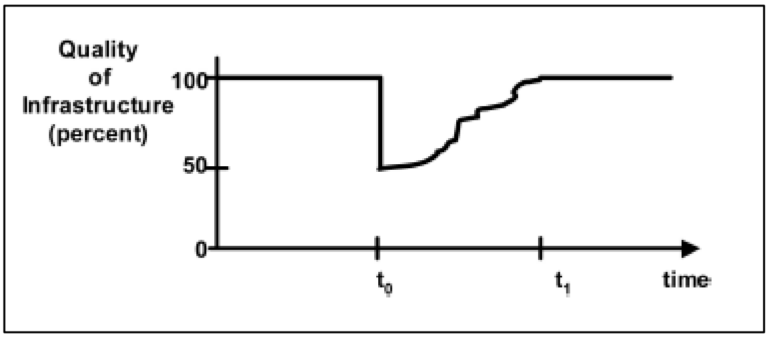


Figure 1.19 - Measure of Seismic Resilience - conceptual definition (Bruneau, et al., 2003)

This illustration defines the quality of infrastructure Q(t) as a percentage of performance capacity at any point in time (t), where 0% would indicate a complete lack of service and 100% would indicate no degradation in service from design levels.

As shown in Figure 1, disruptions or shocks cause a loss of service which is then repaired to design capacity over time. This diminished performance over time then represents the loss of resilience for that specific event. This can be expressed by the integral shown in Equation 1.

$$R = \int_{t0}^{t1} [1 - Q(t)]dt$$

Equation 1 - Loss of Resilience (R) (Bruneau, et al., 2003)

(Bruneau, et al., 2003) also goes on to address Dimensions of Resilience being technical, organisational, social, and economic. This includes illustrating the interdependency of many different systems to contribute to overall community resilience. While this investigation is relevant to the study of community resilience as a whole, it is not relevant to the scope of this research paper which will focus on a single road network only. As such this will not be elaborated further in this paper.

1.5.1.3 Framework Method and Concept

As discussed earlier, (Bruneau, et al., 2003) aims to propose a framework which will be able to measure the resilience of a community and quantify this level of resilience to allow the value to be measured against an established scale. In order to effectively measure the resilience of the community, this framework is required to analyse the ability of an infrastructure system to service a community prior to a disruption, and during a disruption.

Considering these requirements (Bruneau, et al., 2003) has developed a series of performance measures (Figure 1.20) to be used in the assessment of an existing system. These measures are then to be used in conjunction with a Systems Diagram (Figure 1.21) in order to determine the resilience of a community and identify strategies for enhancing this resilience.

Table 1. Centerwide (global) performance measures (illustrative)

PERFORMANCE MEASURES	PERFORMANCE CRITERIA: Robustness	Redundancy	Resourcefulness	Rapidity
TECHNICAL	Damage avoidance and continued service provision	Backup/duplicate systems, equipment and supplies	Diagnostic and damage detection technologies and methodologies	Optimizing time to return to pre-event functional levels
ORGANIZATIONAL	Continued ability to carry out designated functions	Backup resources to sustain operations (e.g., alternative sites)	Plans and resources to cope with damage and disruption (e.g., mutual aid, emergency plans, decision support systems)	Minimize time needed to restore services and perform key response tasks
SOCIAL	Avoidance of casualties and disruption in the community.	Alternative means of providing for community needs.	Plans and resources to meet community needs	Optimizing time to return to pre-event functional levels
ECONOMIC	Avoidance of direct and indirect economic losses.	Untapped or excess economic capacity (e.g., inventories, suppliers).	Stabilizing measures (e.g., capacity enhancement and demand modification, external assistance, optimizing recovery strategies)	Optimizing time to return to pre-event functional levels

Figure 1.20 - Resilience Performance Measures (Bruneau, et al., 2003)

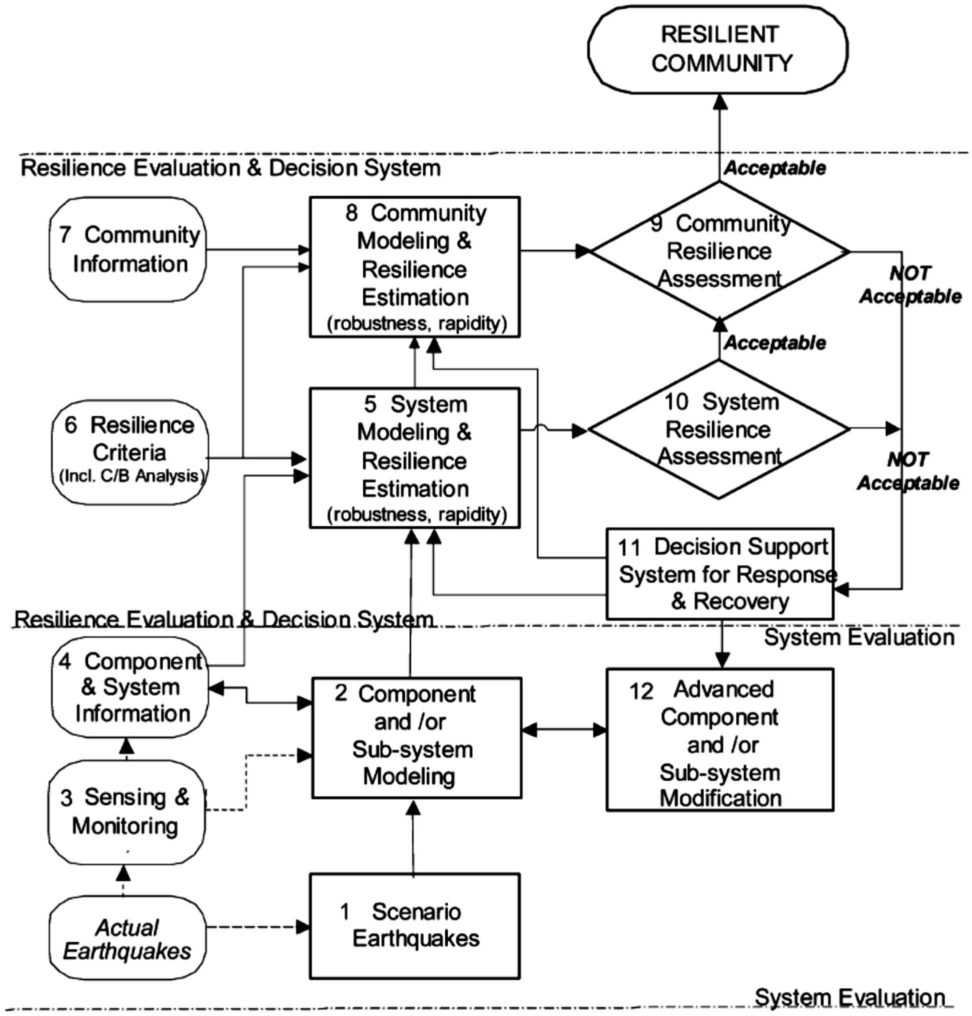


Figure 3. Systems diagram.

Figure 1.21 - System Diagram for Evaluation of System Resilience (Bruneau, et al., 2003)

1.5.1.4 Evaluation of Framework and Suitability

While (Bruneau, et al., 2003) provides valuable and thought provoking prose on the concept of resilience in infrastructure systems, the framework provided does not quantify, or provide the means of quantifying the losses to the community due to a network disruption to a detail significant enough to justify private or public expenditure on the enhancement of these networks.

In order to justify local government expenditure, or apply for additional state government funding, a clear financial benefit will need to be demonstrated to support the proposed upgrade to the Wandoan West Road Network. This financial benefit will need to be shown in terms of reduced maintenance or recovery costs, or if funding is to be provided by the private sector, clear cost savings to the companies to fund the upgrades should the upgrades be implemented.

The features of a resilient system given by (Bruneau, et al., 2003) provide a useful benchmark for high-level analysis of any system, including the Wandoan West Road Network. These features are:

- Reduced failure probabilities
- Reduced consequences from failures
- Reduced time to recovery

These features may be used as effective screening criteria for any proposed upgrades, in order to determine that the proposed upgrade would significantly enhance the resilience of the road network if constructed.

Another concept discussed by (Bruneau, et al., 2003) was the Dimensions of Resilience, specifically the properties of a resilient system described as:

- Robustness: strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function
- Redundancy: the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., 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 some element, system, or other unit of analysis; resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals
- Rapidity: the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption

Similarly to the features of a resilient system discussed above, the above properties of a resilient system will prove valuable as high level screening criteria when evaluating any proposed resiliency enhancing upgrades to the network. These properties also provide a sounds foundation in understanding the concept of resilience, and defining a resilient system.

In summary, the framework proposed by (Bruneau, et al., 2003) provides a comprehensive understanding of the fundamentals of a resilient system, but lacks the specific detail required should the analysis be required as justification of government expenditure. This is not a shortcoming of the framework as the intent of the authors and creators was to create a general framework for assessing the resilience of all systems vital to the overall resiliency of the community, and with this broad scope a detailed analysis is not possible. The framework would provide valuable when evaluating and developing potential network upgrades, as the analysis undertaken seems more to focus on identifying weaknesses in the network, as opposed to quantifying the network resilience into finite data.

1.5.2 A three-stage resilience analysis framework for urban infrastructure systems

The paper *A three-stage resilience analysis framework for urban infrastructure systems* by (Ouyang, et al., 2012), was published in Volume 36 and 37 of the journal Structural Safety.

This article builds on existing literature to propose a new multi-stage framework for the analysis of infrastructure system resilience. At each stage (Ouyang, et al., 2012) identifies possible strategies for the enhancement of the system resilience, before combining the analysis of each stage to determine an Annual Resilience value for the network. The framework proposed effectively elaborates on and combines existing modelling of cascading failures of infrastructure systems, and modelling of the systems restoration processes to provide a full consideration of the overall resilience of an infrastructure system.

To demonstrate the effectiveness of the proposed framework (Ouyang, et al., 2012) undertakes an analysis of the power transmission grid in Harris County, Texas, USA. This analysis is then compared to the analysis of several hypothetical models with resilience enhancing upgrades. The results of this successfully demonstrated the effectiveness of the proposed upgrades, as the calculation of the model’s Annual Resilience (AR) value provided a clear and distinct metric for the comparison of the models and their respective impacts on overall system resilience.

1.5.2.1 Quantification and Concept of Resilience

As the proposed framework is intended for the analysis of a variety of infrastructure systems, (Ouyang, et al., 2012) investigates existing definitions from a number specialised authorities in order to develop a universal conceptual definition of resilience for the purposes of the paper. These definitions applied to the fields of Biology, Information and Systems Engineering, Homeland Security, Earthquake Engineering Research, and others. Following this (Ouyang, et al., 2012) defines resilience as the joint ability of infrastructure systems to resists (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation.

Similar to (Bruneau, et al., 2003), (Ouyang, et al., 2012) defines the resilience of a system as the system performance during the three distinct periods of a system disruption; before the event (the system ability to resist and prevent disruption), during the event (the system ability to reduce and minimise the severity of a disruptive event), and after an event (the ability of the system to recovery from an event and return to a regular level of service).

1.5.2.2 Framework Concept

The framework proposed for analysis of urban infrastructure systems, was proposed to address gaps in the existing literature. Existing research focused on specific disruptive events, or single hazards to the system, and not considering the possibility of multiple events occurring at once. These analyses also did not account for the resilience of the system itself, in the system capacity to resist and absorb the disruptions caused by the event, and recover following.

Identifying these gaps in the existing literature, (Ouyang, et al., 2012) proposes a framework which analyses the system using resilience parameters at each of the three stages to determine an overall Annual Resilience (AR) metric. An illustration of this concept provided by (Ouyang, et al., 2012) is shown in figure 4.

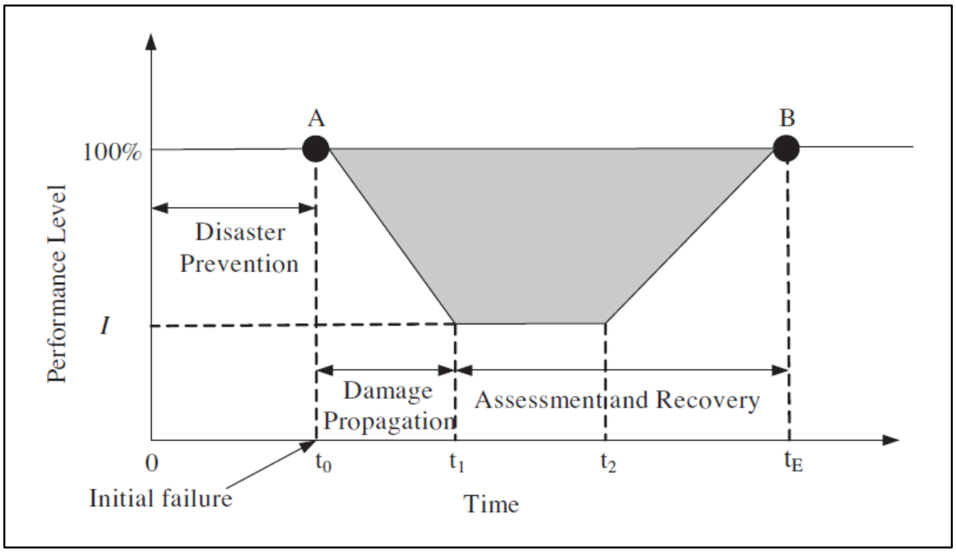
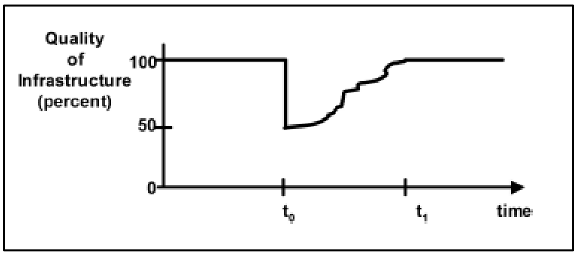


Figure 1.22 - Performance Response curve of an infrastructure system (Ouyang, et al., 2012)

This illustration bears comparison to (Bruneau, et al., 2003) conceptual definition of Seismic Resilience. The two illustrations are shown in Figure 5 below.



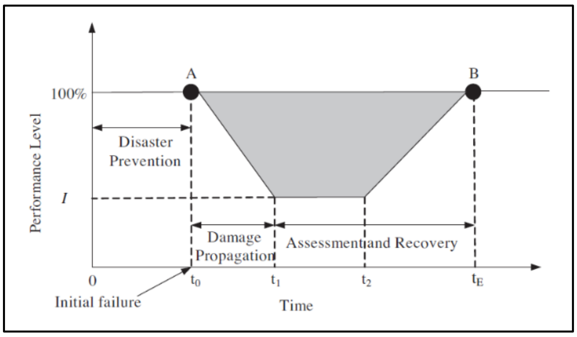


Figure 1.23 - M. Ouyang et al. Performance Response Curve, Bruneau et al. Definition of seismic resilience. (Bruneau, et al., 2003) (Ouyang, et al., 2012)

From the comparison of these two illustrations, it is clear to see the same general concepts or stages of resilient infrastructure performance used in each model. Each model uses the concept of system performance over time as the foundation for the models developed, however (Ouyang, et al., 2012) shows a higher degree of detail in specifying the stages of disruption to a network.

Figure 4 shows the titular three stages of the framework proposed by (Ouyang, et al., 2012). These being the Disaster Prevention Stage, Damage Propagation Stage, and Assessment and Recovery Stage.

1.5.2.3 Stage 1 Disaster Prevention

The first stage, disaster prevention, represents the performance of the system from normal operation to the initial system disruption. This stage reflects the ability of the system to resist and reduce the severity of disruptions and prevent disruptive events. This first stage mainly focuses on local level impacts and translates hazards (disruptions) into component level failures (Ouyang, et al., 2012). The concept of resistant capacity is defined by the "Hazard Frequency" and "Initial Damage Level". These two metrics are used in the determination of system performance in the first stage. This Stage represents the ability of a network to reduce the initial severity of an event. A road network would characterise this by the presence of flood immune infrastructure such as bridges and road ways above flood levels.

1.5.2.4 Stage 2 Damage Propagation

The second stage focuses on the effects of disruptions on a system wide level, effectively representing the specific asset failures identified in stage one as flow on consequences in the rest of the network (Ouyang, et al., 2012). This stage reflects the ability of the network to absorb shocks and continue to operate and provide a minimum level of service during the disruption. This would be characterised in a local road network by the presence of alternative routes and detours should a road be closed. Absorptive Capacity of a network is measured by "maximum impact level" shown in figure 4 by a Performance Level of $(1 - I)$.

1.5.2.5 Stage 3 Assessment and Recovery

The third stage analyses the recovery and reconstruction portion of the response cycle, effectively translating external input into network restoration. In a road network this would be characterised by the time and cost taken to restore a road or network link to a minimum level of service. In this stage resilience is measured by restorative capacity which is represented by recovery time and recovery cost together. (Ouyang, et al., 2012)

A summary of the metrics or "resilience correlates" used by (Ouyang, et al., 2012) in

Table 1
Sample strategies to improve infrastructure system resilience per response process stage.

Stage	Stage resilience correlates	Resilience improvement strategies [sample applications]
First stage (resistant capacity)	Hazard frequency, initial damage level	• Use risk management methods to identify and harden key components [20] • Learn and improve from previous accidents using accident models, such as the Systems-Theoretic Accident Model and Processes (STAMP) approach [21] • Sense, monitor, and update system states in real time along with state visualizations based on emerging infrastructure modeling techniques, such as Bayesian networks [22]. • Improve decision support platforms, staff training, and organizational culture to enhance situational awareness [23]
Second stage (absorptive capacity)	Maximum impact level $(1 - I)$	• Adjust infrastructure system topology [24] • Design for system redundancy [25] • Add self-healing and self-adapting infrastructure system response mechanisms [26]
Third stage (restorative capacity)	Recovery time, recovery cost	• Establish efficient communication channels and coordination for rapid recovery response [27] • Improve decision support platforms to quickly and accurately identify feasible recovery strategies [28]

measurement of system resilience is shown below in table 2.

Table 1 - Sample Strategies to improve infrastructure system resilience per response process stage. (Ouyang, et al., 2012)

1.5.2.6 Calculation of AR Metric

From the above concepts, (Ouyang, et al., 2012) defines the Annual Resilience (AR) metric as the mean ration of the area between the real performance curve and the time axis, and the area between the target performance curve and the time axis. This is expressed mathematically as shown in equation 2.

$$AR = E\left[\frac{\int_0^T P(t)dt}{\int_0^T TP(t)dt}\right]$$

Equation 2 - Annual Resilience Metric Calculation (Ouyang, et al., 2012)

(Ouyang, et al., 2012) goes on to expand on this given equation, taking into account multiple event occurrences at once, occurrence rates per year, hazard intensity, probability density, and probability mass. The addition of these metrics allows for a detailed statistical analysis of any systems AR value, and using this (Ouyang, et al., 2012) provides an extensive and thorough investigation into the resilience of the Harris County, TX power grid. However, to calculate these values requires extensive knowledge of statistical analysis which is beyond the scope of this undergraduate civil engineering research project. The inclusion and calculation of these additional metrics also requires detailed and established data records for the hazard intensity and frequency, data which is currently not available for the region of Wandoan, Qld. Due to these limitations these more advanced methods of calculating a system AR value will not be detailed in this paper.

1.5.2.7 Framework Analysis and suitability

This framework builds on the concepts and principals developed by (Bruneau, et al., 2003) to provide a more detailed and quantified analysis of a system's resilience to disruption. The framework and mathematical process developed by (Ouyang, et al., 2012) allows for a more thorough and more easily visualised comparison of networks and proposed network upgrades.

The use of this framework could successfully be used in the evaluation of the Wandoan West Road Network, in that any proposed upgrades could easily be evaluated for the potential impact on the network and contribution towards enhanced resilience.

However, the three-stage analysis quantifies system resilience as an AR value, or an Annual Resilience Value. This value is a unitless measure of resilience, and while useful when comparing systems on the resilience alone, this value could not successfully be used as supporting justification of increased expenditure on construction project, as is the intent of this paper.

(Ouyang, et al., 2012) quantifies the increases in resilience of the Harris County power grid in the following excerpt:

> *The reliability of the US power grid (with transmission line length of approximately 300,000 km) is 99.97%, and the 0.03% unreliability level costs the economy $150 billion per year [40]. The transmission line length in Harris County is 2 144.5 km; hence, according to the line length ratio from the county to national level (2144.5/300,000 = 0.007), a small resilience improvements may still save millions of dollars per year in Harris County, Texas.*

While this does provide financial justification for the upgrade of the Harris County power grid, the method used to calculate the financial impacts of the differing resilience levels is tenuous, and unlikely to provide significant support to any proposal for the upgrade of this grid.

In summary, this framework effectively and succinctly evaluates the resilience of a system to external disruptions, and may successfully be used in the evaluation of the Wandoan West Road Network. However, considering the methodology and the ability of the analysis to be used as justification for greater government expenditure, the NIRA framework would prove more suitable for the evaluation of the Wandoan West Road Network.

1.5.3 Networked Infrastructure Resilience Assessment (NIRA) Framework

The paper *Assessing Resilience in a Regional Road-based Transportation Network*, was authored by (Omer, et al., 2013) was published in the International Journal of Industrial and Systems Engineering Volume 13, Number 4. This paper details the proposed NIRA framework for the analysis of road based transportation networks.

The Networked Infrastructure Resiliency Assessment (NIRA) Framework was developed by (Omer, et al., 2013) and delivers a multi-metric approach to the assessment and analysis of the resiliency of networked infrastructure systems. This framework can be applied to multiple systems including transportation networks, electrical grids, or water distribution networks.

The NIRA framework proposed by (Omer, et al., 2013) aims to develop quantifiable metrics for use in benchmarking comparable networks. These metrics may also be used as an indication of improvements in the system's resiliency after the implementation of resiliency strategies, as well as being an effective tool for comparing different options for enhancing the system's resiliency (Omer, et al., 2013).

(Omer, et al., 2013) excluded proposal and evaluation of upgrades from the scope of the paper, however this analysis would prove beneficial to the analysis of the Wandoan West Road Network.

1.5.3.1 Definition of Resilience

The definition of resilience in regards to infrastructure systems is defined by (Omer, et al., 2013) as the ability of a system to bounce back after a shock and return to its normal value delivery levels. This definition is in accordance with that given by (Bruneau, et al., 2003) in the Seismic Resilience Framework, and (Ouyang, et al., 2012) in the Three-Stage Resilience Analysis Framework.

Each of these definitions essentially describe the resilience of an infrastructure system as the ability of the system to prevent disruptions to the network, minimise the severity and extent of disruptions, and the ability to return to a normal level of service following disruptions.

1.5.3.2 Framework Concept

The NIRA framework proposed by (Omer, et al., 2013) is intended to quantify the resilience of an infrastructure network to allow the evaluation of the current level of resilience, as well as the potential benefits of any planned upgrades to the network in regards to enhanced resilience. The NIRA network consists of 6 steps split into 3 distinct stages. These are shown in figure 6;

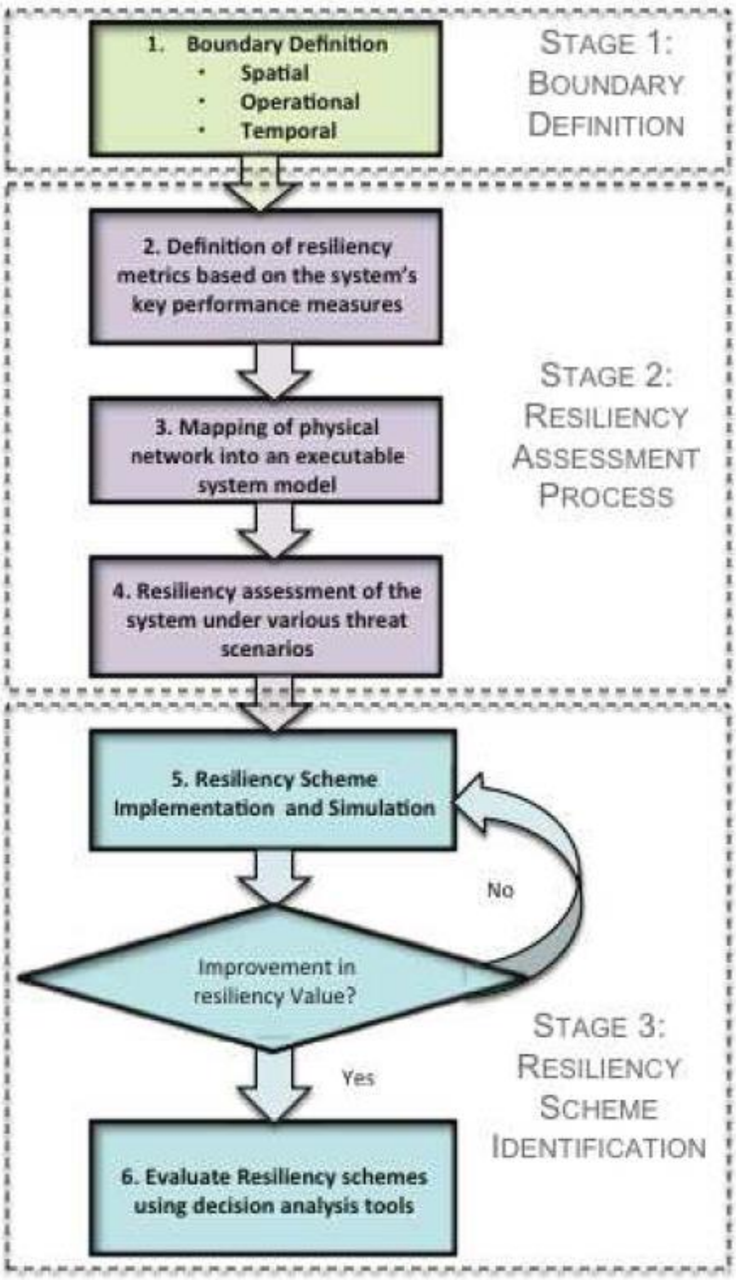


Figure 1.24 - Networked Infrastructure Resilience Assessment (NIRA) Framework (Omer, et al., 2013)

These steps provide a comprehensive evaluation of the current state of resilience of a network. These steps as developed by (Omer, et al., 2013) and the relevant actions to be taken should the NIRA framework be applied to the Wandoan West Road Network, are shown below. Further elaboration on these steps will be shown in the analysis of the network proposed in Chapter 3 of this paper.

1.5.3.3 Step 1: Define the boundary of the system

The boundaries to be defined for the system as defined by (Omer, et al., 2013) include the spatial or geo-locational boundary, the temporal boundary, and the operational boundary. In regards to an analysis of the Wandoan West Road Network these boundaries would be as follows;

- Geo-locational Boundary: The analysis of this network will extend only to roads in the area west of Wandoan, north of Bundi Road, and east of the Roma-Taroom Road.
- Temporal Boundary: The timeframe for this analysis will encompass the duration of one flood event, with the duration of the event to be determined from historical, calculated, or collected data. Increases in travel time due to disruptions will be expressed in hours.
- Operational Boundary: The operational boundary refers to the metric by which performance is measured. For the analysis of traffic flow this will be Average Annual Daily Traffic, defined as a common measure of traffic volume equivalent to the total volume of traffic passing a roadside observation point over the period of one year, divided by the number of days in the year (State of Queensland (Department of Main Roads), 2006).

1.5.3.4 Step 2: Define the resiliency metrics of the system

The resiliency metrics defined in this step will serve as a measure of the key performance indicators (KPIs) of the transport network. Similar to (Omer, et al., 2013), an analysis of the WWRN will use travel time and cost as measures of performance.

These metrics have been chosen as they support the specifications of this research paper, in providing an analysis that is grounded and relevant to the local government operating in the Wandoan area. To achieve this the outputs of this analysis must be in a format to support any application of proposal for further construction projects, and the most effective support for these projects will be a cost-benefit analysis. The financial outputs to be provided by the use of these metrics will allow this.

(Omer, et al., 2009) provides methods for the determination of metric values. This is investigated further in chapter 3.

1.5.3.5 Step 3: Create a network model of the system

(Omer, et al., 2013) defines this step in the NIRA framework as the creation of a logical network from the physical road network, made up of nodes and links.

The creation of this network in the WWRN would involve the creation of nodes and links from intersections, locations, and QCLNG access points on the road network. The addition of QCLNG access points to the model as nodes will allow for a more accurate modelling of the network during a disruption, as sections of the Phase 2 well fields will become accessible at different rates following flood events. By refining the network to this level the effect of the disruptive event on CSG development in the area can be more accurately modelled.

1.5.3.6 Step 4: Resiliency Assessment of the system when exposed to various disruption scenarios

This step will involve modelling disruption scenarios in the model determined in step 3, by the disruption of links by a reduction in performance. The resiliency metrics determined in step 2 will allow the effects of these disruptions to be quantified in terms of the model's performance measures.

1.5.3.7 Step 5: Identify Resiliency enhancing schemes to improve the value of resiliency metrics

The results of step 4 will identify weaknesses to disruption in the system. Using the principles identified by (Bruneau, et al., 2003) and (Ouyang, et al., 2012), potential upgrades will be evaluated.

1.5.3.8 Step 6: Perform assessment of Resiliency enhancing schemes

Remodel the WWRN based on the upgrades identifies in Step 5, and revaluate the network. The differing metrics will provide potential estimates of the potential cost savings due to those proposed upgrades in the event of a network disruption. These potential savings may then be compared to the estimated cost of construction for any proposed upgrades.

1.5.3.9 Framework Analysis and Suitability

The NIRA framework proposed by (Omer, et al., 2013) is a simple, yet effective measure of network performance during disruptions and subsequent analysis of the network resilience. (Omer, et al., 2013) builds on principles explored by (Bruneau, et al., 2003) in regards to resilience, and the quantification of this concept in regards to network performance. The concepts developed have been implemented to quantify the resilience of the network in an easy to comprehend, yet thorough and powerful method which would provide excellent justification of future construction projects to enhance the resilience of the system.

The NIRA framework is favourable for analysis of the WWRN compared to the Seismic resilience framework proposed by (Bruneau, et al., 2003). This is because the NIRA framework successfully quantifies the resilience of the network in terms of real-world considerations, such as travel time, or cost incurred, as opposed to an arbitrary resilience coefficient.

For this same reason the NIRA framework is preferable to the Three-Stage Resilience Analysis Framework proposed by (Ouyang, et al., 2012). The Three-Stage Resilience Analysis Frame work is a thorough and concise framework and was proved an excellent framework for assessment of the Harris County power grid in the case study undertaken. However, the methods used and data required were not suitable for evaluation of the Wandoan West Road Network. In addition to this, the Three-Stage Resilience Analysis framework produces an arbitrary coefficient for the resilience of the system, and as shown in the case study of the Harris County power grid, requires existing records of the cost implications of the event in order to translate this product into a ‘real-world’ value.

Due to this the NIRA framework is the most suitable model for evaluation of the network resilience to flood events, and the financial impacts of this resilience, on the Wandoan West Road Network.

1.5.4 Characterising Resilience of Infrastructure Systems with Expert Judgements

The article *Towards Disaster Resilient Cities: Characterising Resilience of Infrastructure Systems with Expert Judgements* by (Chang, et al., 2014) was published in the journal Risk Analysis, Volume 34, Issue 3.

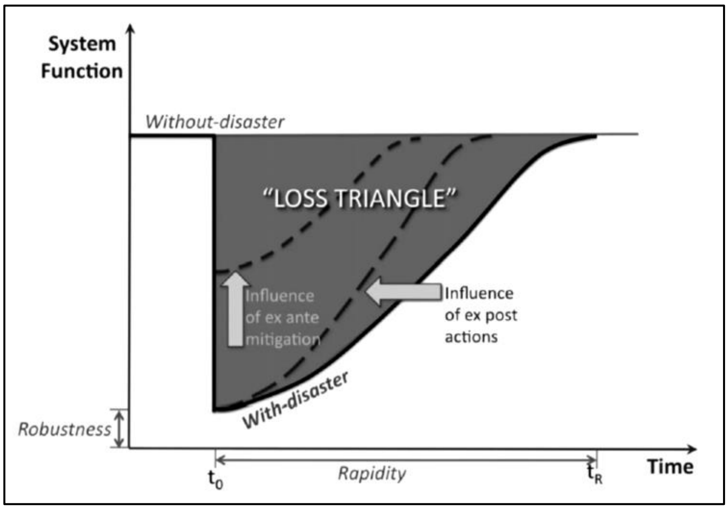
In this article (Chang, et al., 2014) proposes an approach to allow analysts to characterize a community's infrastructure vulnerability and resilience in disasters. (Chang, et al., 2014) aims to address gaps in existing modelling which do not adequately consider cascading failures between dependant infrastructure systems, a sentiment substantiated by (Gordon, et al., 1998) in estimating that approximately one quarter of business interruption losses were caused by the failure of highway bridges, showing a clear dependence of the city's businesses on the transportation network. This proposed approach uses non-probabilistic, judgement based methods to allow the characterisation of a system's resilience to a specific event, and relies heavily on the input of local experts in each of the inter-reliant systems to be evaluated.

To demonstrate this framework (Chang, et al., 2014) undertakes an analysis of the Vancouver, Canada Metro Infrastructure systems in the context of flood and earthquake hazards. The framework considered a variety of infrastructure systems such as: Electricity, Telecommunications, Water Supply, Land Transport, Healthcare, Government, Natural gas, and Wastewater. The use of this framework in this case study highlighted the interdependency of infrastructure systems on others, and the need for communication between the owners and operators of these networks to minimise overall disruption of the network.

1.5.4.1 Concept of Resilience

(Chang, et al., 2014) defines resilience in regards to infrastructure networks as the ability to *"absorb shocks (from extreme events, such as natural disasters) while still maintaining function (in terms of providing the basis for well-being of residents)"*. This definition is fundamentally similar to those explored by (Bruneau, et al., 2003), (Ouyang, et al., 2012), and (Omer, et al., 2013), though is less precise in defining the stages of a disruption and the properties of a resilient system. This reflects the broader and less defined scope of the framework proposed by (Chang, et al., 2014) compared to the other frameworks evaluated.

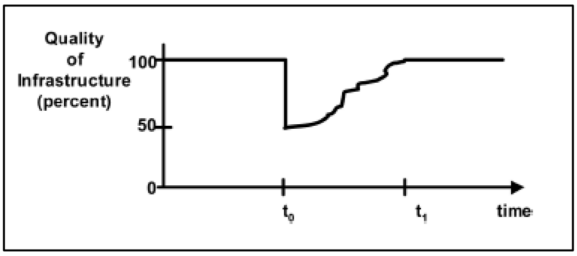
(Chang, et al., 2014) represents the resilience of a system in a similar manner to (Bruneau, et al., 2003) and (Ouyang, et al., 2012) as shown in figure 8. (Chang, et al., 2014)

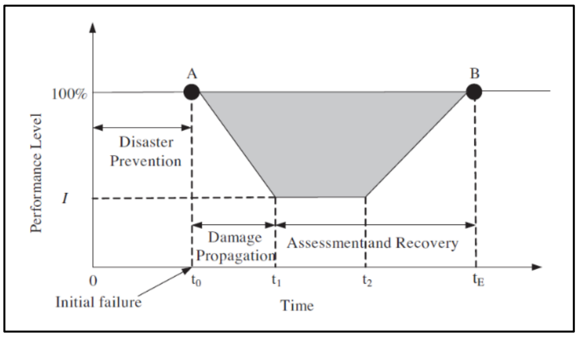


references this figure as adapted from that of (Bruneau, et al., 2003).

Figure 1.25 - Resilience Concept (Chang, et al., 2014)

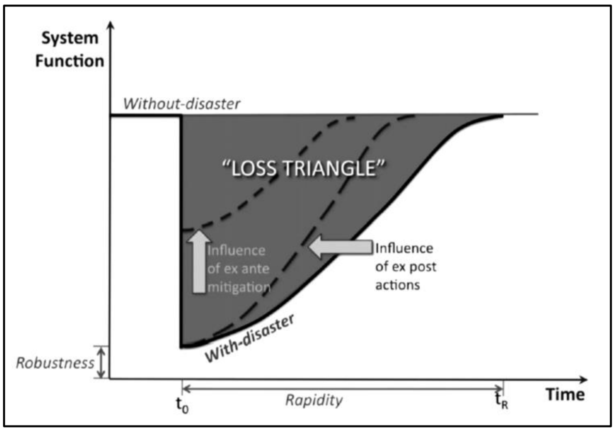
The similarity between this illustration and those developed by (Bruneau, et al., 2003) and





(Bruneau, et al.,

(Ouyang, et al., 2012)



(Chang, et al., 2014)

(Ouyang, et al., 2012) is demonstrated in figure 9.

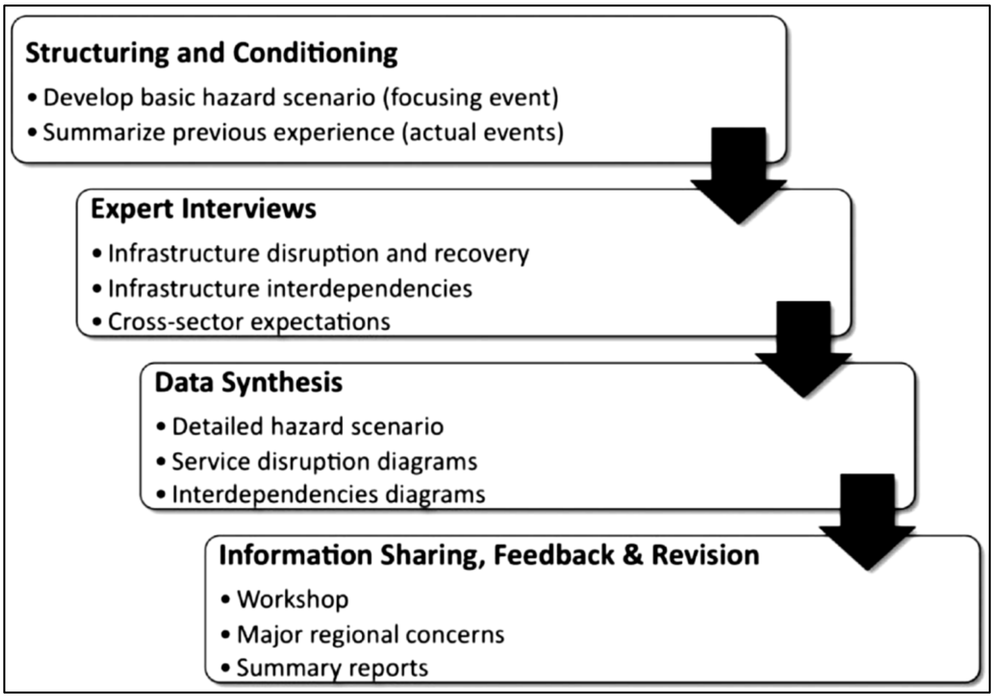
Figure 1.26 - Comparison of Resilience Concept Illustrations (Bruneau, et al., 2003) (Chang, et al., 2014) (Ouyang, et al., 2012)

As shown in the above comparison, all of these frameworks, including the NIRA Framework by (Omer, et al., 2013) though not illustrated, conceptualise the resilience of a system during a disruptive event as the loss of system performance during and after the event. When expressed graphically as above this can be described as the area between the actual performance curve and regular performance benchmark.

A facet of system resilience explored by (Chang, et al., 2014) which was not discussed in the earlier frameworks, is the idea that multiple infrastructure networks are dependent on each other to provide a regular level of performance, and so disruptions to one network may have flow on effects to the others. (Bruneau, et al., 2003) touched on the issue in consideration of multiple infrastructure systems contributing to the resilience of a community as a whole, but (Chang, et al., 2014) expands on this by stating that the reduced performance of one network will affect the reduced performance of another. This is the key differentiating factor in the framework proposed by (Chang, et al., 2014).

1.5.4.2 Framework Concept

The framework proposed by (Chang, et al., 2014) follows a methodological approach in the analysis of a system resilience to disruptions and shocks. This process relies heavily on



interviews and input of experts and operators of each of the interdependent networks to be assessed. This is likely made necessary due to the broad scope of the framework where quantifiable measures as proposed in the NIRA Framework by (Omer, et al., 2013) and the Three-Stage Resilience Assessment Framework by (Ouyang, et al., 2012), would result in a substantial and cost-prohibitive data collection and analysis exercise. The process and framework overview is shown in figure 10.

Figure 1.27 - Methodological Approach (Chang, et al., 2014)

The structuring and conditioning stage is similar to the boundary definition step employed in the NIRA framework, where boundary conditions for the systems to be assessed are defined and the existing data collected. Following this, using an interview sheet developed by (Chang, et al., 2014), Industry experts from each system are interviewed in order to gain a subjective and judgement based assessment of the likely effects the defined event would have on their respective system. The disruptions to these systems are quantified as low, moderate, or severe disruptions, with the classification used to determine the severity shown in figure 11. The duration of the disruption is displayed over the timeframes of 0 hours (the time of event), 72 hours, or 2+ weeks.

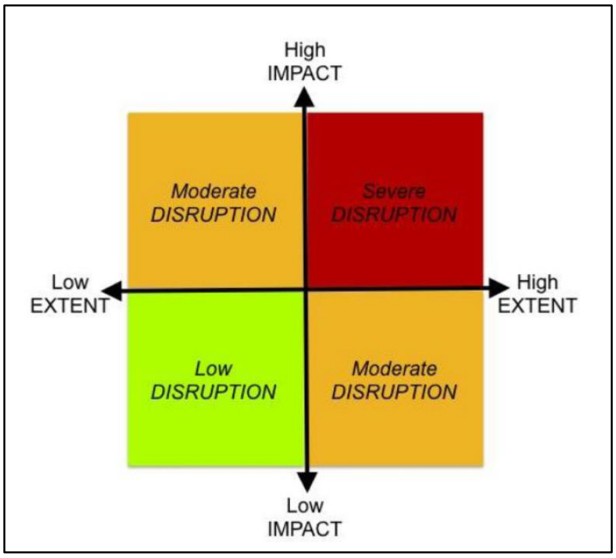
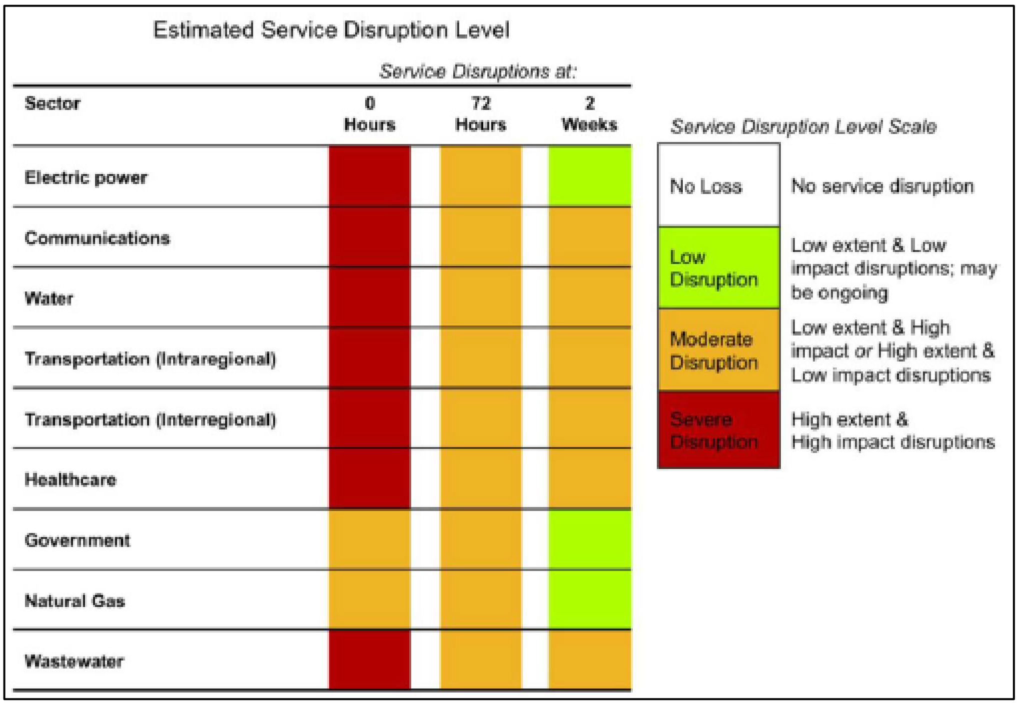


Figure 1.28 - Classification of service disruption levels (Chang, et al., 2014)

Following collection of this data from expert interviews, (Chang, et al., 2014) collates this data into service disruption diagrams and interdependency diagrams. The service disruption diagram provides a graphical overview of the forecast disruption to each network.



The service disruption diagram completed by (Chang, et al., 2014) in the Vancouver Metro case study is shown in figure 12. The Interdependency diagram also stems from the data collected in the expert interviews, and shows the level of disruption in each system, as well as the interdependences of the systems and the severity of the dependencies. The interdependency diagram completed by (Chang, et al., 2014) in the Vancouver Metro case study is shown in Figure 13.

Figure 1.29 - Estimated Service Disruption Levels M7.3 Earthquake Scenario (Chang, et al., 2014)

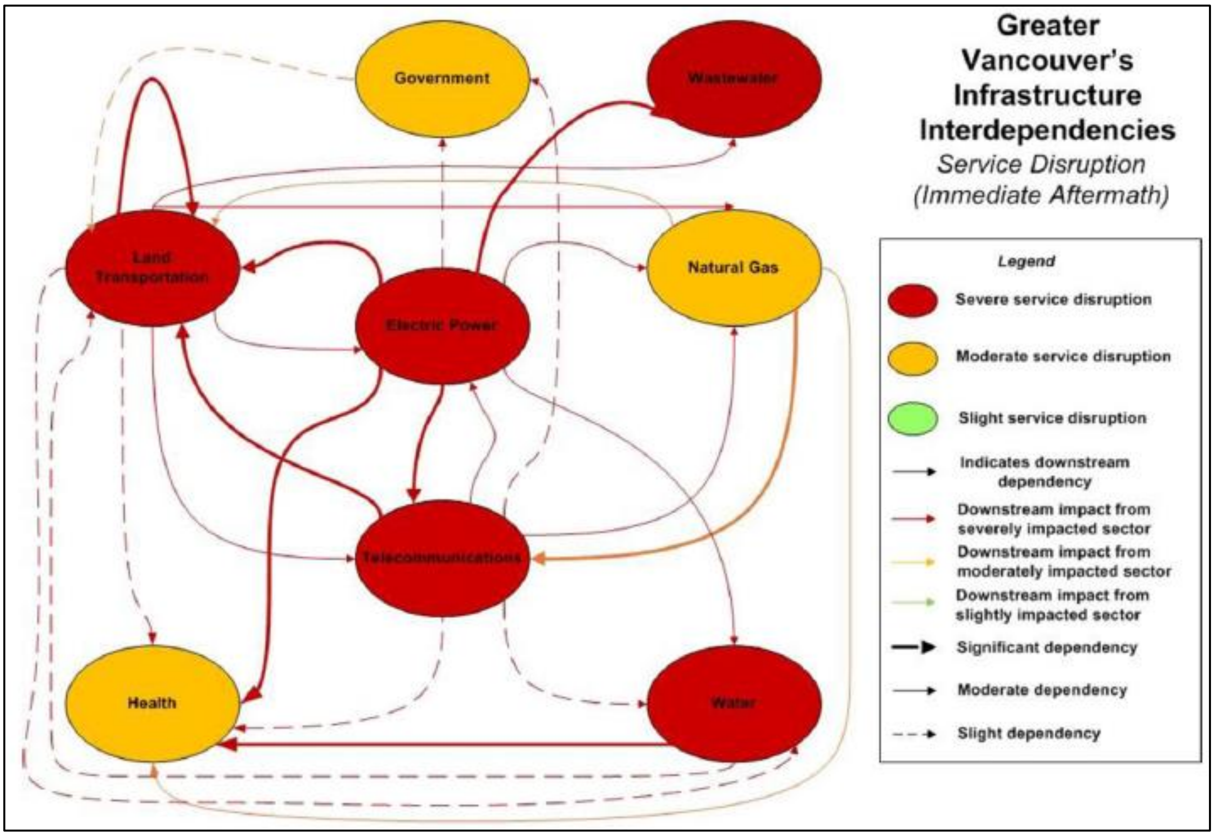


Figure 1.30 - Infrastructure interdependencies and service disruptions (Chang, et al., 2014)

The final step in the framework proposed by (Chang, et al., 2014) involves a workshop involving previously interviewed experts, and a summary report which presents the findings of the analysis, including any additional findings raised at the final workshop. The intention of the final workshop is to gather experts from all the interdependent systems, and present the identified links and dependencies to the group. This then allows the experts of this group to gain a better awareness of the external infrastructure systems which impact on their system, and the systems which their system in turn impacts.

1.5.4.3 Framework Analysis and Suitability

The framework proposed by (Chang, et al., 2014) provides a valuable contribution to the analysis of infrastructure systems through the simple, practical, and easily executed manner of analysis. Of the frameworks analysed this provides the most practical method for enhancing intersystem resilience in a community. The ability to undertake this analysis without advanced computations or data manipulation means that this analysis and the accompanying workshops could likely be undertaken by most local governments, who would otherwise have difficulty sourcing the specialist staff or data required to completed an analysis such as the Three-Stage analysis. Furthermore, the involvement of the system operators in both the workshops and data collection process by (Chang, et al., 2014) will provide these staff with a better understanding of the need for the network analysis, and ensure that the system operators have a vested interest in the outcomes of the study.

While this framework is well suited to a practical analysis of complex communities with many interdependent infrastructure systems, it is not intended for the analysis of a single system's resilience as intended for this research project. However, the concept of the interdependencies diagram provides an interesting and useful concept for the graphical representation of network dependencies and associated weaknesses.

The scope of this paper is the evaluation of the Wandoan West Road Network and the network resilience to flooding. While the impact on the road network will likely impact the performance of other infrastructure systems in the area, this is not to be evaluated and as such this framework is not suitable for use in the analysis to be undertaken.

1.5.5 Selection of Framework for use in the Analysis of the Wandoan West Road Network

Following investigation and evaluation of the existing literature and developed frameworks, the Networked Infrastructure Resiliency Assessment (NIRA) framework proposed by (Omer, et al., 2013) has been identified as the framework most suitable for use in the analysis of the Wandoan West Road Network (WWRN). This is because the outputs of this framework most align with the objectives of this paper, and the desired outcomes of analysis of the WWRN. Furthermore, this framework has previously been successfully applied to the analysis of the Boston-New York regional road network, and the data required to perform this analysis aligns most closely with that available for the WWRN.

2 METHODOLOGY

2.1 OVERVIEW

The methodology section of this paper will detail the processes and constraints to be used in the achievement of the project objectives as detailed earlier. The adopted methodology will include:

- Road Network characteristics for consideration.
  The characteristics that define road network are extensive and diverse. In order to ensure that a reliable dataset is collected and analysed, we must limit the road asset data to be considered and ensure that this is relevant to the planned analysis.
- Economic Consideration Boundaries
  The purpose of analysing the resilience of this particular road network, is to quantify the cost of any reduction in the level of service of the road, and thereby quantify the cost savings of any road upgrades. In addition to traffic generated by CSG development, there will also be traffic produced by other industries and local residents. In order to ensure a reliable dataset and minimise the raw data collection required, certain aspects of the expected traffic and associated cost may not be analysed depending on the quality and quantity of data available.

- Data Collection and Analysis
  Following collection of economic and road network data, the data must be reviewed in order to ensure it is whole, relevant and reliable. Any shortcomings in the data identified by this review must then be accounted for in any subsequent analysis in order to ensure an unbiased and rounded result is determined.

- Consideration of proposed upgrades
  When determining potentially beneficial upgrades as a result of the analysis, it is important to remember the remoteness of the area in which these upgrades will be hypothetically constructed, and the lack of access to certain materials, plant and techniques which may be able to be implemented elsewhere. Any suggested upgrades should be relevant to the constraints posed on site, and able to be constructed using local resources.

- Project Plan

  This section will details the resources, anticipated risks, and necessary requirements to achieve the stated project goals.

2.2 Road Network Characteristics

There are many diverse attributes which may be used to classify a road. For the purpose of this analysis the attributes assessed will be limited to those which will affect the ability of a road to function as designed during and in the period following a flood event.

2.2.1 Network Location

The location of the road network will be limited to the Wandoan Region of the Western Downs Regional Council. The student currently works closely with WDRC in employment to Brandon and Associates, an engineering consulting firm. As such WDRC asset data is available to the student, and permission for the use of this data has been granted by Graham Cook, the Director of Engineering Services for WDRC.

2.2.2 Flood Impact Data

The data to be used in modelling disruptions to the network will be based on historic flood data from one of two major flood events in the years 2011, and 2013. This data has been previously collected by WDRC in their restoration of this work as funded by the Queensland Reconstruction Authority, though is of varying quality.

This data documents the damage to the network and specific locations, as well as the actual cost to repair this damage. This data will provide insight into the reduced level of service as a result of the flood event, as well as anticipated repair costs, and the time taken to return the road to the previous level of service following the flood event.

Analysis of the available data for these two events will be compared, and the most suitable selected for use in modelling of network disruptions.

2.2.3 Road Surface

The characteristic of a sealed surface, as well as the seal width is a key indicator of the roads intended wet weather serviceability. A bituminous wearing surface not only provides longevity to the granular pavement material by preventing wear, but also provides an impervious layer which prevents moisture ingress into the pavement materials. This ensures the pavement material remains fully compacted and tightly bound, preventing deformation under traffic loads.

Lack of a sealed surface will result in a road that is likely to have surface deformations following wet weather requiring maintenance to correct. An unsealed road surface will also require traffic to travel slower due to reduced traction in wet weather, as well as reduced driver confidence in the road conditions.

Furthermore an unsealed road surface which is formation only, that is where there is no imported granular material used as road pavement, likely to have the intended level of service drastically reduced following a flood event due to the factors outlined above, coupled with the poor material properties of a typical insitu material, such as the commonly found loam. These types of roads are susceptible to extensive surface deformation under traffic loads when the material has been subject to moisture ingress, and are considered trafficable during moderate and greater rain events.

2.2.4 Pavement Material

The specific pavement material type will not be considered in this assessment of existing road assets, as this is difficult to determine without extensive materials testing of the road pavement itself. However, the use of stronger materials which are less susceptible to failure when saturated, will be considered as a viable option to increase the resilience of a particular road asset when evaluating upgrade options.

2.2.5 Network Extents

For the purpose of this analysis the extents of the road network to be analysed will be limited to those roads shown in figure 2.1.

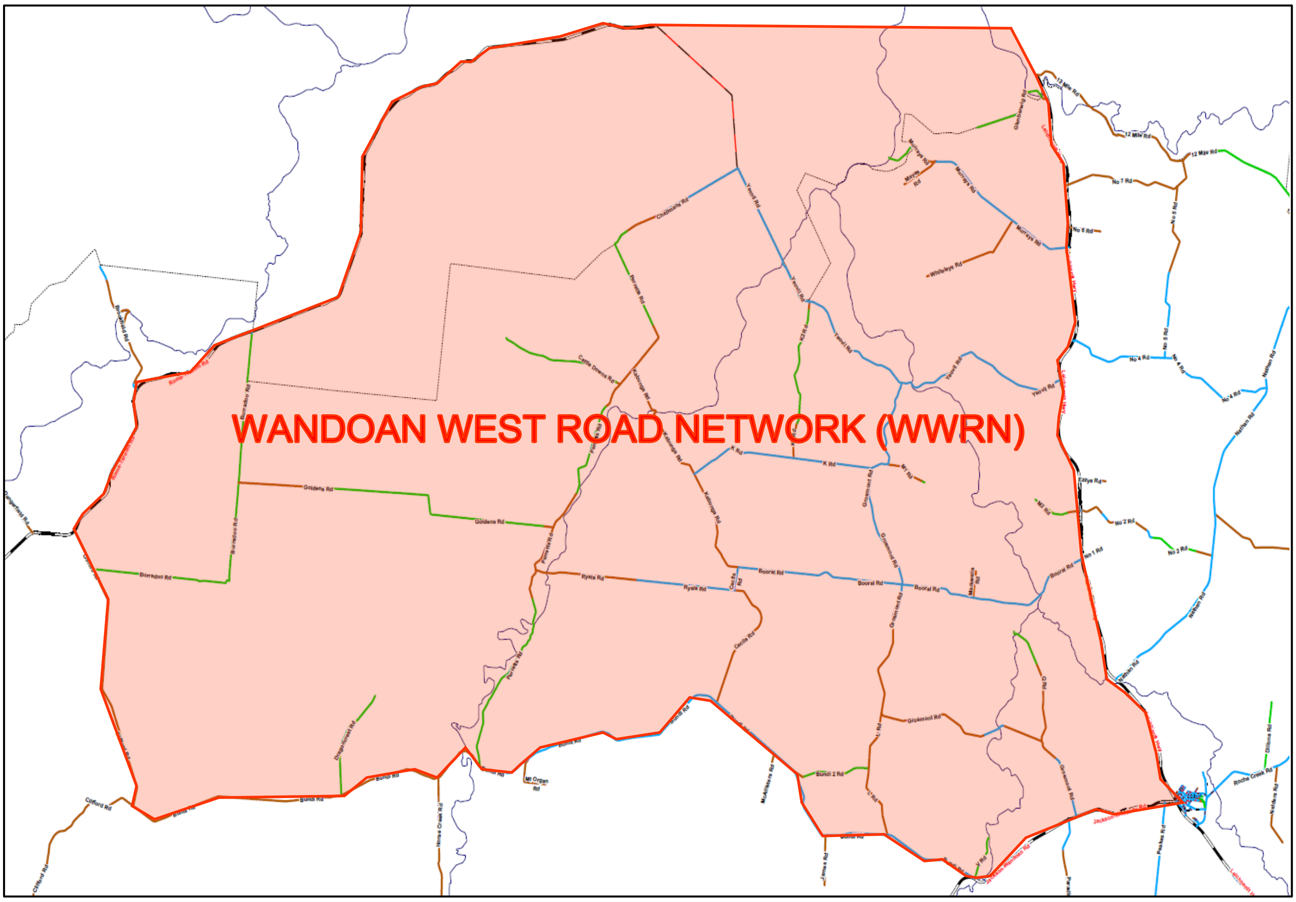


Figure 2.1 - Wandoan West Road Network Extents

The network will be limited to these extents as this road network encompasses all roads likely to be significantly affected by the proposed resource developments, the effects on which are to be analysed.

2.3 Economic Attributes

Resource development is not expected to be the only industry producing traffic which is likely to use the network to be assessed, and as such not the only industry expected to suffer additional development and operational costs as a result of disruptions to the network. These are detailed further below.

2.3.1 Coal Seam Gas Industries

These companies are suspected to be the major industry to be effected by disruptions to the road network, as this industry has the highest running costs, and most significant capital investment of all industries in the area. Taking into account the scale of development currently underway in the area as well, the CSG industry is expected to be that most significantly effected as a result of decreased production and stand down rates of the construction and operations staff.

The costs as a result of lost production will be evaluated as the increased operation cost expected as a result of increased travel time or stand down time for staff travelling to and from site as a result of these disruptions. These may be estimated using traffic volumes if the resource companies are unable to provide this data. The effect of lost profit due to delays in development are also expected to be significant, however these will be more difficult to estimate unless provided by the resource companies.

2.3.2 Other Local Industry

Being a rural area the majority of other local industry is expected to be primary industries, with land not currently in use by the resource industry being used by graziers and for cropping purposes. These industries would rely on the network most heavily when harvesting or transporting stock to sale. Typical of this industry, these business are usually family run partnerships or sole proprietors, and as such records or traffic impacts and losses due to decreased production are not likely to be kept or made available to external parties. In addition to this the majority of the staff required to operate these businesses are expected to live on the property itself, meaning the surrounding road network is not often required as a means of transporting staff to site.

Due to these considerations these industries will not be considered when assessing the economic impacts of disruptions to the local road network.

2.3.3 Local Residents

Local residents are also expected to incur additional cost if required to take an alternative route in the event of disruptions to the network. However, without extensive survey of these landowners this cost would be impossible to determine. As such this will not be included in analysis of the economic impacts of network disruptions

2.4 DATA COLLECTION AND ANALYSIS

2.4.1 Collection of Required Data

As detailed above, all asset and network data will be extracted from the WDRC Asset Register with permission granted by WDRC Management to the use of this material. As the student is currently seconded to WDRC full time in the role of Consultant Technical Officer, they have the ability to access these systems and extract this data directly.

Data regarding expected resource company activity on the network will also be provided by WDRC, as provided to them by QGC as part of the development application associated with these resource works.

Further Economic data to be provided by QGC would prove valuable in the evaluation of costs associated with disruptions to the network. This data will be requested by the student directly to a QGC representative. The contact details of this representative have been provided by WDRC staff liaising with QGC.

2.4.2 Analysis of Data using established Framework

Following collection of this data as detailed above, an established framework for the analysis for network disruptions will be applied. These frameworks have been investigated in the literature review process, and can be readily applied to the asset data and economic data to be collected.

This will require the determination of a network as a series of nodes and links, which can readily be applied to the physical network. This would see intersections be converted to nodes, and linking road segments be converted to links. Further to this, as QGC access to well sites as detailed in Appendix 1 occur along the road lengths between intersections, the major accesses will also be expressed as nodes to allow fine analysis of the economic impacts of an event depending on the restriction of access to the various well sites.

Following determination of the nodal network, disruptions caused by flood events can be modelled by disrupting links in the network corresponding to areas historically prone to damage during the past flood events. These areas can be determined using the historic WDRC flood data collected as detailed earlier, including the time taken to return each link to the design level of service following the flood event. These disruptions can then be assessed using the chosen framework in order to quantify the cost to road users as a result of the disruptions caused by these historic flood events.

Following this analysis of the existing network, the network will be remodelled with a number of currently proposed upgrades included.

The network will then be analysed again with these proposed upgrades in order to provide a quantitative increase in resilience for each suggested project. This increase in resilience will then be compared against the estimated cost of each project, and from this a series of recommendations provided as to possible infrastructure upgrades to be undertaken in the future, in order to increase the resilience of the WDRC Local Roads Network under flooding.

2.4.3 Expected Outcomes

Successful determination and analysis of this network would yield the following deliverables to assist in the determination of key projects necessary for increase in flood resilience of the WDRC local roads network:

- Determination of the most suitable framework for use in the assessment of a regional local government road network. To be suitable for analysis of these networks the framework would be required to consider changes in level of service, repair costs to expected damage, and financial loss incurred by both private and government organisations due to network disruptions.
- Evaluation of the network using the determined framework, and the modelling of actual network disruptions through the use of historic flood data to give an insight into the current level of flood resilience in the network.
- Determination of the most critical points in a network which were subject to failure during these events, the proposal or evaluation of upgrades, and the remodelling of the network with these upgrades in order to determine a quantifiable increase in network resilience as a result of these upgrades.
- Recommendation of a number of network improvements considering the estimated increases in network resilience modelled, and the estimated cost of these upgrades.

2.5 Proposed Upgrade Constraints

When considering the proposed upgrades it is important to ensure any suggested treatments are feasible for construction at the site specified. This must take into account the materials required for production, and the expertise and equipment required.

2.5.1 Availability of Materials

The Western Wandoan region has little in the way of natural gravel deposits suitable for sealed road construction. As such the range of materials is limited to WDRC produced crushed laterite, which typically performs poorly when saturated, or more expensive commercial quarry material.

Concrete is available sourced from a Boral Plant in Wandoan, however supply costs are much higher than experienced in other areas.

Bitumen Chip Seals are the preferred sealing treatment as the nearest asphalt plant is located in Toowoomba, approximately 5hr travel from the region.

Restrictions such as these will need to be considered when assessing the feasibility of the proposed upgrade treatments.

2.5.2 Construction Process

Local WDRC crews are likely to perform any upgrade work undertaken and, though the upgrades suggested in this report are unlikely to be actually constructed, the specialist experience and access to equipment of the staff who would be undertaking the construction should be considered when suggesting possible upgrades.

These local works crews have extensive experience working the local laterite and ridge gravel material, and are capable of finishing these works to a high standard suitable for bitumen sealing. However local WDRC crews have little experience with, and no access to the plant required to perform treatments such as insitu lime or concrete stabilisation.

2.6 PROJECT PLANNING

In order to ensure the successful completion of the process described above, identification of resources required, and risks associated, is required.

2.6.1 Resource Requirements

The resource requirements of the project are detailed in the table below.

Item	Amount	Source	Cost
WDRC Flood Damage Data	N/A	WDRC	NIL
WDRC Asset Register	N/A	WDRC	NIL
Additional Site Specific Data	N/A	Student	NIL
Transportation to Site	N/A	Student	NIL
Word Processor	N/A	Student	NIL
Microsoft Excel	N/A	Student	NIL
Graphics Calculator	N/A	Student	NIL

Table 2 - Project Resource Requirements

Western Downs Regional Council has given permission for the student to access all historic flood damage data, including financial records, for the purpose of this research project. As the legal owner of this information and confidential data, WDRC will retain ownership of this data and therefore must give permission before this information may be used in any form of external analysis or distributed to any third party.

2.6.2 Risk Assessment

The risk assessments below aim to identify hazards to both the person and project during activities that are expected to occur throughout the course of the project. The Risk matrix being used was developed by (University of Southern Queensland, 2008) and is shown below.

Eg 1. Enter Consequence

Eg 2. Enter Probability

Eg 3. Find Action

	Consequence				
Probability	**Insignificant** No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injuries $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L

Recommended Action Guide
E=Extreme Risk – Task ***MUST NOT*** proceed
H=High Risk – Special Procedures Required (See USQSafe)
M=Moderate Risk – Risk Management Plan/Work Method Statement Required
L=Low Risk – Use Routine Procedures

Figure 2.2 - Risk Assessment Matrix (University of Southern Queensland, 2008)

From this the following Personal Risk Assessment and Project Risk Assessment have been developed.

2.6.2.1 Personal Risk Assessment

The below risk assessment details anticipated risks to the student while performing activities expected to be undertaken during the project duration. From these mitigation methods have been determined.

Task	Hazard	Risk	Minimisation
Extended use of computer	Repetitive strain injury or development of bad posture.	**M**	Ensure correct posture and ergonomics are used when spending prolonged periods of time working on computer. Take regular breaks. 5-10 mins every 1.5 hours.
Collection of additional Data Onsite	Exposure to excessive heat or Sun.	**H**	Time site visits for early morning when UV index is low and temperature is mild. Apply appropriate sun protection and consume large amounts of water.
Collection of additional Data Onsite	Driver fatigue when travelling to remote sites	**H**	Break from driving every 1.5 hours and do not undertake a trip if feeling fatigued.
Collection of additional Data Onsite	Isolation when visiting remote sites alone	**H**	Setup a Journey management system where someone is aware of the destination, the route being taken, and the expected time of arrival and return.
Collection of additional Data Onsite	Trip Hazard when navigating uneven ground on site	**H**	Do not run. Walk slowly and maintain 3 points of contact on steep slopes.
Collection of additional Data Onsite	Drowning when visiting bridge sites	**M**	Do not come within 1.5m of any body of water of depth greater than 0.3m, or unknown depth.
Collection of additional Data	Impact with Vehicle when collecting data in a	**M**	Wear appropriate Hi Vis PPE. Maintain alertness to traffic. Only

Onsite	roadway.		cross or work within roadway when necessary and for the minimum time required.

Table 3 - Personal Risk Assessment

2.6.2.2 Project Risk Assessment

An assessment of the anticipated risks to the successful completion of this project has been undertaken, with the results and minimisation strategies shown in table 3.2.

Task	Hazard	Risk	Minimisation
All	Loss of Data	M	Backup all data and working to hard storage and available cloud storage.
All	Poor Time Management	H	Develop study habits which regularly see small sections of work addressed. Set additional reporting dates with supervisor and work colleagues to ensure project development stays on track.
All	Physical health	M	Maintain Healthy Diet and Exercise Routine.
Access to WDRC data	Work commitments see student removed from position with WDRC and lose access to necessary data.	M	Continue monitoring of current workload to ensure that if a shift is to occur, all necessary data has been collected by that time.

Table 4 - Project Risk Assessment

2.6.3 Ethical Considerations

Should the resource companies approach grant access to the specific economic data requested, this data is likely to be highly sensitive as it may be used by other companies when negotiating contracts or fees with the relevant company. In order prevent any negative repercussions to the company as a result of the provision of this data, the Student will suggest that a representative of the company review the finished project prior to submission in order to ensure the data provided has not been misused. The Student will also agree to use this data for the purpose of this research project only, and not distribute said data without the express written permission of the company.

2.6.4 Communication Plan

This Project Communication Plan outlines the communication links necessary for the successful delivery of the project. These links are outlined in both figure 4.2.1 and the sections below.

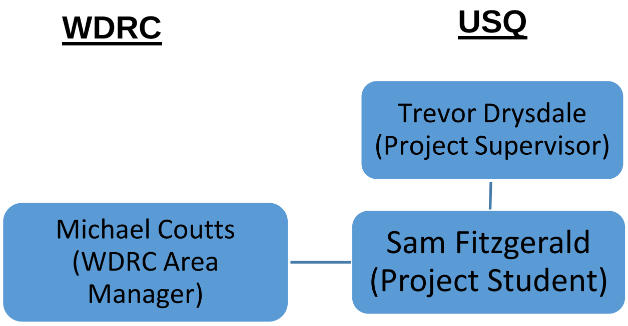


Figure 2.3 - Project Communication Plan

2.6.4.1 USQ Supervisor

Communication between supervisor and student will take place primarily via phone and email as the student is currently working full time and does not have access to USQ on weekdays. Physical visits will be valuable however and the student will aim to achieve a face to face meeting with the supervisor a minimum of once per two months as both parties schedules allow. In addition to this there will be regular monthly updates on student progress to seek input on project development as well as to develop accountability as a form of time management.

2.6.4.2 Western Downs Regional Council

The student will maintain constant contact with WDRC, not only to ensure access to the necessary data, but also to seek input from WDRC as to the development of the project and the outcomes that would prove most valuable to a regional council. In addition to this the WDRC representative is an experienced engineer with many years of practical asset management experience. This practical input will be invaluable in ensuring the outcomes of the project remain useable in the workplace.

2.6.4.3 Resource Companies

In order to gain access to specific economic data to be used in the determination of the costs anticipated during network disruptions, the Student will be required to make contact with the relevant resource companies to request this data. It will also be necessary to have a representative of this company review the finished document in order to approve the context in which the data is used prior to submission.

2.6.5 Special Requirements

At current there are no special requirements. WDRC may enforce confidentiality on any data provided, and will retain ownership of any data used. As such this data will not be released to any third party without express written approval of WDRC. The resource companies approach may enforce similar conditions on any economic data provided.

2.6.6 Project Schedule

This project will consist of the following phases. These timeline of these events is detailed in the Figure 2.4

1. Preliminary Phase
    - 1.1. Development of project specification. This document will detail project aims and objectives.
    - 1.2. Research Proposal. This current document will combine the literature review and project specification along with a course of action for completing the project.
    - 1.3. Literature review. This will expand on the preliminary literature review included with this document and will aim to investigate past and current research into the topic, and provide a sound foundation of knowledge for the development of the project ideas.
2. Start-up phase
    - 2.1. Confirmation of resources. This will include applying for permission to use or access to any data required to complete analysis of the local roads network. This will also include a preliminary review of the existing frameworks in order to determine the extent and types of data required to complete the network assessment.
3. Evaluation Phase

3.1. Framework Evaluation. This will include evaluation of all existing frameworks and the determination of the most suitable framework for use in this particular analysis.

3.2. Data Evaluation. Following the determination of a specific framework, the collected data will be reviewed in order to determine a final scope, dependant on the data required for the chosen framework, and the quality of the data collected from each region.

4. Network Assessment Phase.

4.1. Development of network models. This will include the translation of the selected WDRC Network into a model or series of models which will allow analysis of the physical network.

4.2. Calculation of Network Resilience. This will include the modelling of past network disruptions as indicated by the 2011 and 2013 flood data collected. This data will be modelled using the chosen framework and the impact of the disruption on the entire network analysed.

5. Asset Upgrade Phase.

5.1. Preliminary investigation of upgrade options. This will include assessment of proposed QGC upgrades to the Wandoan West rural Road Network associated with phase 2 development of CSG sites in the area.

6. Reassessment Phase.

6.1. Recalculation of network resilience. This will include modelling of the network with the proposed upgrades in order to assign an increase in network resilience as a result of these upgrades. This will include comparing the potential increases in resilience with the estimated cost of each upgrade.

7. Write-up Phase

7.1. Prepare Preliminary Report.

7.2. Prepare Progress Assessment.

7.3. Draft Dissertation. This will involve collation of all findings into a draft dissertation for supervisor review.

7.4. Final dissertation. This will include the amending of the draft dissertation as per supervisor and other feedback.

	Task Name	Duration	Start	Finish
1	1. Preliminary Phase	129	01/11/14	29/04/15
2	1.1 Development of Project Specification	55	01/01/15	18/03/15
3	1.2 Research proposal	16	01/11/14	21/11/14
4	1.3 Literature Review	99	14/12/14	29/04/15
5	2. Start-Up Phase	45	30/01/15	02/04/15
6	2.1 Confirmation of Resources	45	30/01/15	02/04/15
7	3. Evaluation Phase	44	23/03/15	21/05/15
8	3.1 Framework Evaluation	29	23/03/15	30/04/15
9	3.2 Data Evaluation	15	01/05/15	21/05/15
10	4. Network Assessment Phase	23	20/05/15	19/06/15
11	4.1 Development of Network Models	13	20/05/15	05/06/15
12	4.2 Calculation of network Resilience	10	08/06/15	19/06/15
13	5. Asset Upgrade Phase	26	19/06/15	24/07/15
14	5.1 Preliminary Investigation of Upgrade Options	26	19/06/15	24/07/15
15	6. Reassessment Phase	16	24/07/15	14/08/15
16	6.1 Recalculation of Network Resilience	6	24/07/15	31/07/15
17	6.2 Cost analysis and recomendations	11	31/07/15	14/08/15
18	7. Write-up Phase	159	23/03/15	29/10/15
19	7.1 Prepare Preliminary Report	68	23/03/15	24/06/15
20	7.2 Project Progress Assessment	16	27/05/15	17/06/15
21	7.3 Draft Dissertation	66	17/06/15	16/09/15
22	7.4 Final Dissertation	32	16/09/15	29/10/15

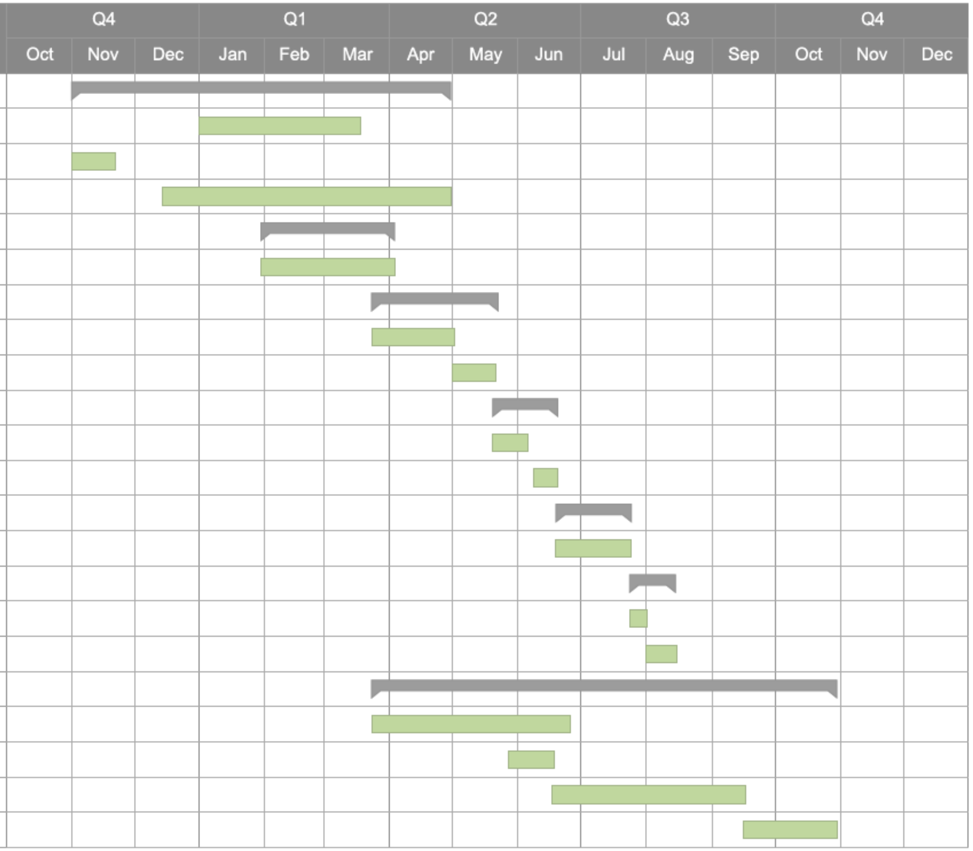


Figure 2.4 - Project Schedule

2.6.7 Quality Assurance

As there is no physical testing involved in this research project, there will be no necessary quality controls needed to be put in place in regards to data capture. This being said, captured data will be review in order to confirm reliability, and identify any missing data to be accounted for. There is expected to be a small degree of modelling and calculation involved. This work will be quality assured by review by associates of the student experienced in both computational and desktop modelling, and advanced mathematics.

The remainder of the project will be reviewed for quality by means of Peer Review. One such peer will be the project supervisor who will review results and drafts periodically at the milestone events indicated in the above project schedule.

Additional peer review will also be undertaken by experienced engineering staff known to the student, including colleagues and mentors as well as graduate engineers and experienced asset management engineers. This will provide a wide and varied range of professionals experienced in all aspects of the project to provide thorough and relevant review of project quality.

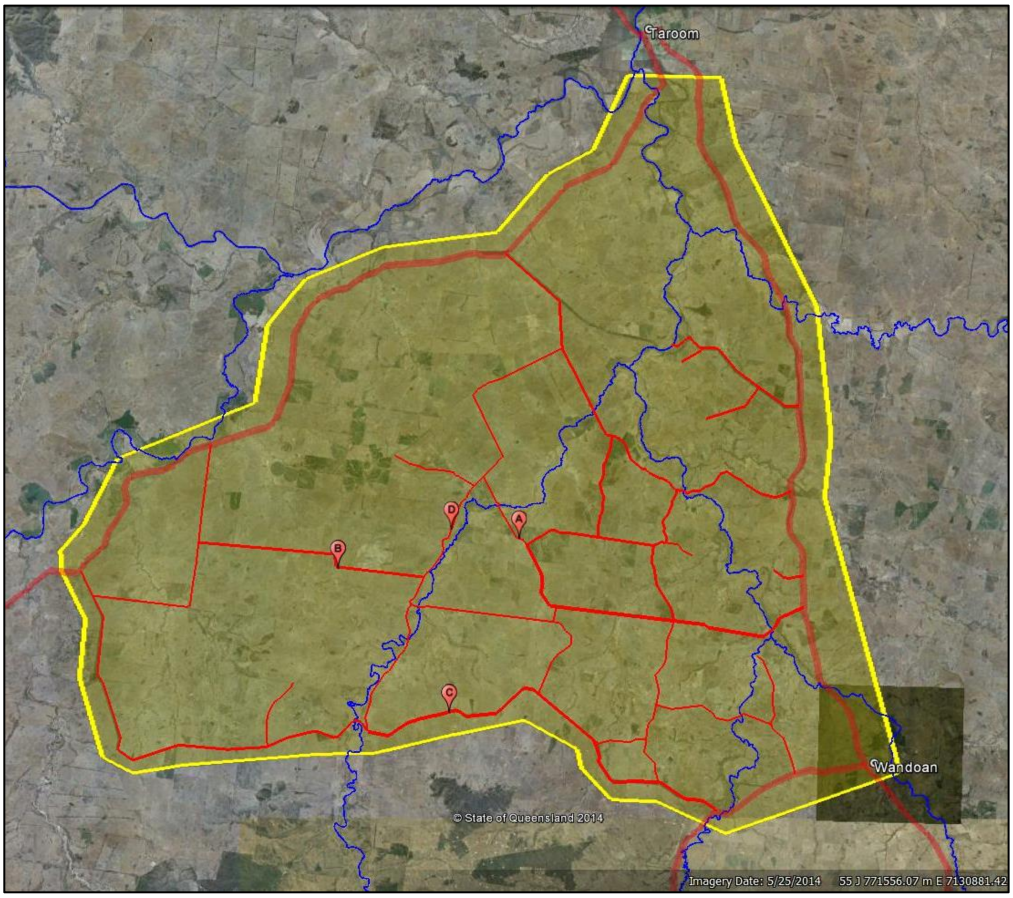
3 NETWORK ANALYSIS

3.1 ANALYSIS OF EXISTING ROAD NETWORK USING NIRA FRAMEWORK

The following section will detail an analysis of the existing network resilience to a Q100 flood event using the NIRA Framework identified, and using historic defect data from a previous Q100 event, the 2011 Flood Event, to estimate and simulate reduced network capacity during and after the event.

3.1.1 Define Network Boundaries

The physical road network to be analysed for the assessment of resilience of the Wandoan West Road Network is shown below. This network constitutes all connected roads between Wandoan, the assumed source point, and the QGC access points as stipulated in Appendix 1 – Phase 2 Tranche 1B off-plot road upgrades. These access points are assumed to be destinations for the purpose of



network analysis.

Figure 3.1 - Physical Transportation Network - Wandoan to QGC Phase 2 Plot Accesses (Google Earth, 2015)

In development of the network model, only those roads likely to be used as alternative routes to the destinations shown will be included. This will exclude access only roads, as well as roads in the more northern and southern areas of the network, as these roads are unlikely to ever be used as by QGC or QGC Contractor traffic when accessing the development sites shown.

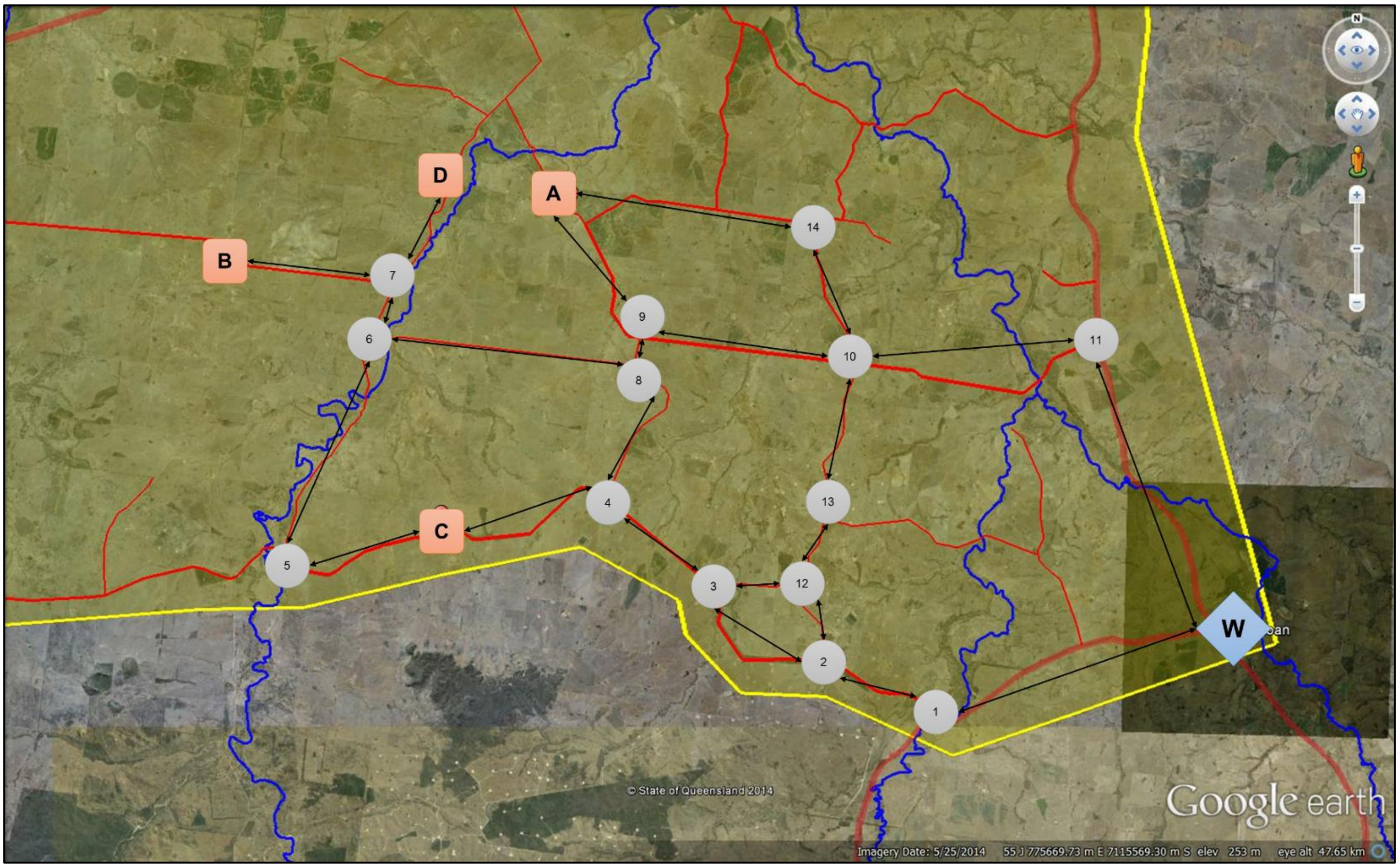


Figure 3.2 - Logical Network of WWRN (Wandoan to QGC Phase 2 Sites)

Two main potential links have been omitted from the network diagram shown in Figure 3.2. Justification for these is as follows:

- Grosmont Road (W-13). This road was excluded as an unsealed road, with a low level bridge. Due to this the bridge will become untrafficable before the bridge on Bundi Rd (1-2) and Booral Rd (11-10), and so does not propose an alternative route of any value during an event. Being an unsealed road as well, it is likely to sustain greater damage than Bundi Rd and Booral Rd following an event.

- Yeovil Road (11-14). This road has been excluded as the main creek crossing on this road is at a low level, similar to Booral Rd (11-10). This road, along with Boral Rd, is sealed for a 6 meter width. As such this road offers no advantage as an alternative route to Booral Rd (11-10-14) apart from a longer route.

With the spatial boundary now defined, the temporal and operational boundaries remain. The temporal boundary, or timeframe for which the analysis will be conducted, will be the full scope of a Q100 flood event network disruption. This timeframe will be assumed to coincide with the construction phase of the QGC Phase 2 developments as detailed in Figure 1.9.

The operational boundary refers to the major product of the system being analysed. As the WWRN is a road transportation network, this boundary would be defined in traffic flow. This value will be analysed in vehicles per hour. As the forecast traffic data provided is in the form of vehicles per day, this will be converted assuming an even distribution of the traffic volumes given, over a standard 12 hour work day.

3.1.2 Define System Metrics for Analysis

System metrics to be used in analysis of the WWRN resilience to flooding, are to be the major performance indicators of the network, which by measurement of these metrics provides an indication of the quality of service provided by the Transport Network (Omer, et al., 2013). As defined by (Bruneau, et al., 2003), resilience can be expressed as a value of 0 to 1, with 1 being optimum performance not affected by disruption, and 0 being a complete lack of performance.

As this paper aims to evaluate the effect of network disruptions during a Q100 Flood Event on CSG development in the area, the metrics chosen must reflect the indicators of highest priority to the companies undertaking these developments.

The primary need and concern of these companies in regards to the performance of the road network, is the supply of materials, plant, and labour to QGC on which these developments are occurring. These concerns can be expressed as the travel time on the network, and the cost of this travel in terms of plant and labour hire costs. Also of concern would be any penalties or lost profits associated with delays to the construction programs of these developments. Unfortunately this information has not been provided at the time of writing this report, and so these additional considerations will be omitted from any evaluation.

There currently exist a number of proposed methods for calculation of travel time reduction due to congestion and reduced capacity, such as the ARRB Travel Cost Method (ATCM), The Austroads National Performance Indicator (NPI) Program, and the ARRB Congestion Model (ACM) (Austroads, 2009). All of these methods are developed specifically to assess congestion of major motorways or urban arterial roads, and as such make use of detailed data collected which details traffic composition, flow, speed, and road capacity.

Roads in the WWRN experience negligible traffic volumes compared to the roads intended for evaluation by these methods, and as such the data required and methodology used is inappropriate for use in assessing the WWRN. However, the principles suggested by the above mentioned methods are relevant, and are similar to the principle of resilience as investigated by (Omer, et al., 2013) and (Bruneau, et al., 2003), in expressing decreases in network performance as a ratio of actual or estimated performance against benchmark or optimum performance. These principles have been the foundation of the below proposed metrics for calculating travel time and travel cost resilience on a rural road network.

$$R\_Cost_{Path} = \sum_{1}^{n} R\_Cost_{Link} \quad (1)$$

$$R\_Cost_{Link} = \frac{Cost\_BE}{Cost\_AE} \quad (2)$$

$$Cost_{BE} = tt_{BE}[(Cost\ per\ LV\ \times Ratio\ LV) + (Cost\ per\ HV\ \times Ratio\ HV)] \quad (3)$$

$$Cost_{AE} = tt_{AE}[(Cost\ per\ LV\ \times Ratio\ LV) + (Cost\ per\ HV\ \times Ratio\ HV)] \quad (4)$$

$$tt_{BE} = t\_Opt(V_{BE}) \quad (5)$$

$$tt_{AE} = t\_Est(V_{AE}) \quad (6)$$

$$t\_Opt = \frac{l}{S\_Opt} \quad (7)$$

$$t\_Est = \frac{l}{S\_Opt \times LRF} \quad (8)$$

$$LRF = 1 - \sum_{H1}^{Hn} RF \quad (9)$$

$$RF = \frac{S\_Haz}{S\_Opt} \times \frac{l\_Haz}{l} \quad (10)$$

$$R\_Time_{Link} = \frac{tt_{BE}}{tt_{AE}} \quad (11)$$

$$R\_Time_{Path} = \frac{\sum tt_{BE}}{\sum tt_{AE}} \quad (12)$$

Where;

R_Cost_{Path}	is the cost resilience of the path, made up of a series of links
R_Cost_{Link}	is the cost resilience per individual link
$Cost_{BE}$	is the Calculated cost of travel per link, Before Event
$Cost_{AE}$	is the calculated cost of travel per link, After Event
tt_{BE}	is the cumulative travel time per link for conditions and traffic volumes before the disruptive event
tt_{AE}	is the cumulative travel time per link for conditions and traffic volumes after the disruptive event
t_Opt	is the optimum travel time per link with no disruptions
t_Est	is the estimated travel time per link considering cumulative reductions in speed due to hazards on the link
LRF	is the Link Reduction Factor, which represents the cumulative effect of multiple reductions in speed due to multiple hazards over an entire link.
RF	is the hazard reduction factor, calculated as a proportion of reduced travel time due to decreased speed caused by an individual hazard against optimal travel time, represented as a proportion of the link length effected.
S_Opt	is the optimum travel speed on the link with no disruptions
S_Haz	is km/h decrease in speed required to negotiate a hazard safely
l_Haz	is the length for which the hazard effects travel speed

l is link length in kilometers

V_{AE} is the traffic volume of the link following a disruptive event, accounting for additional traffic diverted from failed links

V_{BE} is the traffic volume of the link before the disruptive event

R_Time_{Link} is the travel time resilience for a link

R_Time_{Path} is the travel time resilience for a path, or series of links

Equations (7) – (10) allow individual hazards caused by network disruptions to be analysed and their cumulative effect represented as a decrease in link performance for the optimal benchmark. The cumulative increase in travel time can then be illustrated by equations (5) and (6), before translating these additional hours travel to the estimated additional financial impact of these delays by equations (3) and (4). Once this analysis has been completed on a per link basis, these findings can then be applied to determined paths to demonstrate the overall cost in terms of labour and plant, and lost time, by the use of equations (1), (2), (11), and (12).

These series of equations have been formatted to the following excel sheet, to allow input of individual hazards on individual links, determination of the effects of these hazards on the performance of the link, and the analysis of multiple links as paths.

Note the value for reduced speed is a subjective value determined by review of damage photos as included in WDRC Submitted and Approved NDRRA Form 4 Grant Applications. The assumed cost per hour for operators, and light and heavy vehicles is derived from typical costs experienced in the road construction industry for Engineers, Foremen, Plant Operators, and Labourers. The assumed cost per vehicle was likewise determined.

Individual Link Performance Analysis Sheet

Link ID:	11-10

Link Overview

Symbol	Description	Value	Unit
R_Time_{Link}	Link Travel Time Resilience	0.93	
R_Cost_{Link}	Link Travel Cost Resilience	$ 634.04	$/Day
$Cost_{BE}$	Travel Cost Before Event	$ 8,008.18	$/Day
$Cost_{AE}$	Travel Cost After Event	$ 8,642.22	$/Day
tt_{BE}	Travel Time Before Event	48.5	Hours (cumulative)
tt_{AE}	Travel Time After Event	52.4	Hours (cumulative)

Pre/Post Disruption Performance Analysis

	Symbol	Description	Value	Unit
Benchmark/Optimum Performance	*l*	Link Length	10.45	kilometers
	S_Opt	Mean Speed under normal operating conditions	90	km/hr
	t_Opt	Optimum Travel Time	0.12	hours
	V_BE	Traffic Volume under normal operating conditions	418	vehicles per day
	S_Opt	Mean Speed under normal operating conditions	90	km/hr
Disrupted Performance	*LRF*	Link Reduction Factor	0.93	
	t_Est	Estimated Travel Time	0.13	hours
	V_AE	Traffic Volume after event (taking into account increased traffic due to reduced performance of other links	418	vehicles per day

Individual Hazard Input

Hazard ID	Ch. St.	Ch. Fn.	Dist	Description	Reduced Speed	Hazard Reduction Factor
W1-001	2.6	2.9	0.3	Pavement Failure	60	0.019
W1-002	3	3.5	0.5	Pavement Failure	60	0.032
W1-003	3.9	4.2	0.3	Pavement Failure	60	0.019
W1-004	4.6	4.65	0.05	Pavement Failure	60	0.003

Assumed and Given Values

Occupants per LV	1.5	Occupants per HV	1
Cost/hour per LV	$ 35.0	Cost/hour per HV	$ 180.00
Cost/hr per occupant	$ 70.0	Cost/hr per occupant	$ 60.00
Total cost/hr per LV	$ 140.0	Total cost/hr per HV	$ 240.00
Proportion LV	0.750	Proportion HV	0.25

Figure 3.3 - Example Individual Link Performance Analysis Sheet (Link 11-10 Booral Rd)

3.1.3 Development of Network Model

From the physical network a logical network model of nodes and links is developed, and Paths to the four QGC Development Destinations determined. Paths will be modelled on actual design paths as provided in Appendix 1 Phase 2 Tranche 1B Off-Plot Road Upgrades. This same document provides traffic volumes for the period to be analysed. The below figure shows the determined network.

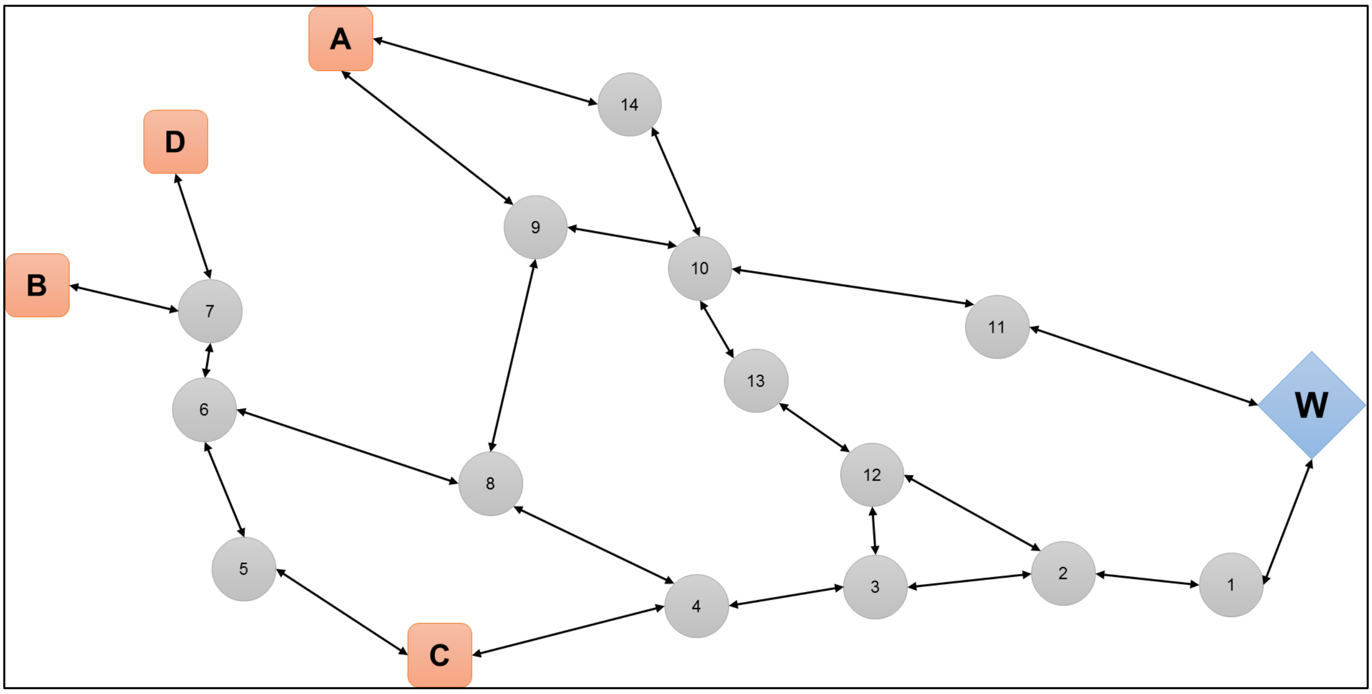
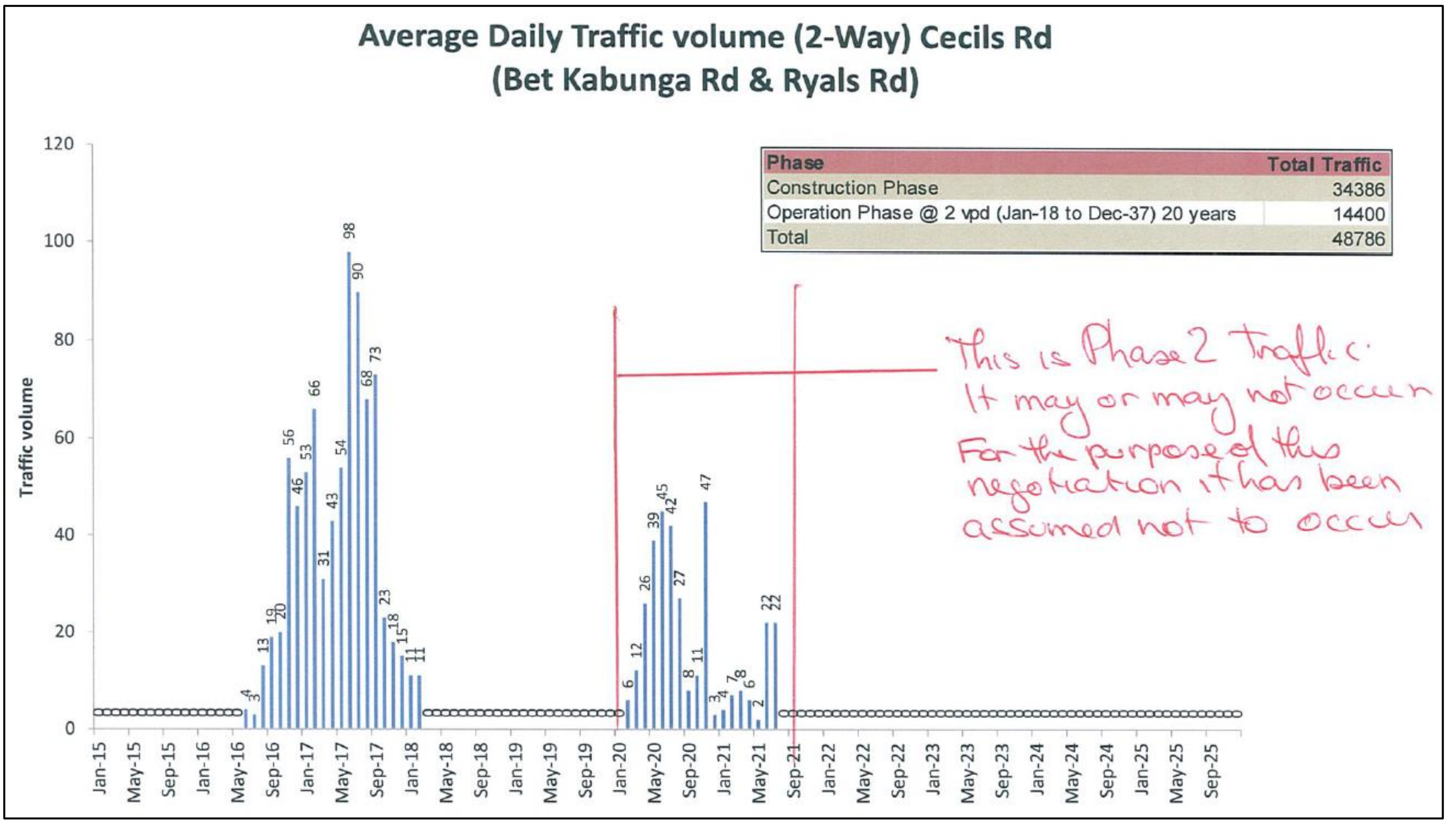


Figure 3.4 - WWRN Logical Network Showing Sources, Destinations, Nodes, and Links

To allow analysis of these links the traffic volume per link (V_BE) and Link Reduction Factor (LRF), must first be determined from collected QGC Histograms as shown in Appendix 1, and WDRC Flood Damage Defect Information as shown in Appendix 5. Note that actual damage photos have not been included due to the significant size and quantity of these records. Examples of these photos can be viewed in Section 1.4.2 of this paper. These damage photographs were used to make a subjective analysis of the individual hazard's impact on the optimal operating speed.

Determination of V_BE per link is undertaken by a comparison of QGC Phase 2 forecast traffic histograms as provided to WDRC, and the corresponding link to the physical network segments represented in these histograms. For example, link (8-9) represents the physical network segment of Cecils Road between the intersection of Ryals Road and Kubunga/Booral Road. The V_BE value for this segment is directly determined from the below histogram excerpt. For the purposes of this analysis, the V_BE value will be taken as the maximum monthly ADT for the first construction



phase.

Figure 3.5 - Excerpt Appendix B (Cecils Rd bet Kubunga Rd and Ryals Rd) forecast traffic histogram

Analysis of the provided histograms yields the following *V_BE* values per link under QGC designated access paths. Note that traffic is not constant for the duration of the path, and this is assumed to be due to QGC traffic accessing various well sites along each link and thereby not travelling Node-Node. For the purposes of this analysis it will be assumed that the traffic volumes given for each link travel from Node-Node on the network. This is necessary as without further data provided by QGC, it is impossible to estimate the length on each link the resource traffic travels.

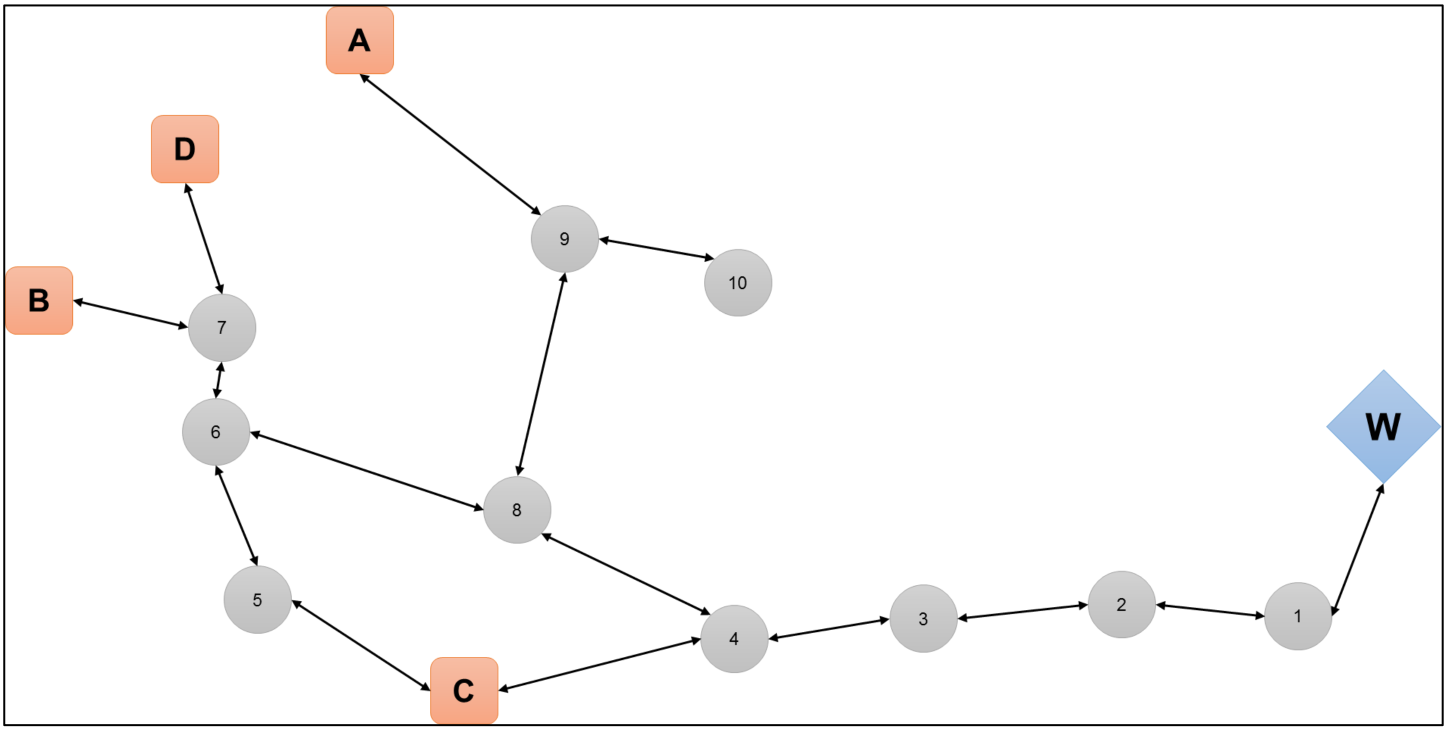
Link	Determined *V_BE*	Comments
W-1	419	Page 4, Average Daily Traffic volume (2-Way) Bundi Rd (Bet Cecils Rd & L Rd)
W-11	0	Not Optimal Design Path
1-2	419	Page 4, Average Daily Traffic volume (2-Way) Bundi Rd (Bet Cecils Rd & L Rd)
2-3	419	Page 4, Average Daily Traffic volume (2-Way) Bundi Rd (Bet Cecils Rd & L Rd)
2-12	0	Not Optimal Design Path
3-4	419	Page 4, Average Daily Traffic volume (2-Way) Bundi Rd (Bet Cecils Rd & L Rd)
3-12	0	Not Optimal Design Path
4-C	285	Page 9, Average Daily Traffic volume (2-Way) Bundi Rd (Bet Point C & Cecils Rd)
4-8	339	Page 6, Average Daily Traffic volume (2-Way) Cecils Rd (Bet Ryals Rd & Bundi Rd)
5-C	158	Page 2, Average Daily Traffic volume (2-Way) Bundi Rd (Point C to Ch 30.98)
5-6	53	Page 14, Average Daily Traffic volume (2-Way) Perretts Rd (Bet Bundi Rd & Ryals Rd)
6-7	73	Page 13, Average Daily Traffic volume (2-Way) Perretts Rd (Bet Goldens Rd & Ryals Rd)
6-8	339	Page 15, Average Daily Traffic volume (2-Way) Ryals Rd (Bet Perretts Rd & Cecils Rd)
7-B	73	Page 8, Average Daily Traffic volume (2-Way) Goldens Rd (Bet Point B & Perretts Rd)
7-D	73	Page 12, Average Daily Traffic volume (2-Way) Perretts Rd (Bet Point D & Goldens Rd)
8-9	98	Page 10, Average Daily Traffic volume (2-Way) Cecils Rd (Bet Kubunga Rd & Ryals Rd)
9-A	98	Page 11, Average Daily Traffic volume (2-Way) Kabunga Rd (Bet Point A & Cecils Rd)
9-10	44	Page 16, Average Daily Traffic volume (2-Way) Booral Rd (Ch: 15.7 to 19.2)
10-11	0	Not Optimal Design Path
10-13	0	Not Optimal Design Path
10-14	0	Not Optimal Design Path
12-13	0	Not Optimal Design Path
14-A	0	Not Optimal Design Path

Table 5 - Determined V_BE values for network links

With the calculation of the above *V_BE* values, the individual link performance analysis sheet can now be completed for each link in the above path using 2011 Flood Damage Restoration Data collected.

3.1.4 Assessment of Network Resilience

The above metrics were applied to each link in the WWRN as identified in the paths discussed earlier. A number of links were not analysed due to the expectation that no QGC or Contractor traffic is expected to travel these roads a part of the forecast



developments. The updated network with redundant links removed is shown below.

Figure 3.6 - Updated WWRN with links redundant to CSG Development Traffic Removed

The metrics for measurement of link performance were applied to each link in the above network using the Individual Link Performance Analysis Sheet. The link values for input, were collected from the relevant sources for each link. The value input for link length was measured using Google Earth and the network overlay constructed earlier, and the value used for mean speed in normal operating conditions was set as a standard 70km/h for unsealed roads, and 90km/h for a sealed road.

The individual hazard information was collected from 2011 Flood Event Form 4 Grant Applications submitted to the QRA by WDRC for funding of restoration of the 2011 Flood Damage works. An extract of the hazard information given by these forms is shown below. An estimation of necessary speed reduction per hazard was made by the student, using damage submission photos and personal driving experience on these roads as references.

Natural Disaster Relief and Recovery Arrangements

Restoration of Essential Public Assets - Grant Application

Department of Infrastructure and Planning
Local Government and Planning Group

multi sites, one road submission

FORM 4

Sheet Number: 4.

NDRRA Event: Queensland Flooding and Tropical Cyclones Tasha and Anthony November 2010 - February 2011

Local Government Area (LGA)	Western Downs Regional Council
Asset / Road Name	Cecils Road
Road Number	X017
Site Number	Section 1

Please tick

- ☐ **Emergent work**
- ☑ **Restoration work**
- ☐ **Actuals**
- ☑ **Estimates**

Asset Description / Service Level

Single lane gravel road 4m wide.

Cause of Damage

Monsoonal rains, creek and overland flooding caused high flow rates across floodways, inundation of pavements and saturation of subgrade. This has resulted in loss of pavement materials, rutting and scouring of table drain.

Chainage / Coordinates Start	Finish	Dist (km)	Photo Reference	Description of Asset Damage	Proposed/Completed Restoration & specification of Engineering Standards / Building Codes (where changing)	Unit	Qty	Rate	Amount
1.3	1.35	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	56	68.55	$3,838.80
1.55	1.6	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
1.61	1.65	0.04	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
1.7	1.75	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	40	68.55	$2,742.00
1.8	1.85	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
2.1	2.15	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
2.2	2.3	0.1	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	90	68.55	$6,169.50
2.4	2.45	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	40	68.55	$2,742.00
2.55	2.59	0.04	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	56	68.55	$3,838.80
2.6	2.64	0.04	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	56	68.55	$3,838.80
2.65	2.8	0.15	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	135	68.55	$9,254.25
3.35	3.4	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
3.5	3.55	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	56	68.55	$3,838.80
3.65	3.7	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
4.1	4.15	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	56	68.55	$3,838.80
5.15	5.2	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
5.8	5.85	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
6.05	6.1	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	56	68.55	$3,838.80
6.2	6.25	0.05	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	40	68.55	$2,742.00
6.98	7	0.02	Cecils RD W	Gravel scouring and rutting	Place 150mm of gravel, mix, re-compact and shape	m3	32	68.55	$2,193.60
7.1	7.2	0.1	Cecils RD Wandoan 7.2		Place 150mm of gravel, mix, re-compact and shape	m3	90	68.55	$6,169.50
20								**Total:**	**$72,594.45**

We certify that the proposed / completed restoration works are required as a result of an activated natural disaster event and complies with the Queensland Disaster Relief and Recovery Arrangements 2009/10. We certify that the photographs supplied are a true and accurate record of the damage sustained to the asset at the specified location indicated above. We certify that no ordinary wages / salaries have been included in this submission nor any other costs that are ineligible under the NDRRA arrangements. We certify that funding approved will only be used for the specified restoration for this site.

Estimator: ______________________ Signature: ______________________ Date: _____/_____/_____

Accountable Officer: Graham Cook - Director of Engineering Services Signature: ______________________ Date: _____/_____/_____

SHEET 1 *of* 1

Figure 3.7 - Form 4 Grant Application (Cecils Rd) 2011 Flood Damage Restoration

The Individual Link Performance Analysis Sheet than calculates travel time and cost prior to and following the disruptions to the network as represented by the hazard data entered. An example of a completed analysis sheet using hazard data given by Figure 3.7 is shown below. A summary of the results of these individual sheets per

Individual Link Performance Analysis Sheet

Link ID:	4-8

Link Overview

Symbol	Description	Value	Unit
R_Time_{Link}	Link Travel Time Resilience	0.74	
R_Cost_{Link}	Link Travel Cost Resilience	$ 1,886.10	$/Day
$Cost_{BE}$	Travel Cost Before Event	$ 5,433.69	$/Day
$Cost_{AE}$	Travel Cost After Event	$ 7,319.79	$/Day
tt_{BE}	Travel Time Before Event	32.9	Hours (cumulative)
tt_{AE}	Travel Time After Event	44.4	Hours (cumulative)

Pre/Post Disruption Performance Analysis

	Symbol	Description	Value	Unit
Benchmark/Optimum Performance	*l*	Link Length	6.8	kilometers
	S_Opt	Mean Speed under normal operating conditions	70	km/hr
	t_Opt	Optimum Travel Time	0.10	hours
	V_BE	Traffic Volume under normal operating conditions	339	vehicles per day
	S_Opt	Mean Speed under normal operating conditions	70	km/hr
Disrupted Performance	*LRF*	Link Reduction Factor	0.74	
	t_Est	Estimated Travel Time	0.13	hours
	V_AE	Traffic Volume after event (taking into account increased traffic due to reduced performance of other links	339	vehicles per day

Individual Hazard Input

Ch. St.	Ch. Fn.	Dist	Effective Dist	Description	Speed Reduction	Hazard Reduction Factor
1.3	1.35	0.05	0.25	Gravel Scouring and Rutting	30	0.013
1.55	1.6	0.05	0.25	Gravel Scouring and Rutting	30	0.013
1.61	1.65	0.04	0.24	Gravel Scouring and Rutting	30	0.013
1.7	1.75	0.05	0.25	Gravel Scouring and Rutting	30	0.013
1.8	1.85	0.05	0.25	Gravel Scouring and Rutting	30	0.013
2.1	2.15	0.05	0.25	Gravel Scouring and Rutting	30	0.013
2.2	2.3	0.1	0.3	Gravel Scouring and Rutting	30	0.016
2.4	2.45	0.05	0.25	Gravel Scouring and Rutting	30	0.013
2.55	2.59	0.04	0.24	Gravel Scouring and Rutting	30	0.013
2.6	2.64	0.04	0.24	Gravel Scouring and Rutting	30	0.013
2.65	2.8	0.15	0.35	Gravel Scouring and Rutting	30	0.019
3.35	3.4	0.05	0.25	Gravel Scouring and Rutting	30	0.013
3.5	3.55	0.05	0.25	Gravel Scouring and Rutting	30	0.013
3.65	3.7	0.05	0.25	Gravel Scouring and Rutting	30	0.013
4.1	4.15	0.05	0.25	Gravel Scouring and Rutting	30	0.013
5.15	5.2	0.05	0.25	Gravel Scouring and Rutting	30	0.013
5.8	5.85	0.05	0.25	Gravel Scouring and Rutting	30	0.013
6.05	6.1	0.05	0.25	Gravel Scouring and Rutting	30	0.013
6.2	6.25	0.05	0.25	Gravel Scouring and Rutting	30	0.013

Assumed and Given Values

Occupants per LV	1.5	Occupants per HV	1
Cost/hour per LV	$ 35.0	Cost/hour per HV	$ 180.00
Cost/hr per occupant	$ 70.0	Cost/hr per occupant	$ 60.00
Total cost/hr per LV	$ 140.0	Total cost/hr per HV	$ 240.00
Proportion LV	0.750	Proportion HV	0.25

link is shown in Appendix 6.

Figure 3.8 - Example Individual Link Performance Analysis Sheet (Cecils Rd) Link (4-8)

This analysis then provides a value for the Travel Time Resilience of the link, as well as the Additional Travel time cost due to disruptions per link. These results are shown in the table below.

Link	R_Time_{Link}	R_Cost_{Link}	Surface Type
W-1	1	$ -	Sealed
1-2	0.84	$ 734.01	Sealed
2-3	0.97	$ 140.23	Sealed
3-4	0.98	$ 81.23	Sealed
4-C	0.98	$ 68.01	Sealed
5-C	0.95	$ 94.80	Sealed
8-9	0.8	$ 64.27	Sealed
9-10	1	$ -	Sealed
4-8	0.74	$ 1,886.10	Pavement Only
6-7	0.78	$ 109.93	Pavement Only
7-D	0.79	$ 139.36	Pavement Only
9-A	1	$ -	Pavement Only
5-6	0.89	$ 165.81	Formation Only
7-B	0.89	$ 137.06	Formation Only
6-8	0.91	$ 787.09	50% Seal/50% Pavement Only

Table 6 - Results of Individual Link Resilience Analysis

These results are also illustrated in the below graphs showing travel time resilience and travel cost resilience per link.

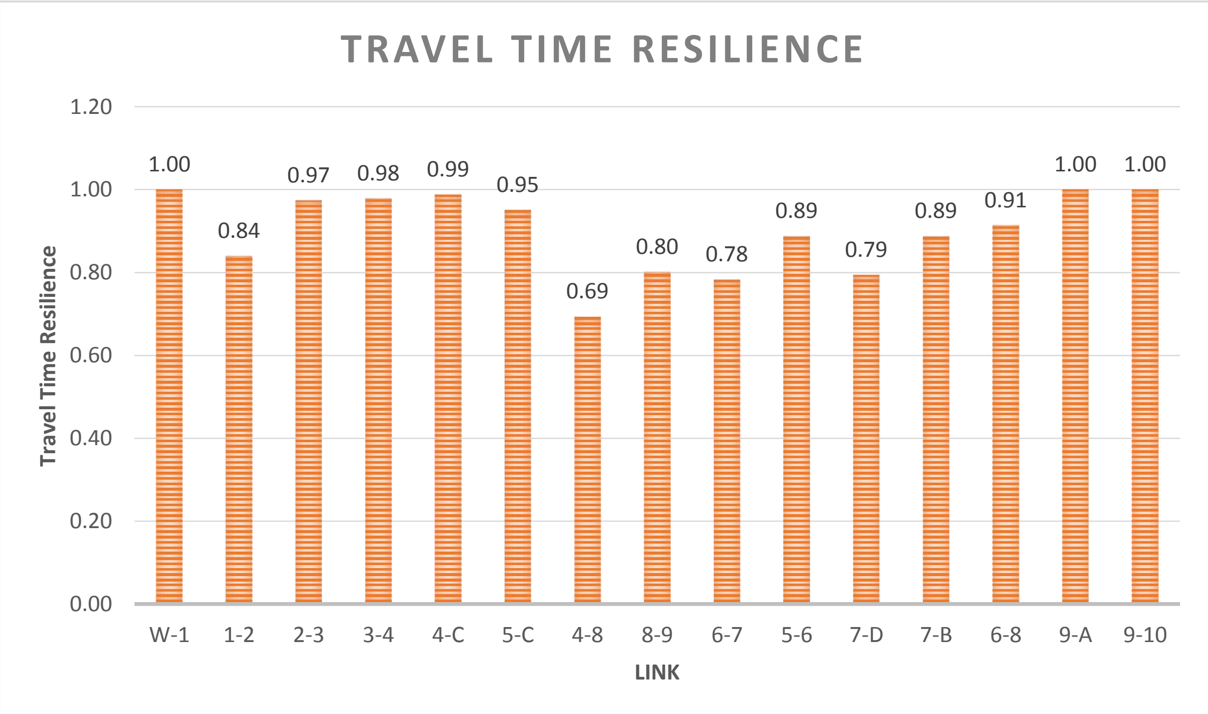


Figure 3.9 - Travel Time Resilience Per Link (WWRN)

Figure 3.9 clearly shows the links most significantly effected in terms of travel time resilience are the pavement only links (4-8), (6-7), and (7-D). This is to be expected as scouring and rutting of pavement are common occurrences during periods of heavy overland flow. The above chart also illustrates the lack of resilience in link (1-2). This link is a sealed road in a low lying, flat area immediately adjacent to Wooleebee Creek. As such this area is known to be susceptible to flooding, with water ponding by the roadside following these events. The factors have resulted in the area of physical network represented by (1-2) being known as a problem area, as reflected in the above chart.

Surprisingly the gravel pavement roads would appear to have a lesser degree of resilience to flood events than the formation only roads. Given that the resilience of the road is directly proportional to the length of road effected by the registered hazards, it is suspected that rather than these pavement only road sustaining less damage than the formation only roads, it is likely that defects requiring a corrective grade only following these event were not registered in the submission to the QRA. This is because the cost of maintenance grading a gravel or formation only road is substantially less than the cost of importing additional pavement material. Due to this, it is likely that any minor maintenance grading on these roads was included in WDRC routine maintenance to the portions of the network, rather than being included in the submissions for restoration.

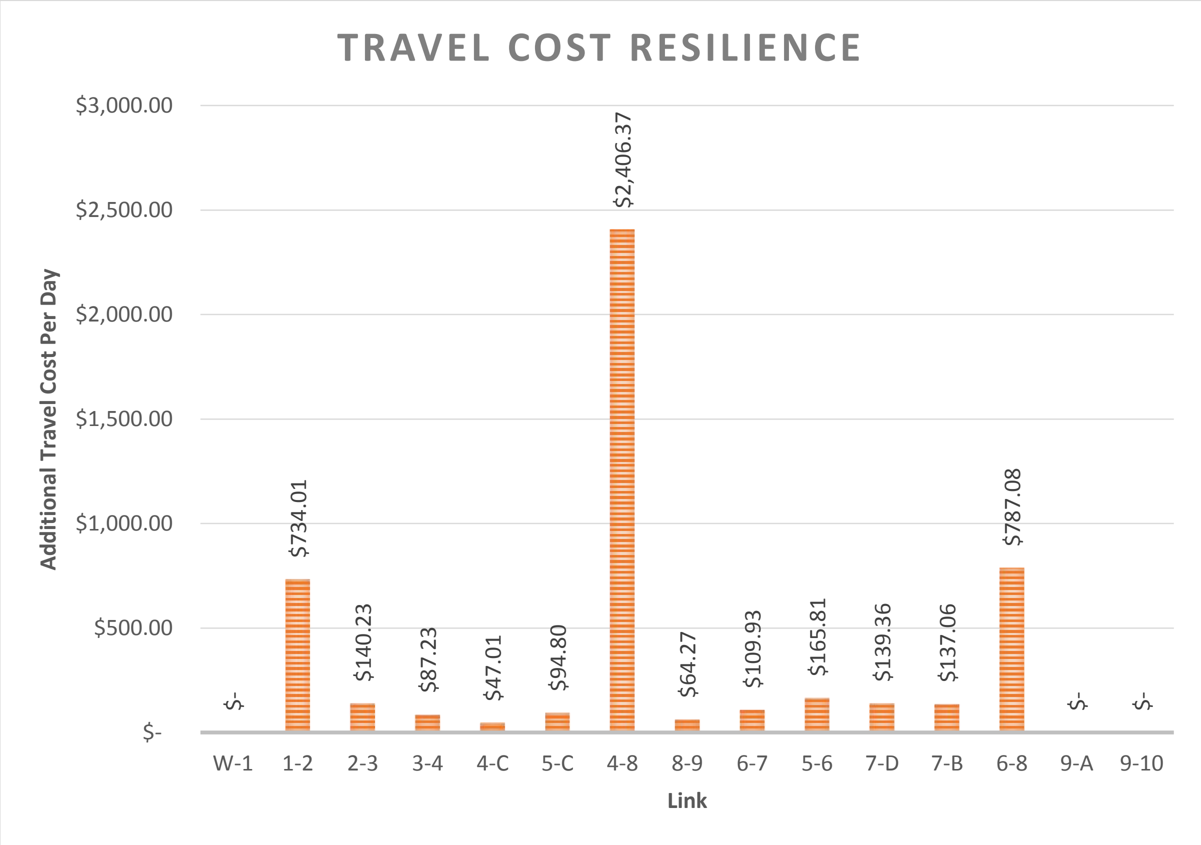


Figure 3.10 - Travel Cost Resilience of the WWRN individual Links

Figure 3.10 expresses the resilience of the WWRN links in as an expected additional travel cost per day for forecast CSG Development traffic travelling on the links. The development of the above chart takes into account not only the travel time resilience per link, but also the volume of traffic expected to utilise each link. This provides weighting to more frequently used links of potentially higher resilience than those of lesser used links of low resilience.

This is necessary for the consideration of the impacts of a flood in terms of financial cost to CSG development, as this identifies the key network links of the greatest vulnerability, and potential for cost to the company. This is shown in Figure 3.10 by the proportionally high cost per day of links (1-2), (4-8), and (8-6).

Link (1-2) is the link discussed earlier which frequently experiences troubles due to flooding or heavy rainfall. This coupled with the fact that all CSG development traffic in the WWRN must use this road to access the area, provides a vulnerable link prone to disruption, with a high traffic volume, and large capacity for additional cost as a result of hazards on the link.

Link (4-8) Cecils Rd is an unsealed road which has a forecast traffic volume of 339 vehicles per day during the construction phase of the planned CSG developments in the area. Being an unsealed road the pavement is susceptible to damage during heavy rainfall and flood events, as demonstrated by the historic defect data extracted from WDRC records in Figure 3.7. This susceptibility to damage coupled with the high traffic volume, provides the most vulnerable link in the network, in terms of potential cost due to increased travel time.

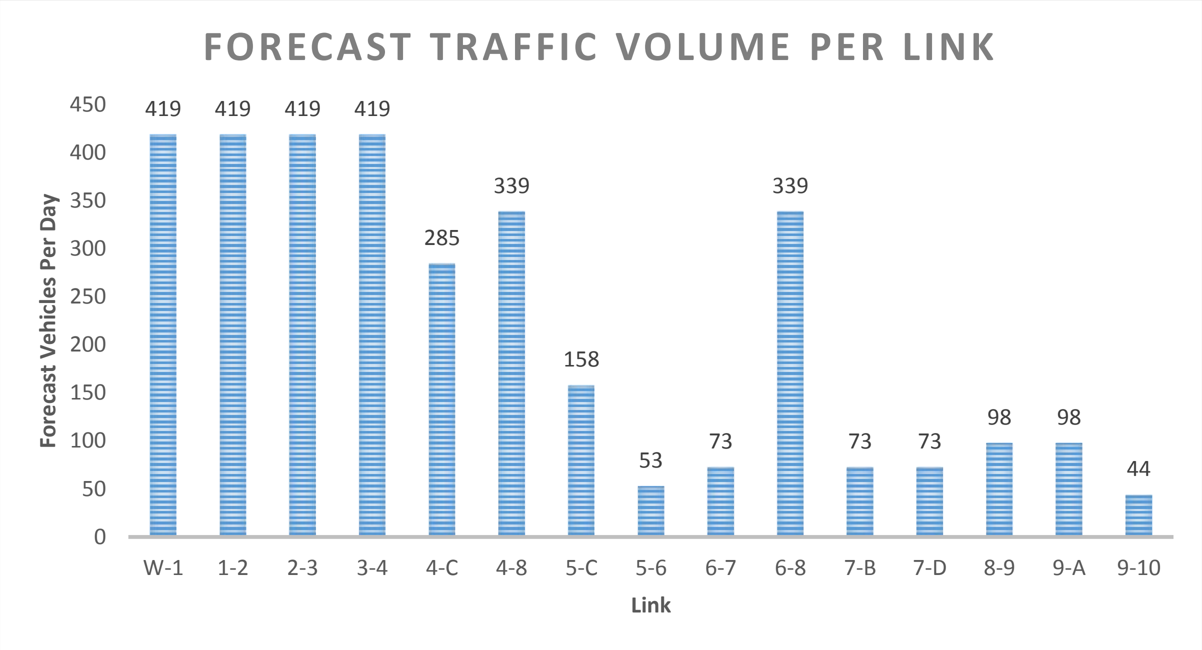


Figure 3.11 - Forecast Traffic Volume Per Link

Link (6-8) records the second highest cost due to increased travel time of the network. The cause of this is similar to that discussed above in regards to link (4-8), with the exception that approximately 5.17km of the total 10.4km link length is sealed. The impact this has on the frequency of hazards, the direct measure of link resilience, is shown by the Form 4 extract below.

Start	Finish	Dist (km)	Photo Reference	Description of Asset Damage
0.3	0.4	0.1	Ryals Road 0.3 - 0.4	Pavement inundation resulting in gravel scouring and rutting
0.5	0.6	0.1	Ryals Road 0.5 - 0.6	Scouring of floodway
0.8	0.9	0.1	Ryals Road 0.8 - 0.9	Pavement inundation resulting in gravel scouring and rutting
2.3	2.4	0.1	Ryals Road 2.3 - 2.4	Pavement inundation resulting in gravel scouring and rutting
2.9	3.1	0.2	Ryals Road 2.9 - 3.1	Pavement inundation resulting in gravel scouring and rutting
9.2	9.25	0.05	Ryals Road 9.2	Scouring of floodway
10	10.05	0.05	Ryals Road 10	Deposits of silt & debris on floodway

Figure 3.12 - Ryals Rd - 2011 Flood Damage Restoration Form 4

Note that 5 of the 7 recorded defects are located in the unsealed section of road from Ch: 0 to Ch: 5.23. It would appear that the 5.17km of bitumen seal on Ryals Rd has contributed substantially to the increased resilience of this road, which would likely be comparable to the resilience of link (4-8) due to similar traffic volume and geography.

Using equations (1) and (2) it is then possible to analyse the total resilience and total cost to CSG development during the restoration period of the flood event. This yields the following results.

R_Time_{total} = 0.90

The total resilience is obtained by finding the ratio of total travel time per day on the network in cumulative hours, before and after the event. In this scenario the total travel time before disruption was 284.52 hours per day, and the time following disruption was estimated at 314.30 hours per day.

R_Cost_{total} = $4,913.16/day

The total cost due to additional travel time is the sum of all costs per link.

Considering that the resilience calculated is a representation of the network performance during the network restoration phase of recovery, the resilience can be plotted against time taking into account the historic firsthand accounts on WDRC staff to calculate the period of total network failure during which all major bridges were unusable. This plot also takes into account the timeframes by which the recovery works were delivered. For the purpose of this analysis it will be assumed that following a lag of 6 months during which submissions were made to the QRA and approvals received, restoration of network performance occurred in a linear manner over a period of an additional 6 months. Given delivery of the 2011 Event was not completed for a duration of 2.5 years following the event, this assumption is considered conservative.

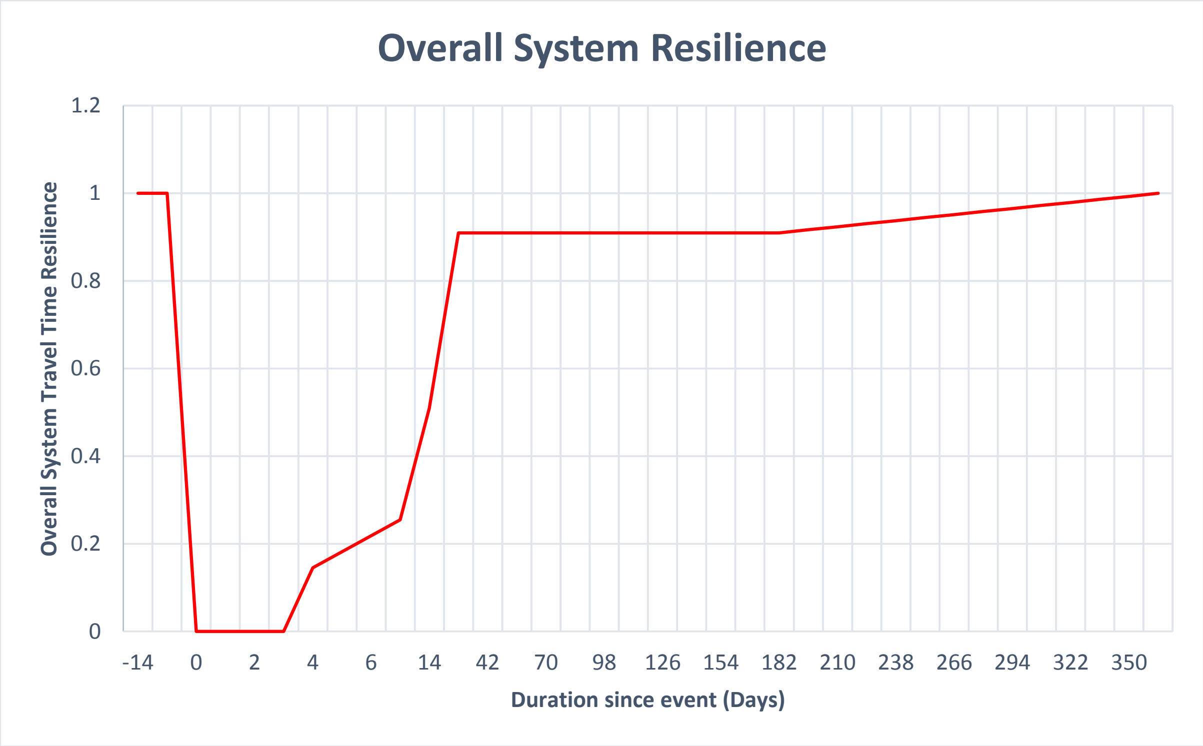
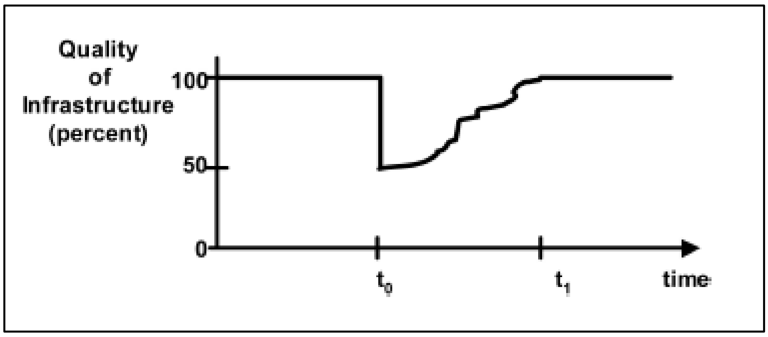


Figure 3.13 - Total System Travel Time Resilience

The above assumptions used in the creation of figure 3.13 are overly simplified for the sake of illustrating the similarity between the chart in figure 3.13, and (Bruneau, et al., 2003) conceptual illustration of resilience, shown below. Though the above chart is a distorted version due to the long timeline of network recovery, the same profile demonstrating an initial shock to the network and decrease in network



performance, and gradual recovery to optimal operating conditions is shown.

Figure 3.14 - Conceptual Definition of Network Resilience (Bruneau, et al., 2003)

Using the same assumed timeframes the cost due to increased travel time over the network can be illustrated. Identical timeframes for network total failure, restoration to minimum level of service, assessment of damage, and linear recovery to full service have been used in calculation of the below chart.

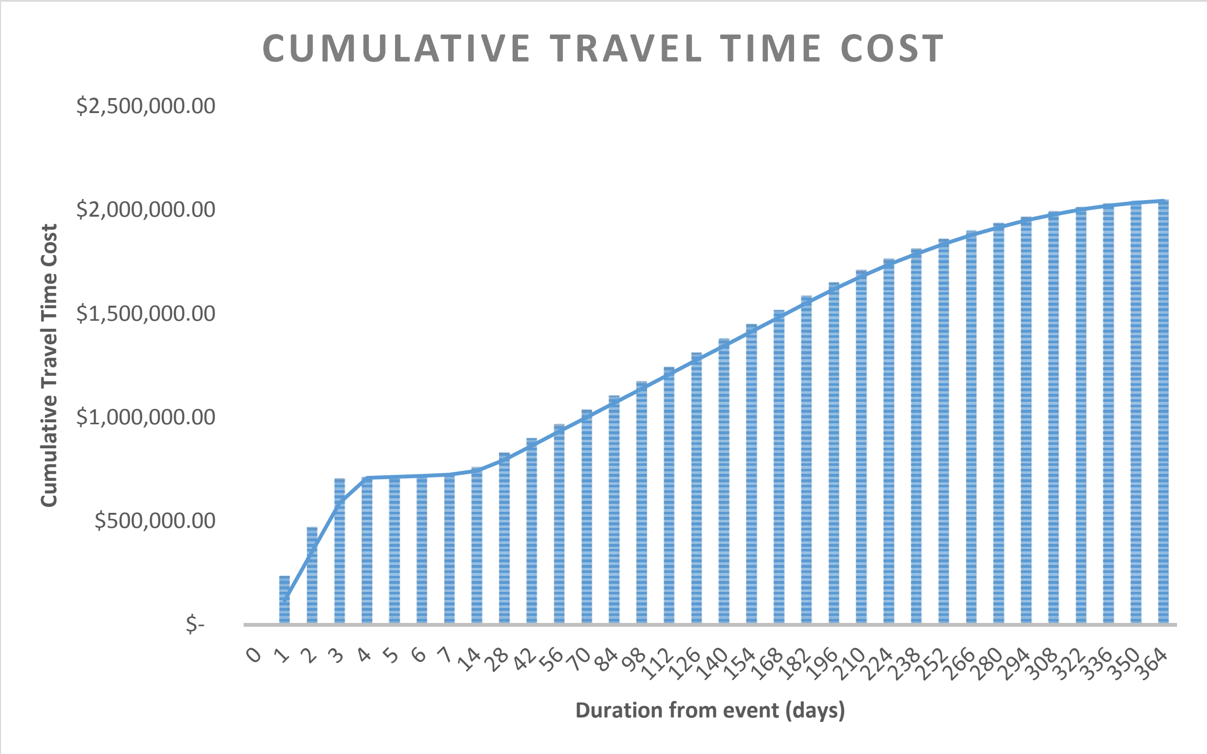
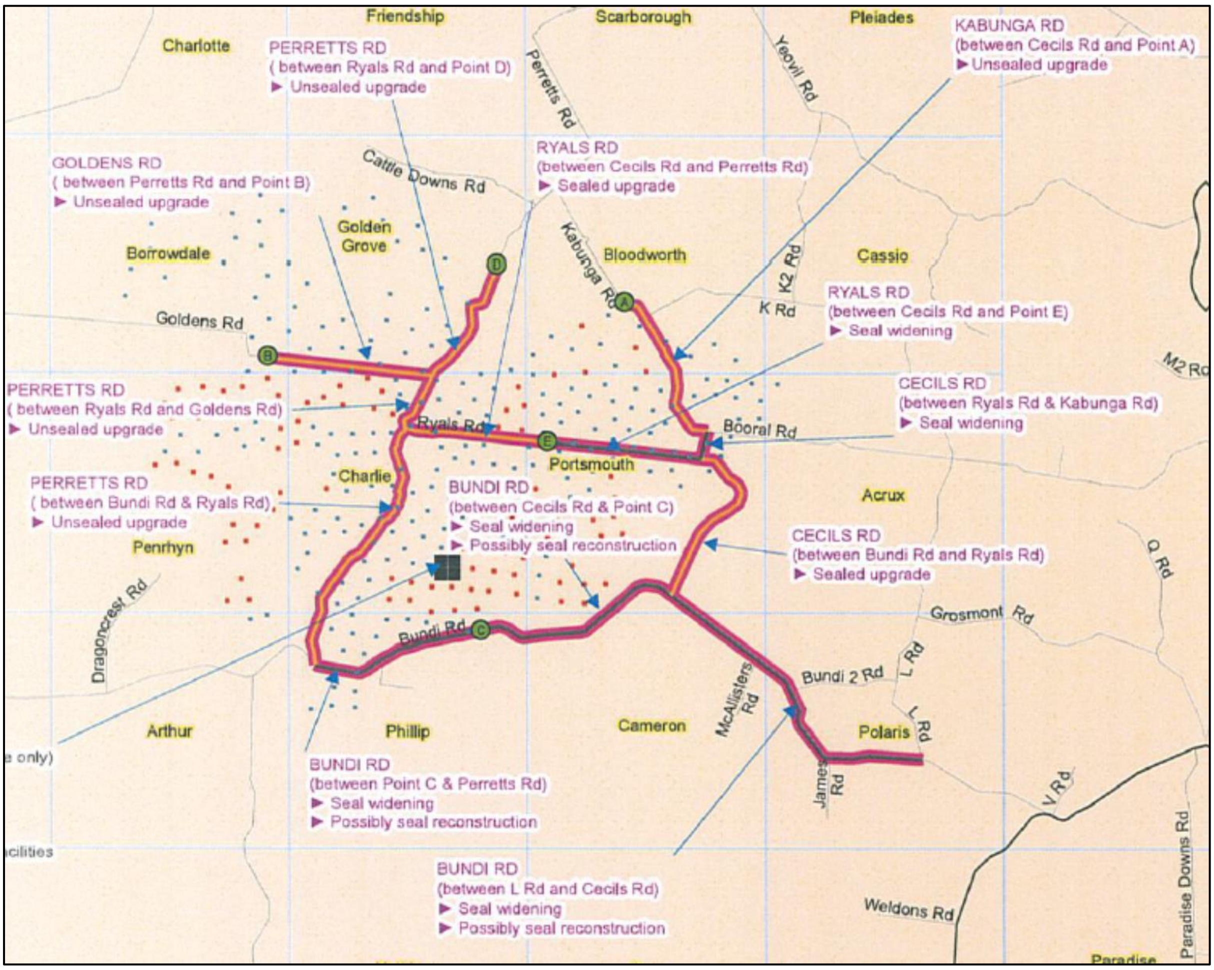


Figure 3.15 - Cumulative Cost Due to Additional Travel Time

This chart follows a similar trend in a sharp increase in cost due to total network failure and the associated stand down and accommodation costs of the entire development workforce, as calculated from the histogram data provided earlier. This is followed by a significant levelling out of cost as the network becomes operational and the additional cost is only that associated with increased travel time. The cost due to increased travel time will continue to accrue in a linear fashion for the 6 months required to undertake collection and submission of defects, and receive approval for works from the QRA. This increase will continue to accrue over the following 6 months but at a diminishing rate as the network is restored to full operational capacity.

3.2 Proposed Network Upgrades

As Part of Phase 2 Off Plot Upgrades, QGC plan to fund sealed and unseal road upgrades to a number of roads which provide access to phase 2 developments. These upgrades are shown as a general summary in the extract of Appendix 1



below.

Figure 3.16 - QGC Phase 2 Planned Off-Plot Road Upgrades

These upgrades are intended to provide as safer road environment for the high volumes of construction traffic forecast to be produced by phase 2 construction, as well as to offset the reduction in useful life of these road assets due to traffic volumes much greater than those designed for.

While these upgrades are not being undertaken with the sole intention of increasing network resilience to flooding, increases in resilience will be achieved due to the higher quality of asset produced.

These proposed upgrades will be modelled in the NIRA framework in the same manner as the existing network, with increases in performance being reflected in the elimination of relevant hazards used in the original analysis, in the upgrade sections. For example, if a gravel road previously recorded scour to pavement caused by heavy rainfall and the proposed upgrade for this section is construction of a bitumen seal, these defects would be eliminated from the Individual Link Performance Analysis Sheet as they are unlikely to occur following the upgrade. This will produce a higher level of resilience for these assets which will then be compared with the resilience metrics of the original analysis.

A summary of the proposed upgrades is given below:

- **BUNDI RD, Links (1-2), (2-3), (3-4), (4-C), and (5-C):** Proposed upgrades include reconstruction and overlay of existing road including reinstatement of bitumen seal to 8+m width. Overlay will increase the level of the road and reduce the chance of overtopping in moderate rainfall and flood events. (SMEC, 2014)
- **CECILS Rd, Links (4-8):** Proposed upgrades include upgrade or replacement of existing drainage structures, construction of pavement to 8m width including 8m width bitumen sealed surface (SMEC, 2014).
- **GOLDENS Rd, Link (7-B)**: Includes upgrade of drainage works and gravel surfacing overlay (SMEC, 2014).
- **PERRETTS RD, Link (6-7):** Includes upgrade of drainage works and gravel surfacing overlay (SMEC, 2014).
- **RYALS RD, Link (6-8):** Includes reconstruction of bitumen pavement, upgrade of drainage works, and gravel overlay to unsealed section. (SMEC, 2014).

3.3 Analysis of Network following implementation of Proposed Upgrades using NIRA Framework

The upgrades proposed as discussed in chapter 3.2 will increase resilience of the network by lessening the severity or nullifying some of the hazards expected as a result of a Q100 Flood Event. To analyse the impacts these upgrades will have on the network, the Individual Link Performance Analysis will be completed for the same scenario, omitting or lessening the effect of hazards where relevant to the upgrade sections. The results of this analysis will then be compared to the original analysis to determine the enhanced resilience of the WWRN with these constructed upgrades.

Changes or omissions to historic 2011 Flood Event hazards per link are shown in Appendix 5. A summary of the calculations of this second iteration analysis is shown in Appendix 7.

This analysis yielded the following results, shown below in comparison to the original resilience values obtained per link.

	Upgrade Analysis		Existing Analysis	
Link	R_Time_{Link}	R_Cost_{Link}	R_Time_{Link}	R_Cost_{Link}
W-1	1.00	$ -	1.00	$ -
1-2	0.92	$ 324.93	0.84	$ 734.01
2-3	0.99	$ 51.72	0.97	$ 140.23
3-4	0.99	$ 43.14	0.98	$ 87.23
4-C	1.00	$ 11.65	0.99	$ 47.01
5-C	0.99	$ 22.81	0.95	$ 94.80
4-8	0.90	$ 619.29	0.69	$ 2,406.37
8-9	0.80	$ 64.27	0.80	$ 64.27
6-7	0.84	$ 72.75	0.78	$ 109.93
5-6	0.89	$ 165.81	0.89	$ 165.81
7-D	0.79	$ 139.36	0.79	$ 139.36
7-B	0.93	$ 87.68	0.89	$ 137.06
6-8	0.96	$ 382.03	0.91	$ 787.08
9-A	1.00	$ -	1.00	$ -
9-10	1.00	$ -	1.00	$ -

Table 7 - Reanalysis Resiliency results for WWRN

This data is shown comparatively in the charts below. These charts best illustrate the increases in Link resiliency due to these upgrades, and the overall network resiliency increase as a result of these strengthened links.

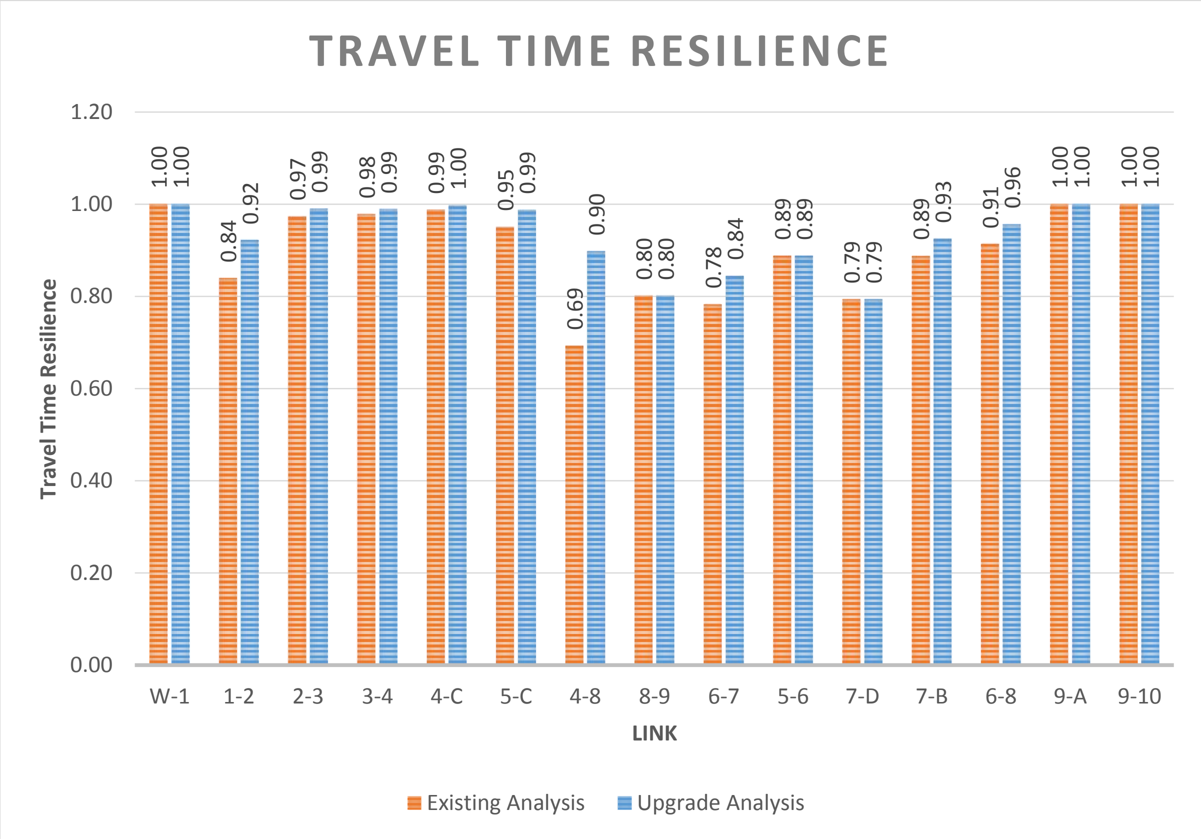


Figure 3.17 - Comparison of Travel Time Resilience Before and After implementation of Proposed Upgrades

The above chart effectively illustrates the increases to resiliency due to the proposed upgrades. The most significant upgrade being link (4-8) with an increase from 0.69 to 0.90 due to the bitumen sealing of the road on this link. As all the hazards on this link were related to wear of loss of gravel pavement materials, this sealing effectively removed the possibility of these hazards occurring, though an allowance was made for scouring of the road shoulder in these same areas.

Link (1-2) show a marked increase from 0.84 to 0.92. This increase is attributed to the overlay and building up of the road above the surrounding flood plain. This is expected to result in less pavement and seal damage due to moisture ingress in a flood event.

Other increases in resilience are observed in links (6-7), (7-B), and (6-8) due to planned gravel and drainage upgrades on these roads. These upgrades are less significant than that observed in (4-8) due to the road remaining an unsealed pavement road, meaning the road will still be susceptible to the same hazards encountered in the initial analysis, though the severity of these hazards has been assumed to be reduced due to the increased useful life of the new gravel pavement, improvements to drainage, and improvements to road geometry.

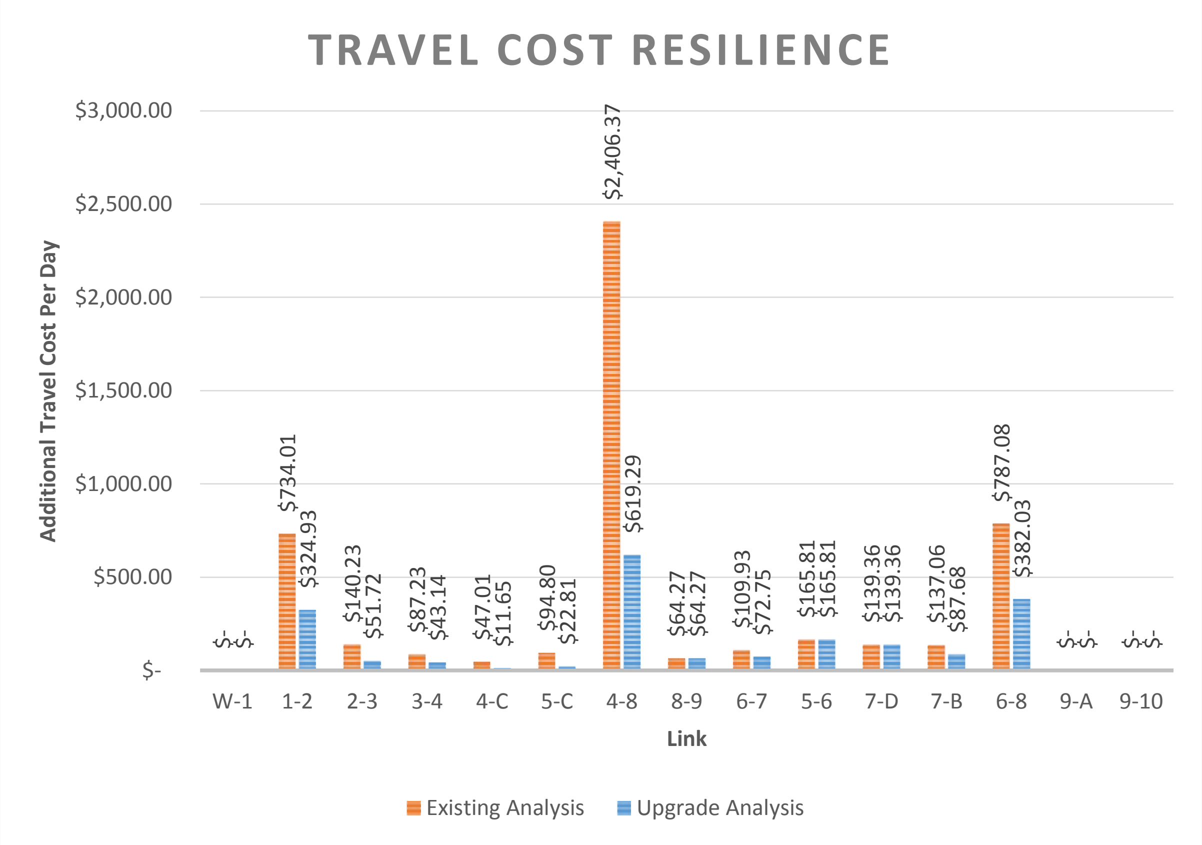


Figure 3.18 Comparison of Additional Travel Costs per Link

The same trends identified in the initial analysis of cost resilience are observed in figure 3.18, with link (1-2), (4-8), and (6-8) still proving the most vulnerable to disruption and increased travel cost, though these values are significantly reduced from those generated in the original analysis. The cause of these decreases in vulnerability and potential loss are the same as those discussed in the above section in regards to increased travel time resilience, improved road geometry and drainage, the sealing of previously unsealed links, and the renewal of gravel pavement material. It is expected that these reductions may be further enhanced if a less conservative analysis of the reductions to hazards as a result of the upgrades was undertaken.

Equations (1) and (2) may be used again in determination of the network wide resiliency values for travel time and cost and thereby calculate the potential financial implications of this increase in network resilience.

R_Time$_{total}$ = 0.93

In this updated scenario the total travel time before disruption was 284.52 hours per day, and the time following disruption was estimated at 296.56 hours per day. This is a total travel time resilience increase of 0.03 or 3.3%.

R_Cost$_{total}$ = $1,985.43/day

The total network cost due to disruption has decreased from a previous value of $4,913.16/day to $1,985.43/day, a decrease in cost and proportional increase in resilience of 59.59%.

Comparison of the above metrics illustrates the comparatively minor increase to overall resilience. Though this time resilience increase is minor, the upgrades are still able to provide significant increase to cost resilience when links with large traffic volumes and high susceptibility to damage, both of which contribute to the potential cost due to disruption of a link, are targeted.

Total resilience of the network over the entire duration of the Flood Event will now be charted to allow comparison of the proposed enhanced network to the existing network analysis performed earlier. All assumed timeframes and impacts will remain constant and unchanged.

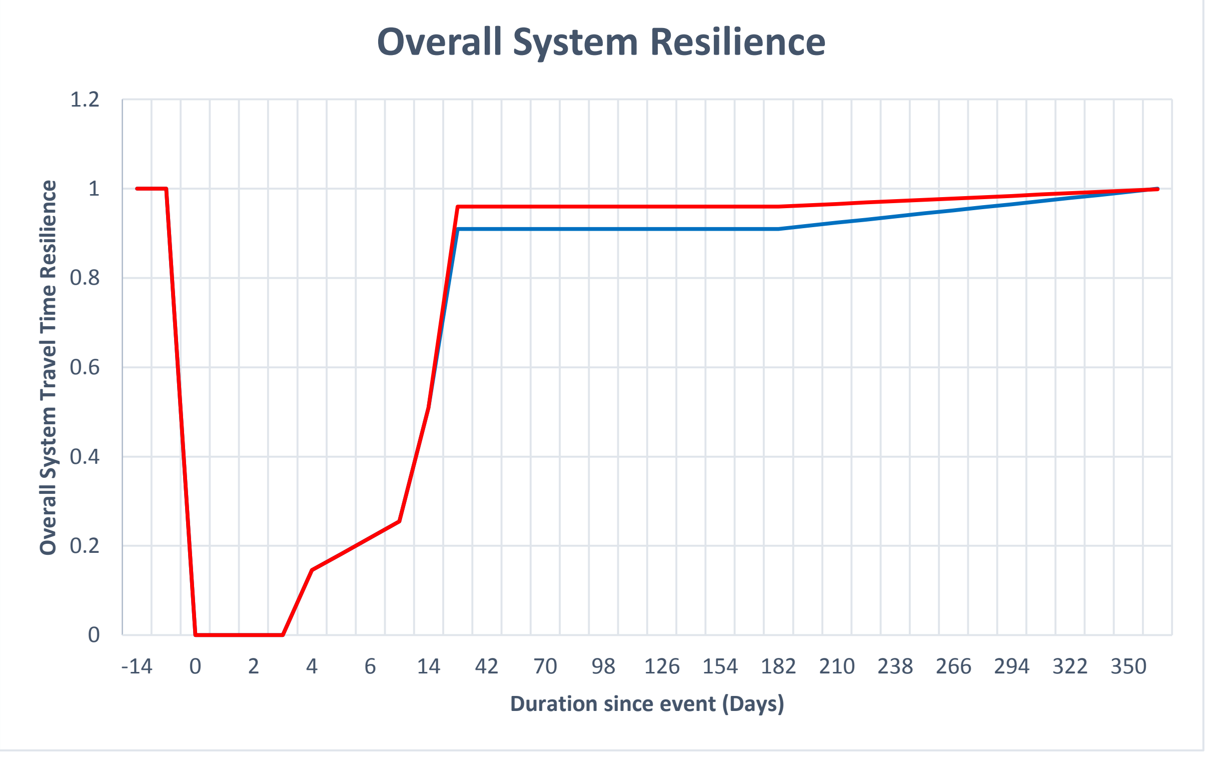


Figure 3.19 - Overall System Resilience Comparison Plot

As observed in the earlier plot, the initial decrease in performance remains constant as the main bridges providing access to the network will remain disrupted in an event. No upgrades at all were proposed for these structures and as such their performance under identical conditions remains unchanged. Likewise emergent works restoration to the level of resilience calculated is assumed to progress identically in a linear fashion. This is likely to actually be completed in a shorter timeframe due to a decrease in emergent works damage that would be expected following the proposed upgrades, however any analysis of this response time would be pure conjecture without data for the original emergent works period, which is not available.

The increase in overall resilience is best demonstrated in the recovery period, as the network is returned to a higher level of service following the emergent works period, due to the greater resiliency of the strengthened network links.

The impact of these strengthened links on expected Travel Cost increases is shown below.

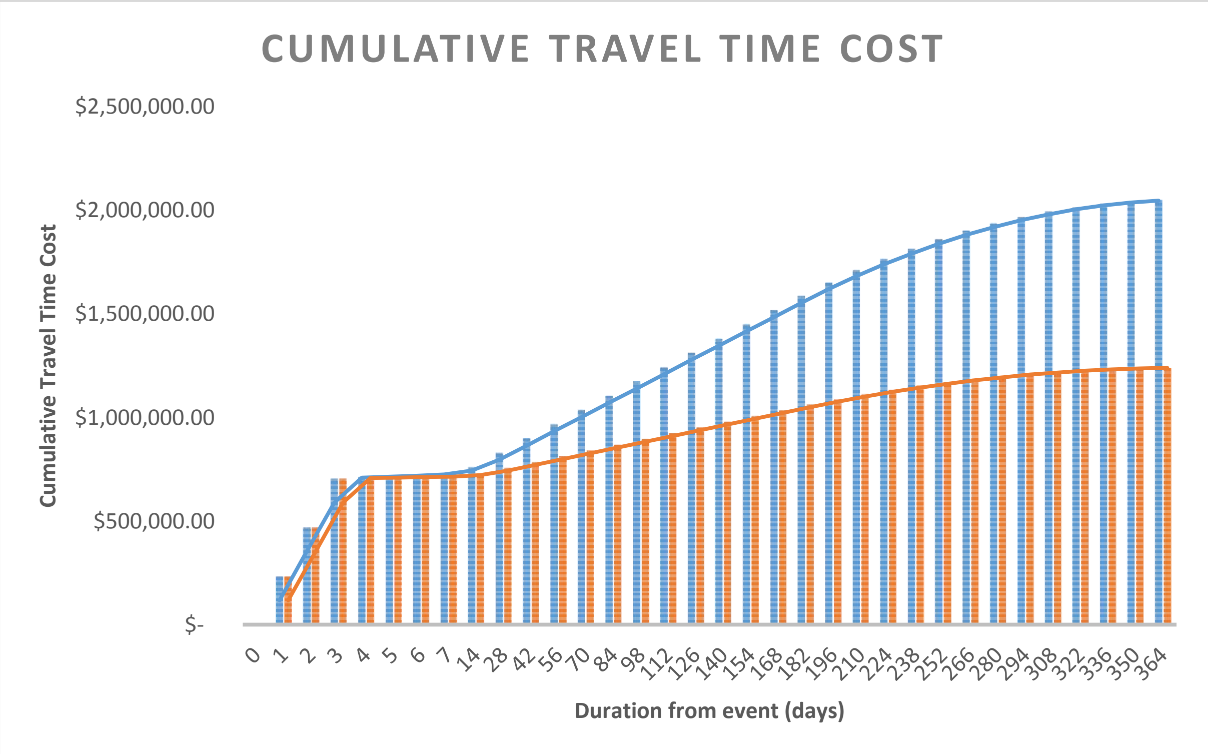


Figure 3.20 - Cumulative Travel Time Cost Comparison Plot

The initial disruption period of this chart is identical to that of the original analysis, due to labour costs per day and the period of total network disruption remaining constant. This is followed by a significant levelling out of cost as the network becomes operational and the additional cost is only that associated with increased travel time, which is 60% lower than that of the original network model analysed. This cost remains constant for a 6 month period in which defects are collected and submitted to the QRA, and then continues to accrue but at a reduced rate as the network is returned to service.

The effect of these upgrades in terms of financial cost savings during a disruption event is clearly shown by the comparison of the two trendlines shown in Figure 3.20. Over the full duration of the event, these upgrades are calculated to provide a cost savings in terms of reduced losses, of $809,519.86.

4 Discussion

4.1 Comparison of Network Before and After Upgrades

The potential cost savings due to increases in link and network resilience are substantial with estimated savings of up to $810,000 over the one year duration of the simulated event recovery. A potential saving of 40% belies the minor 3.3% increase in total network resilience shown by figure 3.19. This disproportionate increase in the differing metrics is due to the weighting of the metric criteria. The total network travel time resilience weights each individual road equally when determining the overall resilience of the network, where travel time cost resilience is magnified by the volume of traffic per link.

When used in conjunction the two metrics provide a useful assessment of hypothetical network performance by providing a snapshot of overall network travel time resilience, while also highlighting the highest priority links for upgrade by identifying the potential losses due to disruptions as shown by figure 3.20.

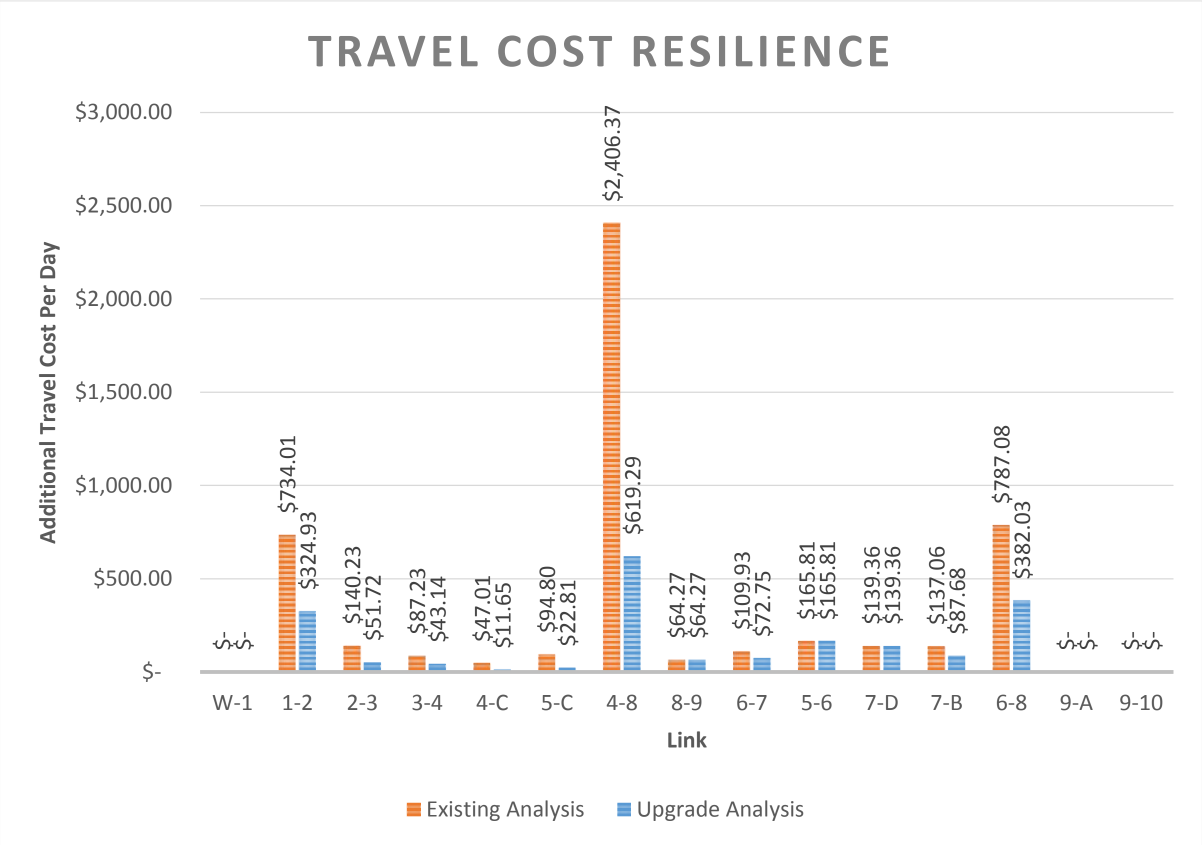


Figure 3.18 Comparison of Additional Travel Costs per Link

The above figure highlights the maximum efficiency of upgrades when applied to the most vulnerable and most frequently used links. Though this statement is likely already a well-established fact and principle of network management, the analysis undertaken provides a means of clearly identifying and quantifying the importance and vulnerability of each link, while also clearly demonstrating the relationship between the two.

As shown in figure 3.20, the most dramatic and effective increases in resilience occur when upgrading the road surfacing to a higher asset class. Link (4-8) was the only link which is currently planned for a surfacing class upgrade, from that of a pavement only road to a bitumen surfaced road. The significant increases in resilience to this road can be attributed to the removal or reduced likely hood of hazards on the road due to this sealed surface upgrade. All historic 2011 Flood Event damage to Cecil's Road was scouring or rutting of the gravel surface. Over the full 6.8km length of the link there was a total of 19 defects. The cumulative effect of these defects was a substantial decrease in travel time due to the speed reductions required to navigate these defects. By sealing the road, this eliminates or substantially reduces the chance and impact of scouring or rutting on the link. This results in savings in travel time, the value of which is amplified by the high traffic volume forecast to use the link.

In contrast the diminished returns of link (6-8) compared to link (4-8) can be attributed to the road upgrade restoring the existing asset class rather than upgrading this to a higher class, as given by the gravel upgrades to the existing gravel road. Indeed, the major increase in this link resilience is due to the elimination of the hazards associated with the existing floodway which is proposed to be upgraded to a large RCBC structure, again attributed to an increase in asset class rather than a restoration of the existing class.

An exception to this is the noted resilience increase in link (1-2). This asset remains a sealed road in the proposed upgrades, however shows a reduction in potential losses of $409, or 55.7%. This can be attributed to the specific upgrades of this link in regards to the specific hazards anticipated. The historic hazards experienced consisted of damage to drainage structures, and damage of the road shoulder due to moisture ingress. The risk of both of these hazards has been offset by the proposed upgrades in raising of road height above flood levels, and the construction and replacement of existing drainage structures. This demonstrates that upgrade of an entire link is not necessary to increase the resilience of the link, but may be achieved by addressing persistent and specific hazards in the link with relevant solutions, such as construction of a culvert where scouring of an invert occurs, or bitumen surfacing in areas where scouring of road pavement is of particular concern.

Overall, while the proposed upgrades to the road network are not proposed with the intention of increasing the network flood resilience only, the proposed upgrades have the potential to offer significant cost savings to the network users in the event of a flood event of the simulated magnitude.

4.2 Savings in Resilience Against Estimated Project Cost

Estimated project costs for the entirety of the proposed upgrades, though existing estimates are available for links (1-2) and (4-8), which are two of the three most significant links in terms of potential savings in travel cost.

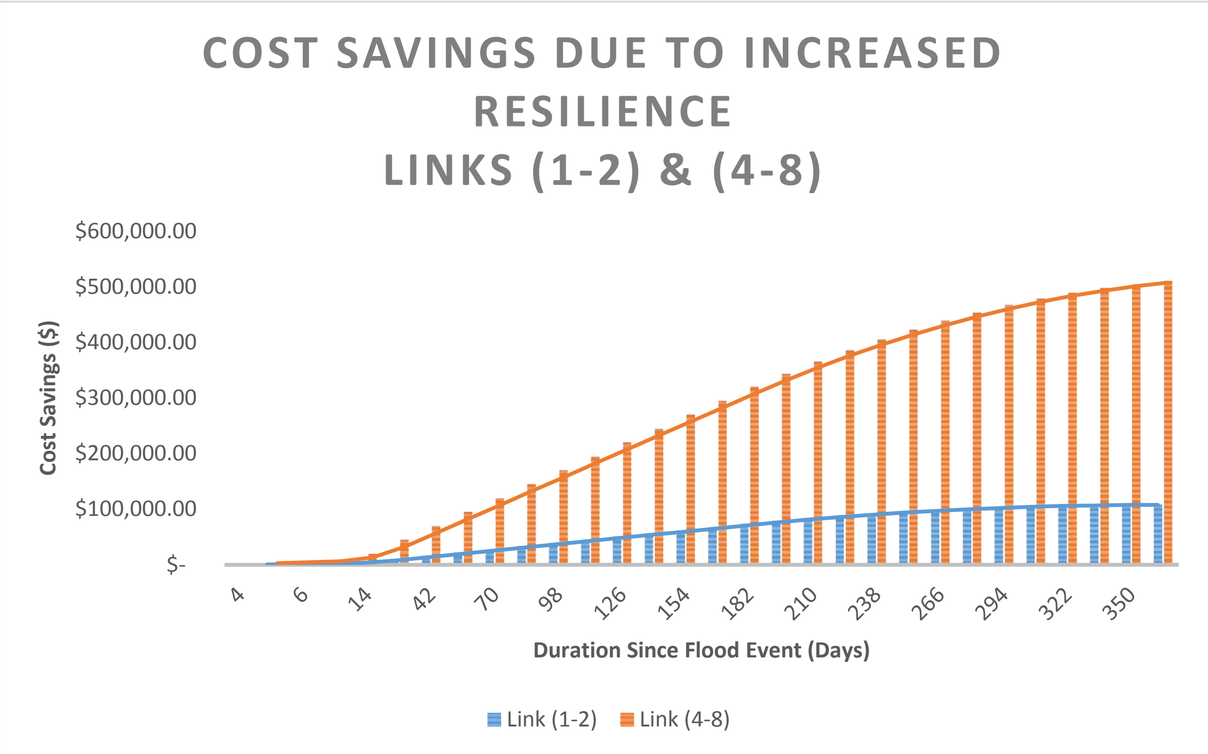


Figure 4.1 - Potential Savings Per Link due to Increased Link Resilience

Modelled in an identical manner to the total network cost shown in figure 3.20 and 3.15, the above chart illustrates well potential savings of the two links over the total event duration. Note that the event period of total network disruption has not been included as the cost incurred in this period remains constant despite the proposed upgrades.

Link (1-2) offers a potential cost saving of $107,571 over the entire event duration of 1 year. The current cost estimate for construction of the proposed upgrades to this link is $1,950,000. At a cost 18.1 times the expected cost savings, this upgrade does not present value for money if constructed for the sole purpose of improving the link resilience to flood events. Likewise, link (4-8) provides an estimated cost saving of $510,335 over the total duration of the simulated event. When compared to an estimated construction cost of the proposed upgrades of $2,500,000, the cost to construct is 4.9 times the expected cost savings again, this does not present sufficient justification for the upgrade of these links.

Other considerations have been the major driving factors in proposing these upgrades. These include, reduced pavement useful life due to significant traffic volume increases, improved road safety for CSG Development generated traffic, and increased capacity to these roads to better cater to the traffic volumes forecast. Considering this, increased resilience and the expected cost savings which accompany the increase in resilience, still show clear financial reasoning for the proposed upgrades and, when used in addition to other supporting factors, may prove effective in justifying a proposal for upgrades to the road network.

4.3 Proposed Further Network Enhancements

As demonstrated by figure 3.20, the major contributing factor to increased cost due to disruption in the simulated event, is the total network failure as caused by inundation of the low level bridges at all creek crossings in the area. The cumulative loss in the first 3 days following the event beginning, an estimated cost of $711,400, was incurred due to labour costs of the entire construction workforce over this 3 day period.

The most vital bridges in regards to the CSG Development traffic would be the two bridges located in link (W-1) and the single bridge located in link (1-2). While the upgrade of these bridges would prove beneficial to the network, this is unlikely to increase network performance in an event of this magnitude as many other floodway’s and low level crossings in the rest of the network are likely to also be unusable. Also the anticipated cost of reconstructing three bridges would be cost prohibitive, especially considering the statistical probability and frequency of the simulated event.

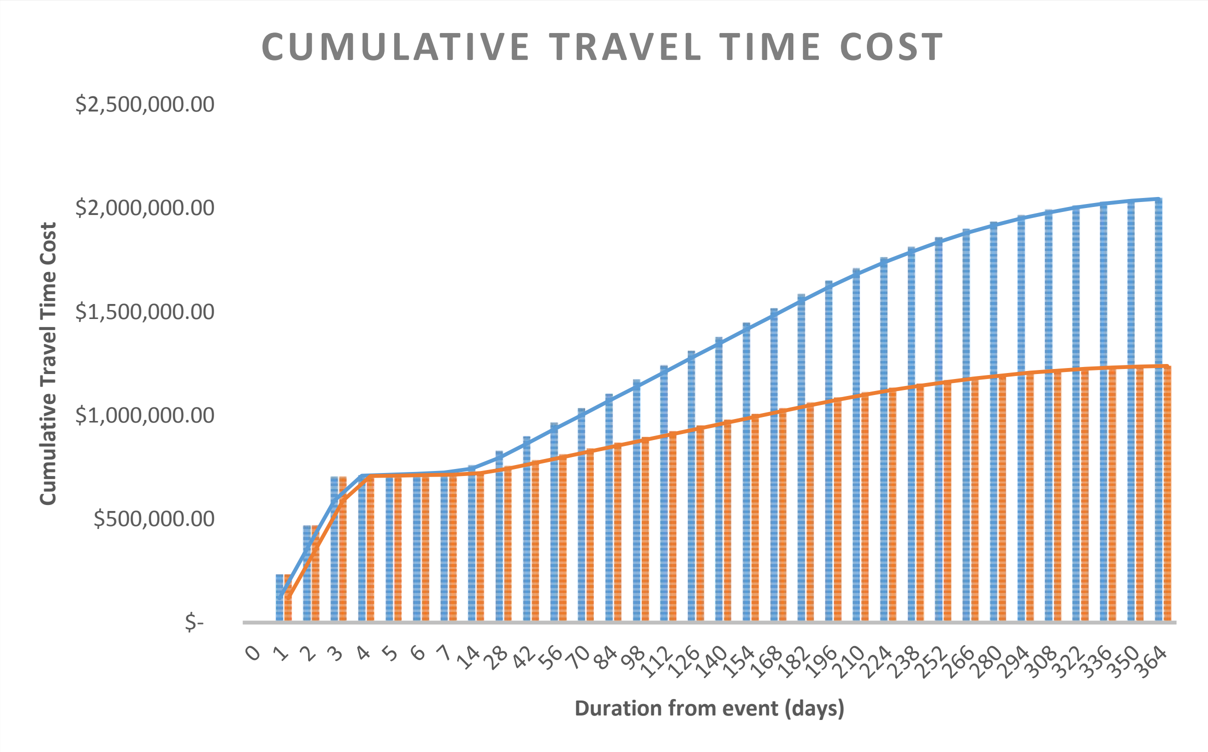


Figure 4.2 - Cumulative Travel Time Cost Comparison Plot

The most practical enhancement to network resilience identified by this analysis, would be an increase in response and restoration times. The cumulative cost of defects to the network during the assessment and submission, and restoration portions of the recovery is shown in figure 3.20. These values are calculated on a cost per day basis considering the effect of hazards on each link, therefore if the duration the link traffic is exposed to the hazard is reduced, the cost associated will reduce proportionally.

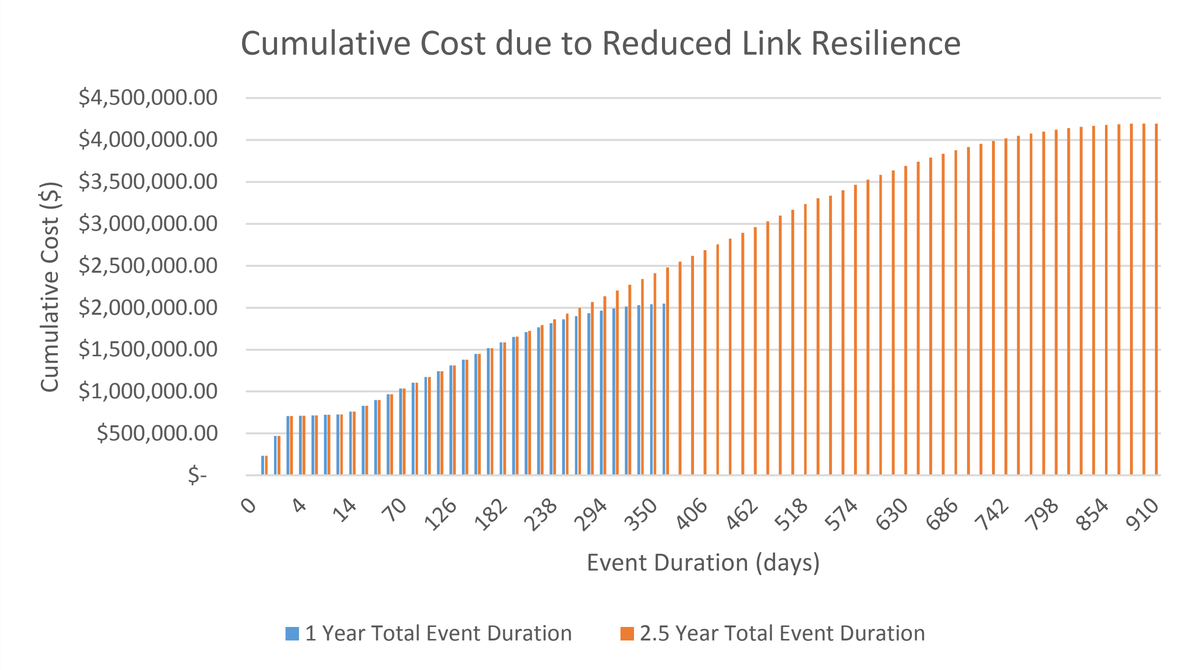


Figure 4.3 - Event Duration Cost Comparison

The above figure illustrates the potential cost savings due to swifter restoration network links to full operational capacity. This chart compares the 1 year duration assumed in earlier analyses, with a 2.5 year duration which better reflects the actual delivery time of the 2011 Flood Damage Restoration Program.

4.4 Potential Improvements and Further Considerations

4.4.1 Framework Suitability

Considering the low volume and rural environment of the Wandoan West Road Network, the majority of the frameworks evaluated were not suitable as these relied on expansive and detailed data for the road network to be analysed. The NIRA network provides a simple and logical method of analysing the resilience of a network to disruptions, though the methods for quantifying the metrics used (Omer, et al., 2013) heavily relied on in-depth network data. Due to this a proportional method for quantifying the metrics of travel time and cost due to increased travel time was developed. This method proved simple enough to utilise the limited data available, but robust enough to provide relevant and useful analysis of the network.

A limiting factor in the use of this method is that it provides an assessment of a moment in time, meaning that it is not dynamic in modelling the changes in resilience over time. Should this be required to be analysed, multiple iterations of the analysis must be undertaken at key points in the recovery timeline, and the results extrapolated between these points. While this proved simple enough for a simple low volume network such as the Wandoan West Road Network, if a larger, more complex network were being considered this method would prove time consuming and ineffective.

Similarly to the above, the network analysis undertaken considers only a single event. In the example of this paper, the cost savings calculated apply only to a Q100 magnitude event, though there would be increases in resilience and associated cost savings in more minor events as a result of these same upgrades to the network. To fully consider these additional cost savings would require flood modelling of the catchments and waterways in the network area, and similarly further iterations of the analysis would be required for each of these lesser magnitude events.

The framework used also does not consider the probability of the events being analysed occurring. This would be a key component in any analysis undertaken to provide justification for upgrade of the network, as the likelihood of the cost savings calculated would be required in order to provide a thorough cost benefit analysis of the proposed upgrades.

While the above limitations do not subtract from the validity of the analysis undertaken in this paper, they do highlight potential areas for improvement in the framework which would provide a more comprehensive and useful analysis should this be used in the industry.

4.4.2 Network Model

The model developed for the Wandoan West Rural Road Network was a logical system of nodes and links reflecting the physical network, and proved a satisfactory medium for the evaluation of the network performance metrics.

The metric analysis could be improved by a more standardised method of assessing the impact of hazards on travel speed. This is the major defining factor in determination of the link and network resilience, and as such the development and application of a standardised method for assessing these hazards would provide more consistent and reliable assessment of the network.

These findings could also be better presented in the cumulative travel time plots and overall system resilience plots by increasing resilience proportionally as individual roads are restored to full function. This could be achieved by application of actual delivery timeframes from the 2011 Flood Event Recovery by WDRC, and would provide a more realistic representation of the network resilience over time, though this would require a more detailed collection of the data, as discussed in the sections below. This required data collection was not available for the analysis undertaken for the Wandoan West Rural Road Network.

4.4.3 Traffic Flow Modelling

The model and framework could be improved by incorporating the assessment of alternative paths in the calculation of optimal travel paths. This would give a more accurate analysis of the network as a whole, as these alternative paths may provide quicker travel times and there by increased network resilience.

The use of traffic flow modelling methods was considered for use in this paper, but was deemed unnecessary for a number of reasons. Firstly, due to the defect data collected being available for only the recovery period of the event, the functionality of all network links was restored to a minimum performance level of 69% (Link 4-8) prior to the point in recovery at which the analysis was undertaken, with the majority of links greater than this. Due to the level of service available, traffic models which consider alternative routes due to link friction, or reduced performance, would not provide any alternative routes from those already determined.

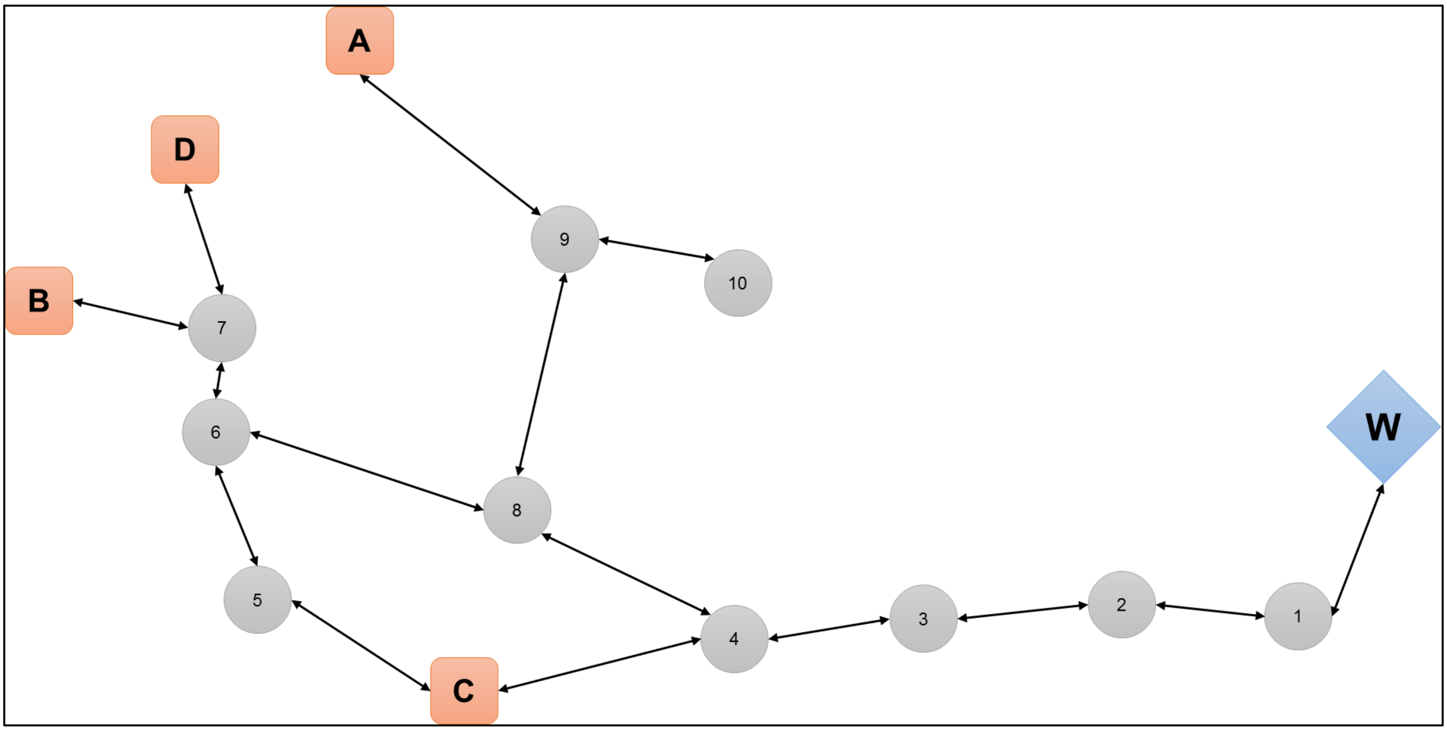


Figure 4.4 - Updated WWRN with links redundant to CSG Development Traffic Removed

Secondly, as shown in figure 3.6, the network analysed is simple, meaning the possibility and opportunity for alternative routes is limited to the paths between nodes 4 and 6. While a traffic flow analysis may indicate a traffic flow redistribution between these links, the high level of network performance restored at the end of the betterment recovery period means this is unlikely.

Modelling of traffic flow distribution is likely to yield significant results only during the Emergent recovery period where significant and dangerous defects in the network exist. In order to analyse this more data would be required for the Emergent recovery period than was available for the purposes of this project. The cumulative effect of any financial impacts calculated in this period is also likely to be less significant than that calculated for the recovery period, due to the short duration of the emergent period. However, analysis of this aspect of the flood event disruption is necessary in order to provide a comprehensive assessment of network performance over the entire period of the event.

4.4.4 Data Quality

There were a number of gaps in the 2011 Flood Damage Data available which did not become apparent until the analysis was undertaken. A significant gap that would assist in delivery of better analysis is greater record keeping of hazards restored during the Emergent works period, and the timeframes these works were delivered in. The hazards restored during this works period are the most hazardous and disruptive to network function, hence the need to restore these immediately. Due to the severity of these defects, the effect on link performance during these hazards is likely to be significant, and yield valuable findings on the efficiency of the work undertaken during the emergent works period. However, given that the links were restored to a minimum 69% performance (Link 4-8) following the Emergent work period, the works undertaken can be assumed to be efficient and effective at restoring the network to a satisfactory level of performance.

Another minor flaw in the data collected, is that the hazards and defects recorded were recorded with the purpose of application for external funding for restoration, and not for the analysis of network performance and resilience. Due to this it is inferred that were the work required to restore a hazard was not of significant cost, this hazard was not collected and instead was restored during WDRC routine maintenance. An example of this encountered during analysis was the higher level of travel time resilience recorded on formation only roads, as opposed to pavement only roads. As discussed in the literature review of this paper, formation only roads are much more susceptible to wet weather damage than pavement only roads, and as such would be expected to suffer a much higher degree of damage in an extreme event such as that modelled. However, as the cost to restore a formation only road is much lower than the cost to restore a pavement only road (approximately $4.5 per lineal meter as opposed to $50 per lineal meter) the damage to these roads was likely not collected. This is shown in the defects recorded for Perretts Rd, which consisted only of areas requiring gravel resheeting, and did not include any maintenance grading.

In order to ensure the suitability of collected data, the purpose of the data collection should be established prior to undertaking the collection. This was done when collecting the data used for this analysis, however the purpose was to secure external funding to repair damage to the road network. This data has been used in the analysis of network resilience, but as this is not the purpose for which the data was collected there are imperfections in the data which have effected the integrity of the analysis, such as the discrepancy on formation only roads discussed earlier. Ideally, the data would be collected with the purpose of analysing network resilience in mind, ensuring all hazards, no matter how minor or inexpensive to repair, would be collected and a true representation of the decreased performance of the network collected.

4.4.5 CSG Developer Data

The addition of data provided by QGC for this analysis would greatly improve the real world applications of this assessment. As the only data provided was that available to WDRC, traffic histograms and design files, certain assumptions were made regarding plant and labour costs. Should accurate information be provided, the analysis would be a closer representation of actual network conditions and costs expected to be incurred. In addition to this, an aspect not considered is the lost profits or potential losses due to delayed project delivery. This data would be required to be provided by QGC as no means of estimating these values is available to the student. The inclusion of these potential losses in the analysis would provide a more accurate representation of current network vulnerability in regards to CSG development.

4.5 ANALYSIS APPLICATIONS AND USES

Given the limitations of the framework discussed above and the restricted scope of the analysis undertaken, the intended use of the analysis as supporting justification for funding applications of network upgrades is limited. Should the recommended changes above be implemented the analysis would provide a thorough and practical representation of the benefits and savings of proposed upgrades to the road network.

In addition to analysing the cost of decreased network performance during flood events, the framework could be applied to network disruptions of other natures, such as roadworks or traffic accidents. This could also be applied to analysis of speed zones or other design standards to determine the advantages offered by the construction of a higher asset class.

5 CONCLUSIONS

5.1 SUMMARY OF MAIN POINTS

The purpose of this paper was to investigate methods of assessing and quantifying the resilience of a rural road infrastructure network, assess the resilience of an existing network on CSG development in the region, analyse the impact a series of proposed upgrades will have on this level of resilience, and draw conclusions as to the potential savings of these upgrades against the estimated upgrade cost. This was achieved for the Wandoan West Road Network area in the Western Downs Regional Council using historic damage information collected during and after the 2011 Flood Event. The defect information was applied to the network using the NIRA Framework (Omer, et al., 2013) and the impacts on network performance assessed.

The initial assessment identified Cecils Rd between Bundi Rd and Ryals Road (link 4-8) as the link with the greatest susceptibility to increased travel cost, with a calculated additional cost per day of $2406.37. Link 6-8 was second most vulnerable with an estimated increased travel cost per day of $787.08, and Link 1-2 third with an increased travel cost of $734.01 per day.

A series of currently proposed upgrades were then modelled to evaluate the potential increases to resilience due to these upgrades. The impacts of these were modelled in reducing the severity of the hazards recorded, which directly correlates to network performance.

These upgrades greatly increased the performance of the network during the flood event, to differing extents dependant on the link and the nature of the proposed upgrade. The most significant savings were shown on the most vulnerable links, as these links had the most significant upgrade due to the vulnerability being intuitively recognised by WDRC Engineering staff. Following upgrade a total network cost saving of $2927 per day was identified, which extrapolated of the full recovery duration of the event, results in a cost saving of $809,519.

Compared to an estimated construction cost of $4.1 Million, this saving does not greatly endorse the upgrade of these roads as a means of increasing resilience alone. However, these upgrades provide a slew of other benefits to road users and

CSG developers, including decreased travel time and wear on plant, increased safety for road users, and greater reliability and service. These other factors are difficult to quantify, but obviously proved compelling enough to undertake these upgrades as they are currently planned for construction. The cost savings due to flood resilience would only strengthen the proposal for these works.

5.2 Deductions from Findings

It is apparent from the analysis undertaken that the long term damage sustained by the Wandoan West Road Network during a flood event of 2011 Event magnitude has the capacity to cause significant financial loss to QGC developments in the area.

5.2.1 Vulnerable Link Characteristics

On examination of the Cost Resilience results per link obtained, it is apparent that the vulnerability of a link to financial loss is a direct result of the travel time resilience of the link, or the physical resilience to damage, and the traffic volume of the link. This is a fact intuitively known by local government engineers in constructing roads of a higher hierarchy to a higher standard.

The identification of these most vulnerable links will allow local government or governing bodies to best identify the sections of the network with the greatest potential value for upgrade. This was demonstrated in the analysis of the proposed upgraded network, in which a total saving of $809,519 for the entire network was calculated, of this saving $617,935 was due to the upgrade of links 1-2 and 4-8, or 76% of the total saving. This shows greater potential for value in upgrading of the most vulnerable links only.

Also identified in the cost savings due to upgrades, was that the most significant increases in resilience were noted on links where the upgrades were to a higher asset class, rather than reconstruction or rehabilitation to the existing class. It can be inferred that this is because upgrade to a higher asset class provides greater resistance to wet weather, where if the asset class were to remain as existing, the existing vulnerabilities are retained.

5.2.2 Enhancement of Network Resilience

Finally, the cost-benefit comparison of the proposed upgrades shows that the construction cost of the proposed upgrades far outweighs the cost savings during the flood event, and because of this the greatest and most cost effective opportunity for increased resilience is decreasing the time to recovery, including prioritisation of restoration of the most vulnerable links. As cost due to disruptions accrue linearly while defects are present, logically, decreasing the duration for which the network is effected by those defects translates directly to cost savings.

5.3 FUTURE WORK

From the analysis and research undertaken, areas of future improvement have been identified.

5.3.1 Development of Dynamic Framework

The NIRA framework was appropriate for providing an analysis of the network resilience at a single point in time. In order to increase the usefulness of the analysis, the analysis should be modified to assess network performance over the duration of an event. This would mean performing the analysis as done in this paper, but introducing the hazards not only in a physical location, but also a temporal location, meaning each hazard is assigned a duration and timeframe by which it affects network performance. This would better integrate the analysis performed in which cumulative costs are calculated, and total resilience expressed.

In consideration of a truly dynamic framework, if a network of greater traffic volume and higher complexity was to be analysed, consideration should be given to modelling traffic distribution across the links to account for redistribution of traffic flow due to link disruptions. This was unnecessary for the analysis undertaken by this paper, but would be vital to obtain the true resilience of a network of greater complexity.

5.3.2 Procedures for Data Collection

To avoid skewing results due to gaps or errors in the collected data, a procedure would be required in order to properly assess the quantity and characteristics of defects present in the road network to be analysed. This procedure would clearly outline criteria to better identify hazards which require collection, and the properties to be recorded. The properties to be recorded would be similar to those used for the analysis undertaken in this paper, but stricter criteria would be required in order to ensure that all defects are recorded irrespective of the cost to repair and whether or not additional funding is required.

5.3.3 Standardised Hazard Impact Analysis

The hazard impact analysis, or the determination of the impact each individual hazard will have on the performance of the network, is a core component to determining the level of resilience indicated by those hazards. For the purposes of this analysis, and as there was no standardised method available, this was purely subjective based on the student's experience. Quite obviously this is not ideal as different operators will record different results.

In order to correct this a standardised method of analysing the speed reduction required per hazard is necessary. This requires further research, but potentially could be expressed as a function of road roughness, or defect dimensions. If so these characteristics would then be included in the criteria for data collection discussed above.

5.3.4 Concluding Statements

In summary, the framework selected and methods of analysis used in this paper were suitable for the low volume and simple network being analysed. The analysis undertaken provides a useful summary of a network's performance, and the current vulnerabilities of the network. While the analysis needs further refining in order to be successfully used as supporting justification for additional expenditure, the results obtained and vulnerabilities shown provide a useful tool for the analysis of network weaknesses. This provides focus to network administrators in identification of the network vulnerabilities and areas requiring investigation.

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APPENDIX 1 – PROJECT SPECIFICATION

University of Southern Queensland

Faculty of Health, Engineering & Sciences

ERP2015 ENGINEERING RESEARCH PROJECT 2015

PROJECT SPECIFICATION

Student: **Sam Fitzgerald**

Topic: Resilient Infrastructure Development and Management

Supervisor: Trevor Drysdale

Enrolment: ERP2015 Engineering Research Project 2015

Project Aim: To assess the ability of an existing rural road network to resist disruptions and return to an adequate level of serviceability during major flood events, and to provide recommendations to increase the resilience of the network.

Sponsorship: Western Downs Regional Council

Programme: **Revision B, 18th March 2015**

1. Determine the key criteria to be used in the analysis of the Western Wandoan Road network as vital infrastructure for Coal Seam Gas Developments in the region. Collect data on these criteria from either Western Downs Regional Council, or the relevant resource company.
2. Research existing frameworks for the analysis of a Road Network resilience to disruptions. Compare these frameworks against the identified criteria selecting or developing the most relevant framework.
3. Analyse the existing network using the identified framework and collected data, in order to determine the impact a major flood event would have on the network, and the subsequent financial cost of this to WDRC and Resource Companies.
4. Develop a series of recommended upgrades to the network which would decrease the vulnerability of the network to disruption during flood events. Provide basic cost estimates for the undertaking of the recommended upgrades.
5. Re-evaluate the network resilience with the recommended upgrades implemented, determining the financial cost experienced by all organisations during and following a major flood event.
6. Evaluate the financial implications of each resilience model, taking into account estimated construction costs of the recommended upgrades. Draw conclusions as to the cost effectiveness of increased network resilience due to disaster mitigation as opposed to recovery.

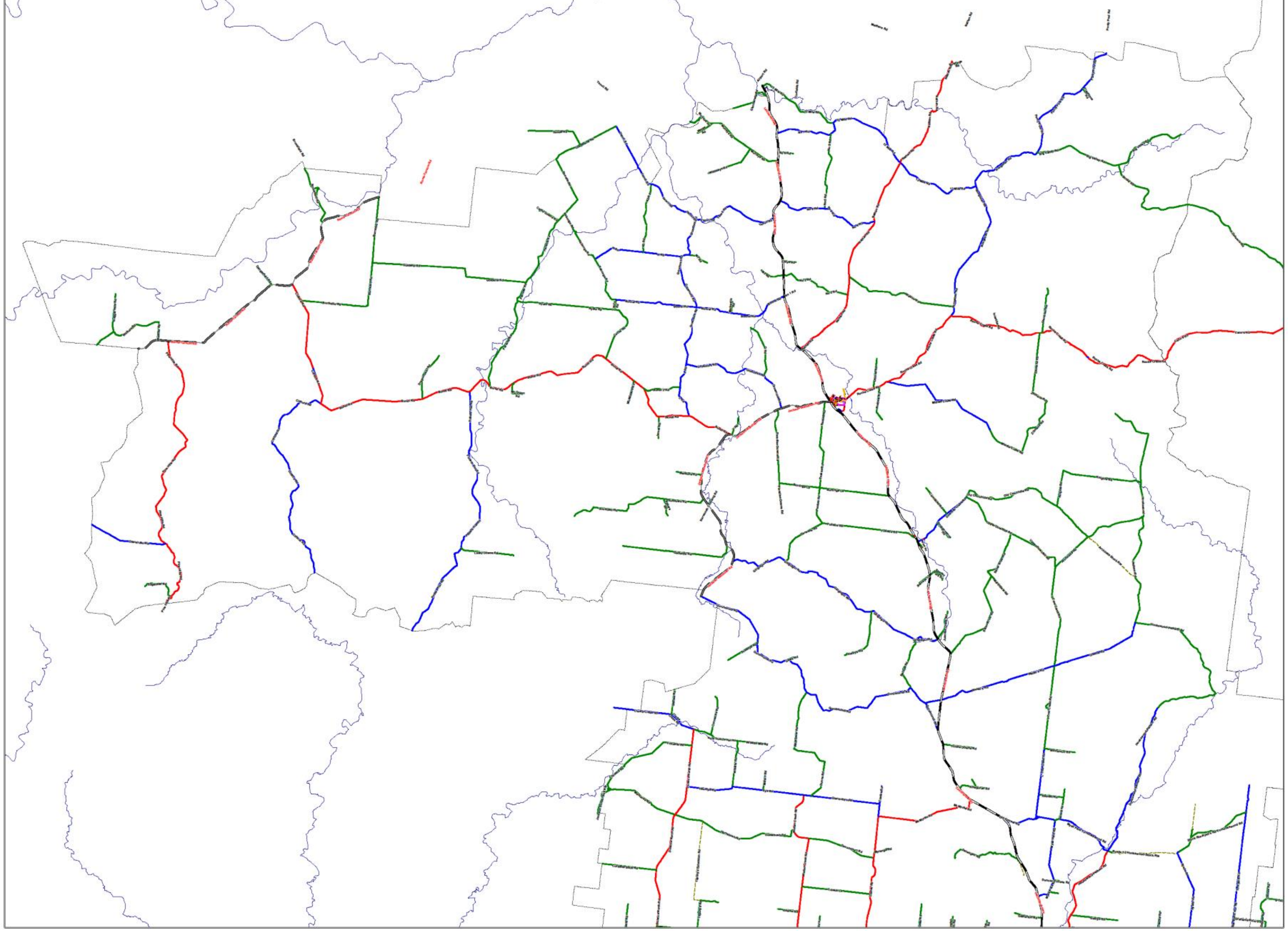
Agreed:

Student: Sam Fitzgerald
18/03/2015

Supervisor: Trevor Drysdale
18/03/2015

APPENDIX 2 – WANDOAN RURAL ROAD HIERARCHY

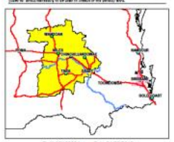
Wandaon Rural Road Hierarchy



WESTERN DOWNS REGIONAL COUNCIL

Roads Hierarchy

- Highways
- Main Roads
- Ruarl Arterial
- Rural Collector
- Rural Feeder
- Rural Access
- Urban Collector
- Urban Feeder
- Urban Access
- Parking Lane / Onstreet Parking
- Private Road
- Unformed
- Major Watercources

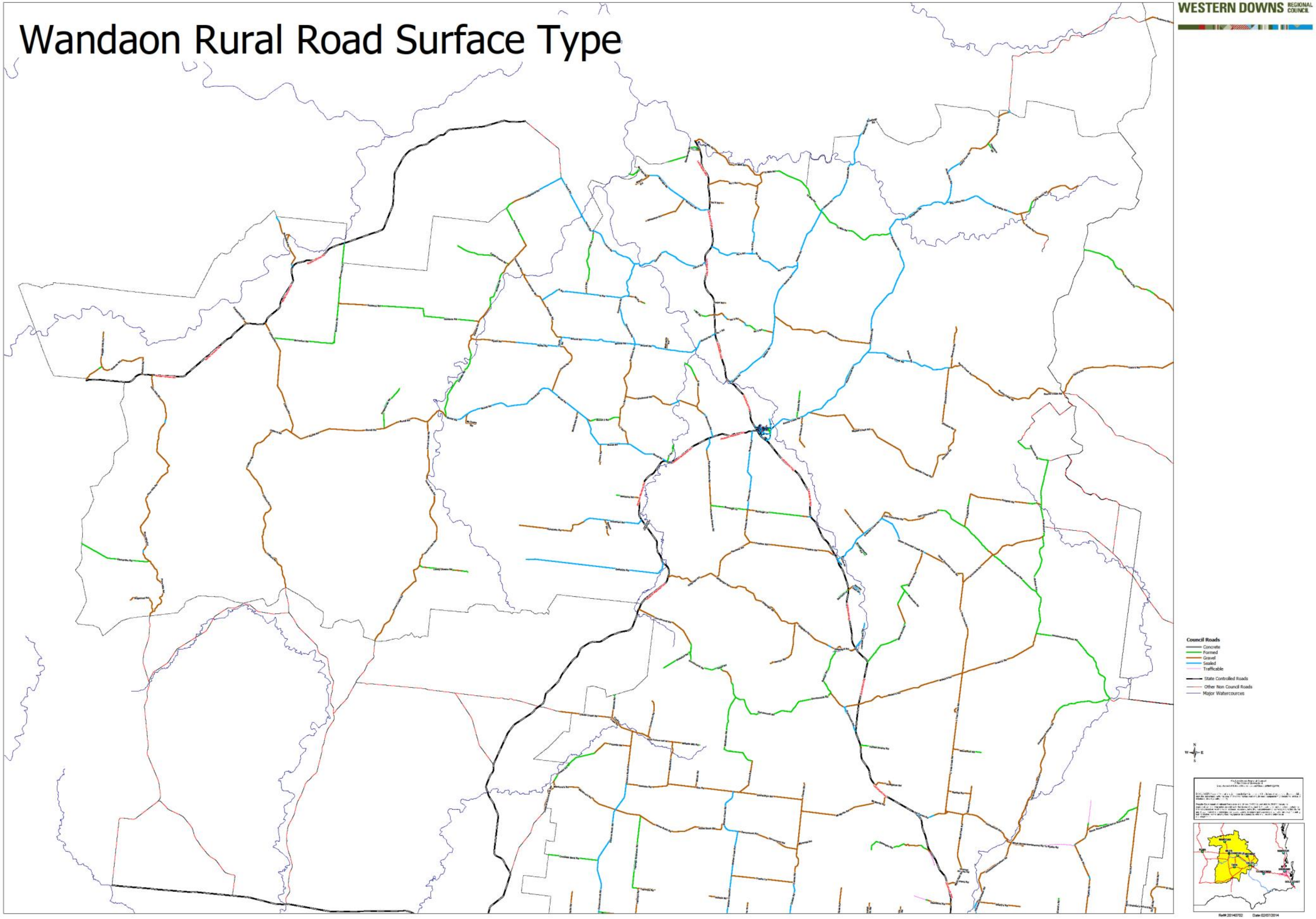


Ref#:20100624 Date:24/06/2010

APPENDIX 3 – WANDOAN RURAL ROAD SURFACE TYPE

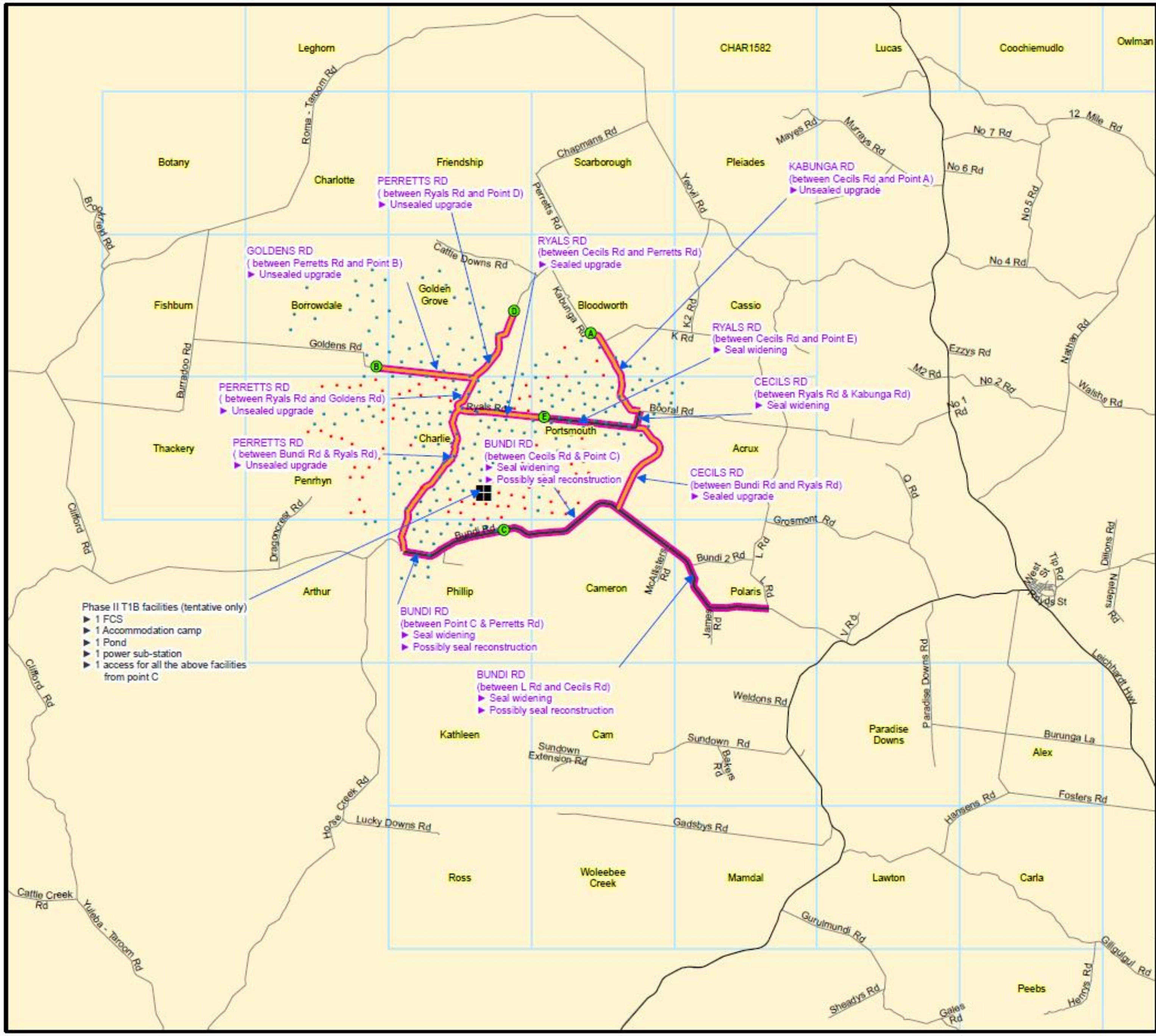
WESTERN DOWNS REGIONAL COUNCIL

Wandaon Rural Road Surface Type



Ref#:20140702 Date:02/07/2014

APPENDIX 4 - OFF-PLOT ROAD UPGRADES OPTION A



Phase II Tranche 1B Off-Plot Road Upgrades Option A Upgrade Work

Legend

- Roads in Option A
- Existing Sealed Section
- Existing Unsealed Section
- WDRC Road
- Well drilling in year 2016
- Well drilling in year 2017

Baded on QGC schedule dated 26 June 2014

DATE:	10/07/2014	MAP NO:	Road_Upgrade
CREATED BY:	SSJ	REV NO:	
PLAN REF:	XXXXXXXXXXXX		

N

0 5 10
Kilometres

GDA

Map Projection: GDA 94 SCALE: 1:230,000 (A3)

DATA SOURCE:
Road/ Transport

Note: Every effort has been made to ensure this information is spatially accurate. The location of this information should not be relied on as the exact field location.

QGC
A BG Group business

APPENDIX 5 – HISTORIC TRAFFIC VOLUMES WANDOAN RURAL

WESTERN DOWNS REGIONAL COUNCIL
Traffic Counts for the Wandoan District

Printed 20/12/2010

Road No.	Road Name	Traffic Counter Site				
		Site No.	Decription	Date	* AADT	# CV%
Wandoan Area						
201	Grosmont	2011	near J/W	Jan-03	35.0	7.0
201	Grosmont	2013	near J/W	Jan-09	22.0	33.0
201	Grosmont	2012	near Yeovil Rd	Oct-04	8.0	78.0
204	Baileys					
205	Bakers					
206	Big Valley					
207	Booral	2071	near Hwy	May-02	30.0	21.0
207	Booral	2072	near Grosmont	Mar-03	58.0	16.0
207	Booral	2073	near Hwy	Jan-09	58.0	33.0
208	Bocks					
209	Brookfield (Roma Rd to Richon)					
210	Bruggemanns					
211	Bundi 2					
214	Bungaban	2141	near Roche Ck	Sep-02	76.0	80.0
215	12 Mile (East of No 7 Rd)					
216	Burradoo	2161	0.2km from Roma-Taroom Rd int.	Nov-05	6.0	21.0
217	Burunga Lane	2171	near the Int of Leichhardt Hwy	Future		
218	Bundi	2181	near J/W	-	46.0	15.0
218	Bundi	2182	near J/W Rd	Jan-09	117.0	36.0
219	Cattle Downs					
221	Cecils	2211	near Booral	Aug-03	11.0	58.0
221	Cecils	2212	near Booral	Apr-09	24.0	42.0
222	Chapmans (West of Sands Rd)					
223	Clifford	2231	0.2km from Roma-Taroom Rd int.	Nov-05	24.0	19.0
223	Clifford	2232	0.2km from Shire Boundary (school period)	Mar-06	21.0	42.2
223	Clifford	2232	0.2km from Shire Boundary (normal period)	Mar-06	20.0	42.2
223	Clifford	2232	0.2km from Shire Boundary (xmas period)	Jan-06	19.0	42.2
224	Cormacks					
225	Dorset					
226	Dangarfield					
227	Dillons					
228	Dragoncrest					
229	Downfall Creek	2291	near Hwy	Jun-00	79.0	95.0
231	Ezzys					
233	Flagstone					
234	Fosters	2341	Near Leichhardt Hwy	Future		
235	Barneys Lane					
236	Iolanthe					
237	Gadsbys					
238	Gales					

APPENDIX 6 – 1ST ITERATION ANALYSIS EXISTING NETWORK

Link Properties								Hazard Input					Resilience Characteristics						
Link ID	***l***	***S_Opt***	***t_Opt***	***V_BE***	***LRF***	***t_Est***	***V_AE***	***Ch. St.***	***Ch. Fn.***	***Dist***	***Effective Dist***	***Speed Reduction***	***HRF***	***tt_{BE}***	***tt_{AE}***	***$Cost_{BE}$***	***$Cost_{AE}$***	***R_Cost_{Link}***	***R_Time_{Link}***
W-1	12	90	0.133	419	1.00	0.133	419							55.87	55.87	$ 9,218.00	$ 9,218.00	$ -	1.00
1-2	5	90	0.056	419	0.84	0.066	419	0.1	0.105	0.005	0.205	40	0.018	23.28	27.73	$ 3,840.83	$ 4,574.84	$ 734.01	0.84
1-2	5	90	0.056	419	0.84	0.066	419	1	1.2	0.2	0.4	40	0.036	23.28	27.73	$ 3,840.83	$ 4,574.84	$ 734.01	0.84
1-2	5	90	0.056	419	0.84	0.066	419	1.2	1.2	0	0.2	30	0.013	23.28	27.73	$ 3,840.83	$ 4,574.84	$ 734.01	0.84
1-2	5	90	0.056	419	0.84	0.066	419	1.52	1.52	0	0.2	60	0.027	23.28	27.73	$ 3,840.83	$ 4,574.84	$ 734.01	0.84
1-2	5	90	0.056	419	0.84	0.066	419	3	3.05	0.05	0.25	40	0.022	23.28	27.73	$ 3,840.83	$ 4,574.84	$ 734.01	0.84
1-2	5	90	0.056	419	0.84	0.066	419	4.1	4.4	0.3	0.5	40	0.044	23.28	27.73	$ 3,840.83	$ 4,574.84	$ 734.01	0.84
2-3	6.8	90	0.076	419	0.97	0.078	419	10.4	10.5	0.1	0.3	40	0.020	31.66	32.51	$ 5,223.53	$ 5,363.76	$ 140.23	0.97
2-3	6.8	90	0.076	419	0.97	0.078	419	11	11	0	0.2	20	0.007	31.66	32.51	$ 5,223.53	$ 5,363.76	$ 140.23	0.97
3-4	5.17	90	0.057	419	0.98	0.059	419	14.55	14.6	0.05	0.25	40	0.021	24.07	24.60	$ 3,971.42	$ 4,058.65	$ 87.23	0.98
4-C	7.44	90	0.083	285	0.99	0.084	285	22.1	22.1	0	0.2	40	0.012	23.56	23.84	$ 3,887.40	$ 3,934.41	$ 47.01	0.99
5-C	6.3	90	0.070	158	0.95	0.074	158	26.3	26.4	0.1	0.3	40	0.021	11.06	11.63	$ 1,824.90	$ 1,919.70	$ 94.80	0.95
5-C	6.3	90	0.070	158	0.95	0.074	158	27.5	27.5	0	0.2	40	0.014	11.06	11.63	$ 1,824.90	$ 1,919.70	$ 94.80	0.95
5-C	6.3	90	0.070	158	0.95	0.074	158	29.4	29.4	0	0.2	40	0.014	11.06	11.63	$ 1,824.90	$ 1,919.70	$ 94.80	0.95
4-8	6.8	70	0.097	339	0.69	0.140	339	1.3	1.35	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	1.55	1.6	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	1.61	1.65	0.04	0.24	30	0.015	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	1.7	1.75	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	1.8	1.85	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	2.1	2.15	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	2.2	2.3	0.1	0.3	30	0.019	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69

4-8	6.8	70	0.097	339	0.69	0.140	339	2.4	2.45	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	2.55	2.59	0.04	0.24	30	0.015	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	2.6	2.64	0.04	0.24	30	0.015	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	2.65	2.8	0.15	0.35	30	0.022	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	3.35	3.4	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	3.5	3.55	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	3.65	3.7	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	4.1	4.15	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	5.15	5.2	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	5.8	5.85	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	6.05	6.1	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
4-8	6.8	70	0.097	339	0.69	0.140	339	6.2	6.25	0.05	0.25	30	0.016	32.93	47.52	$ 5,433.69	$ 7,840.06	$ 2,406.37	0.69
8-9	1.12	70	0.016	98	0.80	0.020	98	6.98	7	0.02	0.22	30	0.084	1.57	1.96	$ 258.72	$ 322.99	$ 64.27	0.80
8-9	1.12	70	0.016	98	0.80	0.020	98	7.1	7.2	0.1	0.3	30	0.115	1.57	1.96	$ 258.72	$ 322.99	$ 64.27	0.80
6-7	2.3	70	0.033	73	0.78	0.042	73	17.4	17.4	0	0.2	40	0.050	2.40	3.06	$ 395.76	$ 505.70	$ 109.93	0.78
6-7	2.3	70	0.033	73	0.78	0.042	73	17.6	17.7	0.1	0.3	40	0.075	2.40	3.06	$ 395.76	$ 505.70	$ 109.93	0.78
6-7	2.3	70	0.033	73	0.78	0.042	73	17.4	17.7	0.3	0.5	30	0.093	2.40	3.06	$ 395.76	$ 505.70	$ 109.93	0.78
5-6	10.52	70	0.150	53	0.89	0.169	53	0.7	0.9	0.2	0.4	50	0.027	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	3.7	3.8	0.1	0.3	30	0.012	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	10.6	10.8	0.2	0.4	30	0.016	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	11.7	11.8	0.1	0.3	20	0.008	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	12	12.05	0.05	0.25	30	0.010	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	12.3	12.4	0.1	0.3	30	0.012	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	19.5	19.6	0.1	0.3	30	0.012	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	20.8	20.8	0	0.2	50	0.014	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
7-D	4.3	70	0.061	53	0.79	0.077	53	15.8	16.3	0.5	0.7	50	0.116	3.26	4.10	$ 537.19	$ 676.55	$ 139.36	0.79
7-D	4.3	70	0.061	53	0.79	0.077	53	15.8	16.3	0.5	0.7	30	0.070	3.26	4.10	$ 537.19	$ 676.55	$ 139.36	0.79
7-D	4.3	70	0.061	53	0.79	0.077	53	16.7	16.7	0	0.2	30	0.020	3.26	4.10	$ 537.19	$ 676.55	$ 139.36	0.79
7-B	6.3	70	0.090	73	0.89	0.101	73	0.7	0.8	0.1	0.3	30	0.020	6.57	7.40	$ 1,084.05	$ 1,221.11	$ 137.06	0.89

7-B	6.3	70	0.090	73	0.89	0.101	73	2.4	2.5	0.1	0.3	30	0.020	6.57	7.40	$ 1,084.05	$ 1,221.11	$ 137.06	0.89
7-B	6.3	70	0.090	73	0.89	0.101	73	2.8	2.9	0.1	0.3	30	0.020	6.57	7.40	$ 1,084.05	$ 1,221.11	$ 137.06	0.89
7-B	6.3	70	0.090	73	0.89	0.101	73	3.7	3.75	0.05	0.25	30	0.017	6.57	7.40	$ 1,084.05	$ 1,221.11	$ 137.06	0.89
7-B	6.3	70	0.090	73	0.89	0.101	73	5.2	5.25	0.05	0.25	30	0.017	6.57	7.40	$ 1,084.05	$ 1,221.11	$ 137.06	0.89
7-B	6.3	70	0.090	73	0.89	0.101	73	5.9	5.95	0.05	0.25	30	0.017	6.57	7.40	$ 1,084.05	$ 1,221.11	$ 137.06	0.89
6-8	10.43	70	0.149	339	0.91	0.163	339	0.3	0.4	0.1	0.3	30	0.012	50.51	55.28	$ 8,334.32	$ 9,121.40	$ 787.08	0.91
6-8	10.43	70	0.149	339	0.91	0.163	339	0.5	0.6	0.1	0.3	30	0.012	50.51	55.28	$ 8,334.32	$ 9,121.40	$ 787.08	0.91
6-8	10.43	70	0.149	339	0.91	0.163	339	0.8	0.9	0.1	0.3	30	0.012	50.51	55.28	$ 8,334.32	$ 9,121.40	$ 787.08	0.91
6-8	10.43	70	0.149	339	0.91	0.163	339	2.3	2.4	0.1	0.3	30	0.012	50.51	55.28	$ 8,334.32	$ 9,121.40	$ 787.08	0.91
6-8	10.43	70	0.149	339	0.91	0.163	339	2.9	3.1	0.2	0.4	30	0.016	50.51	55.28	$ 8,334.32	$ 9,121.40	$ 787.08	0.91
6-8	10.43	70	0.149	339	0.91	0.163	339	9.2	9.25	0.05	0.25	30	0.010	50.51	55.28	$ 8,334.32	$ 9,121.40	$ 787.08	0.91
6-8	10.43	70	0.149	339	0.91	0.163	339	10	10.05	0.05	0.25	30	0.010	50.51	55.28	$ 8,334.32	$ 9,121.40	$ 787.08	0.91
9-A	5.8	70	0.083	98	1.00	0.083	98						0.000	8.12	8.12	$ 1,339.80	$ 1,339.80	$ -	1.00
9-10	3.5	90	0.039	44	1.00	0.039	44						0.000	1.71	1.71	$ 282.33	$ 282.33	$ -	1.00

7 APPENDIX 7 – TABLE OF OMISSIONS AND VARIATIONS TO EXISTING HAZARDS DUE TO PLANNED ROAD UPGRADES

W-1					
Ch. St.	**Ch. Fn.**	**Description**	**Speed Reduction**	**Hazard Reduction Factor**	**Comments**
					No Hazards Recorded
1-2					
Ch. St.	**Ch. Fn.**	**Description**	**Speed Reduction**	**Hazard Reduction Factor**	**Comments**
0.1	0.105	Shoulder washed away from edge of bitumen	20	0.005	Full Road Reconstruction undertaken in this area with widening of seal and improved drainage profile. These hazards may still occur in extreme events but have been reduced in severity to reflect the lessened likelihood of this occuring
1	1.2	Shoulder washed away from edge of bitumen	20	0.053	
1.2	1.2	Scouring off end of pipe	20	0.053	
1.52	1.52	Pipe washed out - has been fixed	20	0.068	
3	3.05	Shoulder washed away from edge of bitumen	20	0.136	
4.1	4.4	Scouring on edge of bitumen	20	0.196	
2-3					
Ch. St.	**Ch. Fn.**	**Description**	**Speed Reduction**	**Hazard Reduction Factor**	**Comments**
10.4	10.5	Scour to Pavement	20	0.010	
11	11	Scour to Floodway Slab	0	0.000	Removed due to full floodway replacement as part of planned upgrade
3-4					

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
14.55	14.6	Scour to Pavement	20	0.011	Reduced due to full width reconstruction

4-C

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
22.1	22.1	Scour to Pavement	10	0.004	Reduced due to planned full width reconstruction in this area.

5-C

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
26.3	26.4	Scour to Pavement	10	0.005	Reduced due to full width reconstruction in this section
27.5	27.5	Scouring Edge of Bitumen	10	0.004	
29.4	29.4	Scouring Edge of Bitumen	10	0.004	

4-8

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
1.3	1.35	Gravel Scouring and Rutting	10	0.004	Scouring of gravel significantly reduced due to sealing of road. Hazards only lessened not eliminated as scouring of pavement is likely to be replaced by scouring of the road shoulder
1.55	1.6	Gravel Scouring and Rutting	10	0.004	
1.61	1.65	Gravel Scouring and Rutting	10	0.004	
1.7	1.75	Gravel Scouring and Rutting	10	0.004	
1.8	1.85	Gravel Scouring and Rutting	10	0.004	
2.1	2.15	Gravel Scouring and Rutting	10	0.004	
2.2	2.3	Gravel Scouring and Rutting	10	0.005	
2.4	2.45	Gravel Scouring and Rutting	10	0.004	

2.55	2.59	Gravel Scouring and Rutting	10	0.004	
2.6	2.64	Gravel Scouring and Rutting	10	0.004	
2.65	2.8	Gravel Scouring and Rutting	10	0.006	
3.35	3.4	Gravel Scouring and Rutting	10	0.004	
3.5	3.55	Gravel Scouring and Rutting	10	0.004	
3.65	3.7	Gravel Scouring and Rutting	10	0.004	
4.1	4.15	Gravel Scouring and Rutting	10	0.004	
5.15	5.2	Gravel Scouring and Rutting	10	0.004	
5.8	5.85	Gravel Scouring and Rutting	10	0.004	
6.05	6.1	Gravel Scouring and Rutting	10	0.004	
6.2	6.25	Gravel Scouring and Rutting	10	0.004	

8-9

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
6.98	7	Gravel Scouring and Rutting	30	0.084	No upgrade planned. Hazards as per previous analysis
7.1	7.2	Gravel Scouring and Rutting	30	0.115	

6-7

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
17.4	17.4	Scouriing of invert	30	0.037	Hazards reduced slightly. Planned verticle alignment upgrade should reduce scour, but not eliminate completely
17.6	17.7	Scouriing of invert	30	0.056	
17.4	17.7	Scouring out edge of pavement	20	0.062	

5-6

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
0.7	0.9	Washout of Road	50	0.027	No upgrades planned. As per original analysis

3.7	3.8	Scouring of invert	30	0.012	
10.6	10.8	Scouring of invert	30	0.016	
11.7	11.8	Scouring out edge of pavement	20	0.008	
12	12.05	Scouirng of invert	30	0.010	
12.3	12.4	Scouring of invert	30	0.012	
19.5	19.6	Scouring of Pavement	30	0.012	
20.8	20.8	Silt Buildup	50	0.014	

7-D

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
15.8	16.3	Washout of Road	50	0.116	No upgrades planned. As per original analysis
15.8	16.3	Scouring of invert	30	0.070	
16.7	16.7	Scouring of Pavement	30	0.020	

7-B

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
0.7	0.8	Gravel Scouring and Rutting	20	0.014	Hazards reduced slightly. Planned verticle alignment upgrade should reduce scour, but not eliminate completely
2.4	2.5	Gravel Scouring and Rutting	20	0.014	
2.8	2.9	Gravel Scouring and Rutting	20	0.014	
3.7	3.75	Gravel Scouring and Rutting	20	0.011	
5.2	5.25	Gravel Scouring and Rutting	20	0.011	
5.9	5.95	Gravel Scouring and Rutting	20	0.011	

6-8

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
0.3	0.4	Pavement inundation resulting in gravel scouring and rutting	20	0.011	Reduced slightly due to gravel upgrade. Upgrade will not

0.5	0.6	Scouring of floodway	20	0.016	eliminate hazards completely.
0.8	0.9	Pavement inundation resulting in gravel scouring and rutting	20	0.025	
2.3	2.4	Pavement inundation resulting in gravel scouring and rutting	20	0.066	
2.9	3.1	Pavement inundation resulting in gravel scouring and rutting	20	0.085	
9.2	9.25	Scouring of floodway	0	0.000	Floodway upgrade to causeway expected to eliminate hazards
10	10.05	Deposits of silt & debris on floodway	0	0.000	

9-A

Ch. St.	Ch. Fn.	Description	Speed Reduction	Hazard Reduction Factor	Comments
				0.000	No hazards recorded

APPENDIX 8 – 2ND ITERATION NETWORK ANALYSIS POST UPGRADE

Link Properties								Hazard Input					Resilience Characteristics						
Link ID	*l*	*S_Opt*	*t_Opt*	*V_BE*	*LRF*	*t_Est*	*V_AE*	*Ch. St.*	*Ch. Fn.*	*Dist*	*Effective Dist*	*Speed Reduction*	*HRF*	tt_{BE}	tt_{AE}	$Cost_{BE}$	$Cost_{AE}$	R_Cost_{Link}	R_Time_{Link}
W-1	12	90	0.133	419	1.00	0.133	419							55.87	55.87	$ 9,218.00	$ 9,218.00	$ -	1.00
1-2	5	90	0.056	419	0.92	0.060	419	0.1	0.105	0.005	0.205	20	0.009	23.28	25.25	$ 3,840.83	$ 4,165.76	$ 324.93	0.92
1-2	5	90	0.056	419	0.92	0.060	419	1	1.2	0.2	0.4	20	0.018	23.28	25.25	$ 3,840.83	$ 4,165.76	$ 324.93	0.92
1-2	5	90	0.056	419	0.92	0.060	419	1.2	1.2	0	0.2	20	0.009	23.28	25.25	$ 3,840.83	$ 4,165.76	$ 324.93	0.92
1-2	5	90	0.056	419	0.92	0.060	419	1.52	1.52	0	0.2	20	0.009	23.28	25.25	$ 3,840.83	$ 4,165.76	$ 324.93	0.92
1-2	5	90	0.056	419	0.92	0.060	419	3	3.05	0.05	0.25	20	0.011	23.28	25.25	$ 3,840.83	$ 4,165.76	$ 324.93	0.92
1-2	5	90	0.056	419	0.92	0.060	419	4.1	4.4	0.3	0.5	20	0.022	23.28	25.25	$ 3,840.83	$ 4,165.76	$ 324.93	0.92
2-3	6.8	90	0.076	419	0.99	0.076	419	10.4	10.5	0.1	0.3	20	0.010	31.66	31.97	$ 5,223.53	$ 5,275.25	$ 51.72	0.99
2-3	6.8	90	0.076	419	0.99	0.076	419	11	11	0	0.2	0	0.000	31.66	31.97	$ 5,223.53	$ 5,275.25	$ 51.72	0.99
3-4	5.17	90	0.057	419	0.99	0.058	419	14.55	14.6	0.05	0.25	20	0.011	24.07	24.33	$ 3,971.42	$ 4,014.56	$ 43.14	0.99
4-C	7.44	90	0.083	285	1.00	0.083	285	22.1	22.1	0	0.2	10	0.003	23.56	23.63	$ 3,887.40	$ 3,899.05	$ 11.65	1.00
5-C	6.3	90	0.070	158	0.99	0.071	158	26.3	26.4	0.1	0.3	10	0.005	11.06	11.20	$ 1,824.90	$ 1,847.71	$ 22.81	0.99
5-C	6.3	90	0.070	158	0.99	0.071	158	27.5	27.5	0	0.2	10	0.004	11.06	11.20	$ 1,824.90	$ 1,847.71	$ 22.81	0.99
5-C	6.3	90	0.070	158	0.99	0.071	158	29.4	29.4	0	0.2	10	0.004	11.06	11.20	$ 1,824.90	$ 1,847.71	$ 22.81	0.99
4-8	6.8	70	0.097	339	0.90	0.108	339	1.3	1.35	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	1.55	1.6	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	1.61	1.65	0.04	0.24	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	1.7	1.75	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	1.8	1.85	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	2.1	2.15	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	2.2	2.3	0.1	0.3	10	0.006	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	2.4	2.45	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	2.55	2.59	0.04	0.24	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	2.6	2.64	0.04	0.24	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	2.65	2.8	0.15	0.35	10	0.007	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90

4-8	6.8	70	0.097	339	0.90	0.108	339	3.35	3.4	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	3.5	3.55	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	3.65	3.7	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	4.1	4.15	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	5.15	5.2	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	5.8	5.85	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	6.05	6.1	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
4-8	6.8	70	0.097	339	0.90	0.108	339	6.2	6.25	0.05	0.25	10	0.005	32.93	36.68	$ 5,433.69	$ 6,052.97	$ 619.29	0.90
8-9	1.12	70	0.016	98	0.80	0.020	98	6.98	7	0.02	0.22	30	0.084	1.57	1.96	$ 258.72	$ 322.99	$ 64.27	0.80
8-9	1.12	70	0.016	98	0.80	0.020	98	7.1	7.2	0.1	0.3	30	0.115	1.57	1.96	$ 258.72	$ 322.99	$ 64.27	0.80
6-7	2.3	70	0.033	73	0.84	0.039	73	17.4	17.4	0	0.2	30	0.037	2.40	2.84	$ 395.76	$ 468.52	$ 72.75	0.84
6-7	2.3	70	0.033	73	0.84	0.039	73	17.6	17.7	0.1	0.3	30	0.056	2.40	2.84	$ 395.76	$ 468.52	$ 72.75	0.84
6-7	2.3	70	0.033	73	0.84	0.039	73	17.4	17.7	0.3	0.5	20	0.062	2.40	2.84	$ 395.76	$ 468.52	$ 72.75	0.84
5-6	10.52	70	0.150	53	0.89	0.169	53	0.7	0.9	0.2	0.4	50	0.027	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	3.7	3.8	0.1	0.3	30	0.012	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	10.6	10.8	0.2	0.4	30	0.016	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	11.7	11.8	0.1	0.3	20	0.008	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	12	12.05	0.05	0.25	30	0.010	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	12.3	12.4	0.1	0.3	30	0.012	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	19.5	19.6	0.1	0.3	30	0.012	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
5-6	10.52	70	0.150	53	0.89	0.169	53	20.8	20.8	0	0.2	50	0.014	7.97	8.97	$ 1,314.25	$ 1,480.06	$ 165.81	0.89
7-D	4.3	70	0.061	53	0.79	0.077	53	15.8	16.3	0.5	0.7	50	0.116	3.26	4.10	$ 537.19	$ 676.55	$ 139.36	0.79
7-D	4.3	70	0.061	53	0.79	0.077	53	15.8	16.3	0.5	0.7	30	0.070	3.26	4.10	$ 537.19	$ 676.55	$ 139.36	0.79
7-D	4.3	70	0.061	53	0.79	0.077	53	16.7	16.7	0	0.2	30	0.020	3.26	4.10	$ 537.19	$ 676.55	$ 139.36	0.79
7-B	6.3	70	0.090	73	0.93	0.097	73	0.7	0.8	0.1	0.3	20	0.014	6.57	7.10	$ 1,084.05	$ 1,171.73	$ 87.68	0.93
7-B	6.3	70	0.090	73	0.93	0.097	73	2.4	2.5	0.1	0.3	20	0.014	6.57	7.10	$ 1,084.05	$ 1,171.73	$ 87.68	0.93
7-B	6.3	70	0.090	73	0.93	0.097	73	2.8	2.9	0.1	0.3	20	0.014	6.57	7.10	$ 1,084.05	$ 1,171.73	$ 87.68	0.93
7-B	6.3	70	0.090	73	0.93	0.097	73	3.7	3.75	0.05	0.25	20	0.011	6.57	7.10	$ 1,084.05	$ 1,171.73	$ 87.68	0.93
7-B	6.3	70	0.090	73	0.93	0.097	73	5.2	5.25	0.05	0.25	20	0.011	6.57	7.10	$ 1,084.05	$ 1,171.73	$ 87.68	0.93
7-B	6.3	70	0.090	73	0.93	0.097	73	5.9	5.95	0.05	0.25	20	0.011	6.57	7.10	$ 1,084.05	$ 1,171.73	$ 87.68	0.93
6-8	10.43	70	0.149	339	0.96	0.156	339	0.3	0.4	0.1	0.3	20	0.008	50.51	52.83	$ 8,334.32	$ 8,716.35	$ 382.03	0.96

6-8	10.43	70	0.149	339	0.96	0.156	339	0.5	0.6	0.1	0.3	20	0.008	50.51	52.83	$ 8,334.32	$ 8,716.35	$ 382.03	0.96
6-8	10.43	70	0.149	339	0.96	0.156	339	0.8	0.9	0.1	0.3	20	0.008	50.51	52.83	$ 8,334.32	$ 8,716.35	$ 382.03	0.96
6-8	10.43	70	0.149	339	0.96	0.156	339	2.3	2.4	0.1	0.3	20	0.008	50.51	52.83	$ 8,334.32	$ 8,716.35	$ 382.03	0.96
6-8	10.43	70	0.149	339	0.96	0.156	339	2.9	3.1	0.2	0.4	20	0.011	50.51	52.83	$ 8,334.32	$ 8,716.35	$ 382.03	0.96
6-8	10.43	70	0.149	339	0.96	0.156	339	9.2	9.25	0.05	0.25	0	0.000	50.51	52.83	$ 8,334.32	$ 8,716.35	$ 382.03	0.96
6-8	10.43	70	0.149	339	0.96	0.156	339	10	10.05	0.05	0.25	0	0.000	50.51	52.83	$ 8,334.32	$ 8,716.35	$ 382.03	0.96
9-A	5.8	70	0.083	98	1.00	0.083	98						0.000	8.12	8.12	$ 1,339.80	$ 1,339.80	$ -	1.00
9-10	3.5	90	0.039	44	1.00	0.039	44						0.000	1.71	1.71	$ 282.33	$ 282.33	$ -	1.00

END