Analysing impacts of natural disasters on logistics activities: flood risks and petroleum fuels in Queensland, Australia

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Abstract

Natural hazards cause much damage to lives, assets, and the economy as a whole. The functional discontinuity of businesses impacted by a natural disaster has a direct impact on affected community’s quality of live. In regional and remote communities petroleum fuels are an essential commodity, particularly in post-disaster situations, given the supply chains of many other commodities are dependent on fuel supply. The aim of this study was to develop a framework and use it to analyse petroleum supply to communities affected by flooding across Queensland, Australia. The intent was to assist industry partners in identifying vulnerable localities and to development methods for application to other commodities. The approach focused on both the demand and supply side and used socio-spatial datasets, transport and commodity data. A multi-agent model was developed to represent the situation of petroleum fuel supply chain before and after a disaster event. The results identify both the broad sweep of vulnerable locations in key regions in Queensland as well as particular issues for communities in Cape York in far north Queensland. The approach proved viable, despite the limitations of publically available commodity datasets in Australia, and should therefore be of assistance to policy makers elsewhere seeking to identify system vulnerabilities and increase resilience.

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1. Introduction

The frequency and intensity of natural disasters has been increasing in recent years (Whybark et al., 2010). Disasters such as typhoons, floods and earthquakes create damage to lives, assets, and the economy as a whole. Businesses struggle to recover in the aftermath. Australia is a particularly disaster-prone country where floods, bushfires, storms, earthquakes, and landslides often occur. The 2010-11 flooding events in Queensland were the worst in recent Australian history (Department of Agriculture, Fisheries, and Forestry, 2012). The floods strongly impacted the economy as a whole with IBISWorld downgrading the country’s GDP by 0.3 percent solely as a result of flooding (IBISWorld, 2011). Disruption was caused to all transport modes including road, rail, air, and sea. According to the major report on the floods’ impacts (Department of Agriculture, Fisheries, and Forestry, 2012), at its peak 155 major roads were flooded and damaged. This caused severe disruption to supply chains preventing numerous cities and towns from being resupplied. Shortages of essential items occurred and, in the worst case, petroleum fuels had to be barged in to the city of Townsville and emergency food drops by helicopter were required to numerous localities. The report suggested the major impacts of the floods on supply chains were due to the disruptions of transport routes, warehousing and manufacturing facilities, and also to production. Identifying vulnerabilities in such systems, and building resilience, can help alleviate problems in future.

Petroleum fuels are a critical commodity in regional areas of nations such as Australia. Fuel is required not only for people to access work, education and the goods and services they need in daily life, it is also essential to carrying goods by road or rail. The supply chains of all other commodities are dependent on petroleum fuel supply. Fuels are also essential for heavy equipment needed for repair and restoration of transport networks and other infrastructures, and for the generation of electricity in communities where electrical grids are knocked out by a disaster. As such, many nations use countermeasures to prepare for petroleum shortages, storing additional capacity in strategically placed reserves. Local media reporting through recent floods in Australia shows how customers have had to wait many days for fuel until roads are reopened (News.com.au, 2011) and how limited remaining supplies had to be triaged in other locations for emergency services and other priority vehicles when floods have struck (Whitsundaycoastguardian, 2013).

Vulnerability analysis of critical infrastructures is used to identify possible effects in advance of disasters. Vulnerability may be defined as the degree to which a system is susceptible to adverse effects. It is a similar but somewhat different concept to resilience, which incorporates a network or a community’s capacity to deal with and bounce back from a disaster. The critical infrastructures considered are often lifeline systems including transportation, energy, information and telecommunication, and drinking and underground water systems (Kroger, 2011). In disaster logistics research, vulnerability analysis is used to identify vulnerable nodes and links in a transport network, so to assist planners to retrofit or manage future hazards. Two broad approaches are used: i) qualitative analysis, often focused on learning from past events to discern how to better manage risk in future; and ii) quantitative analysis, using transport and commodity data, and modelling both supply and demand, to identify vulnerabilities, and simulate and forecast impacts under various disaster scenarios. We focus on quantitative approaches in this paper.

There is great diversity in the literature on quantitative vulnerability assessments for transport networks, given the many elements of both road networks and supply chains that are vulnerable to disasters, at different scales. But much of the work seeks to harness what may be termed ‘accessibility-based network vulnerability analysis’ (Taylor, 2008). Chang and Nojima (2001) evaluated the transportation network performance in the 1995 Kobe Earthquake in terms of transport accessibility. Sohn (2006) proposed an accessibility approach to evaluate the significance of highway links under flood damage. He derived an accessibility score based on distance and traffic volume, suggesting highway links having a high percentage of accessibility loss will have higher significance. Taylor et al. (2006) considered the socio-economic impacts of network degradation due to the change in the level of accessibility for the analysis of vulnerability of a road network. Their framework used a number of indices including generalized travel cost, the Hansen integral accessibility index, and an Australian remoteness index, highlighting how other socio-spatial datasets can be employed in vulnerability analysis. Others have focused on failure at the link level. Taylor
(2008) proposed a method to identify critical locations in a network considering the consequences of the failure due to congestion, delay, and pollution. Jenelius et al. (2006) introduced the concepts of link importance and site exposure in which the indices were derived based on the increase in generalized travel cost when links are closed. As nodes are also an important part of a network, failure of a node can cause disruption to the system as much as links. Bana e Costa et al. (2008) used a multi-criteria value model, considering various factors including public safety, emergency response, local economic impact, and interference with other infrastructures, to prioritize bridges and tunnels for earthquake preparedness. Further, the impact of road failure can influence the pattern of travel. Erath (2011) integrated the feedbacks of road closure into the two steps of trip distribution and modal choice of the four step approach to provide a method to analyse the vulnerability of road networks. Other vulnerability analyses using accessibility can be found in the works of Chen et al. (2007) and Kurauchi et al. (2009).

Finding vulnerability assessment approaches that best meld community demand for essential commodities with supply-side network and link capacities remains a difficult task. In order to advance this agenda, the aim of this study was to develop a framework using demand and supply-side parameters, and to use it to analyse petroleum supply to communities affected by flooding across Queensland, Australia. The next section provides a multi-agent model developed to represent the normal situation of petroleum fuel supply chain. The paper then puts forth a set of hazard scenarios derived from historical flood data to identify impacts on transport infrastructure. The model is used to assess the consequences of such hazards on the fuel supply chain. The results of a vulnerability analysis of fuel supply, dependent on the road network, is then provided to identify critical locations. Finally, a set of countermeasures to alleviate the problem are suggested, along with the limitations of the study and options for future enquiry.

2. Approach and Method

The approach taken employs both demand and supply side elements. Conceptually, the approach sought to appraise petroleum fuel demands across the state of Queensland in a manner that could then be linked to road networks, and to impacts of natural hazards (in this case flooding) on those networks. We did not include rail, given the lower volumes of petroleum fuels carried by this mode through most of Queensland, or sea, given petroleum fuels are not generally distributed along the coastline. Emphasis was placed on individual petrol stations and supply depots across Queensland, and the methods had to recognize that branded stations tend to be supplied from particular depots.

The methods include: (1) an estimation of the petroleum fuel demand at petrol stations and their links to petroleum depots in order to represent the flow of petroleum fuel in the supply chain, (2) a natural disaster scenario applied to the road network, and (3) a vulnerability assessment of the overall system to analyze the impact of the disasters on the petroleum supply chain. Due to the problems of data availability in Queensland, the flows of commodities and the demands at individual petrol stations could only be synthesized using available sources. Use was made of geo-coded vehicle registration data, supplied estimations of total fuel consumption in each region of Queensland, and geo-spatial locations of petrol stations and petroleum depots across the state, from mainly state and Commonwealth government sources.

The conceptual framework for understanding the elements and relationships in the petroleum supply chain is shown in Figure 1. Roads are divided into two types: normal (local) roads and state-controlled roads (the latter representing almost all of Queensland’s arterial road system). Using vehicle registration data one can locate and assign the Queensland vehicle fleet to the road network. Next, using the locations of petrol stations and depots, and the road network, the relationship between petrol stations and their resupply depots may be represented. Conceptually, if one can understand the impact of natural hazards on the road network, then vulnerability analysis for the rest of this system can be accomplished. The methodology for the estimation will be presented in more detail later in this section.
2.1 Estimation of Fuel Demand

The analysis framework is presented in Figure 2. The Queensland vehicle registration database (Queensland Government, 2014) was examined by postcode. When found to be representative, each vehicle was assigned to a local street in each postal region using Monte Carlo Simulation. More than 4.6 million vehicles were allocated to streets across Queensland. The vehicle registrations were then examined by postcode and synthesized with estimated annual fuel usage. The estimated annual fuel consumption in Queensland in 2010 was 4,014 million, 2,175 million, and 242 million liters, for petrol, diesel, and LPG, respectively (Department of Infrastructure and Transport, 2011). This approach is not perfect, with vehicles in small town areas less accurately allocated than in larger centers. The generated vehicles were assigned to petrol stations, where they would be expected to source fuel, considering the distance to each petrol station based on travel impedance. The capacity of each petrol station was assumed at 600 thousand liters/month and 40 million liters/month for each petroleum depot. All available petrol stations (with demand still less than capacity) within a 5 km range were identified as possible candidates with the nearer the petrol station, the higher possibility that the station was chosen. In cases where there was no petrol station available within range, the nearest available petrol station was chosen. Petrol stations in key locations in NSW were also included for this analysis, to ensure no erroneous results along the state boundary. Next, the number of customers estimated for each petrol station was used to represent likely fuel demand at each location. The links between petrol stations to petroleum depots was undertaken in a similar way, albeit each petrol station was connected to the nearest depot of the same brand where that information was available. In the latter case, the distance matrix calculated using the state controlled road network was used as the main road network for deliveries by petroleum trucks. The national GIS databases of petrol stations and petroleum depots were used to identify the locations of these sites. Finally, the demands at each petrol station and each depot were estimated with the results shown in Figures 3(a) and 3(b), respectively.
Figure 2 Analysis framework

Figure 3 Estimated fuel demand
2.2 Estimation of Natural Disaster Impact

When road infrastructure is disrupted by a natural hazard like flooding, the supply chain of goods is also interrupted, preventing commodities from being resupplied. The immediate reaction of people when their usual petrol station is unavailable will be finding an unaffected, accessible station. This behavior creates additional demand at the unaffected stations, and may lead to an increased demand from the facilities in the upper level of the supply chain.

The framework for analysis of changes in petroleum demand due to flooding is shown in Figure 4. From hazard mapping and historical road closure data, the locations of petroleum depots and petrol stations as well as the links in the transport network that are likely to be damaged from flooding can all be identified. For modelling purposes we assume that in the aftermath of a major flooding event that drivers will seek supply from the nearest accessible stocked petrol station location, regardless of other preferences. By assigning vehicles to petrol stations in this way, projected demand at each petrol station can be derived. A similar set of behaviours is assumed for the relationship between petrol stations and petroleum depots. We assume resupply from the nearest depots, regardless of brand. As a result, the increased demand at petrol stations and petroleum depots can be obtained. This framework can be applied to other types of natural hazards as well.

![Figure 4 Analysis framework for demand due to flood impact](image)

2.3 Vulnerability analysis

In order to identify the critical link in the road transport on the petroleum fuel supply chain, each link in the road network was analyzed for the impact in case of its failure. The calculation process was performed such that each link was set to be closed one-by-one and the new shortest path of the detour route was recalculated as a result of the closure. The travel distance between each origin and destination was calculated using the Dijkstra shortest path technique. This process was repeated for every link in the entire road network. The evaluation method proposed by Jenelius et al. (2006) was adopted in this study. The importance of a link was measured by how many vehicles will be impacted when the link is completely disrupted. The additional travel distance was calculated as follows:
\[ \Delta c_{ij}^e = c_{ij}^e - c_{ij}^0 \]  

(1)

\( \Delta c_{ij}^e \) is the increase in travel distance from origin \( i \) to destination \( j \), when link \( e \) fails [km]

\( c_{ij}^e \) is the travel distance from origin \( i \) to destination \( j \) when, when link \( e \) fails [km]

\( c_{ij}^0 \) is the travel distance from origin \( i \) to destination \( j \) under normal condition [km]

However, measuring only the delay caused by the detour may not be adequate. The importance of the link should also be measured in ways that allow one to understand how many road users are waiting for supply and for how long. If the failure of the link would cause a large delay to a very large number of people, then the link should be given a higher priority. In order to integrate this issue, the previous delay was multiplied by the number of road users waiting on supply from each petrol station. The importance of link \( e \) becomes:

\[ I_e = \frac{\sum_i \sum_{j \neq i} \Delta c_{ij}^e D_{ij}}{\sum_i \sum_{j \neq i} D_{ij}} \]  

(2)

Where,

- \( I_e \) is the importance level of link \( e \)
- \( D_{ij} \) is the amount of goods transported from origin \( i \) and destination \( j \)

Where the delivery relies only on a single road, the petrol station will become inaccessible when the access road fails. Thus, the unsatisfied demand should be measured as having a larger impact. Here, a penalty of an equal distance of 72 hours of travel was applied to the link that causes unsatisfied demand. To identify the level of vulnerability of the link, the probability of disruption of each link was integrated via the formulation shown in Equation (3). The possibility and level of damage will vary by the intensity of the disaster and the strength of the road structure itself. A failure probability calculated based on the historical road failure in the past disasters at each location can be applied. The estimation of road failure probability is discussed in the next section.

\[ V_e = P_e \frac{\sum_i \sum_{j \neq i} \Delta c_{ij}^e D_{ij}}{\sum_i \sum_{j \neq i} D_{ij}} \]  

(3)

Where,

- \( V_e \) is the vulnerability level of link \( e \)
- \( P_e \) is the probability of failure of link \( e \)

2.4 Road Failure Probability

The rate of link failure can be estimated based on historical road closure data for the period 2009-2014, which included severe flooding in far north Queensland every year, and major events in central and south-eastern Queensland in 2010/11 and 2013. Here, only a closure of more than 3 days was considered since, based on industry partner sources, the storage of fuel at petrol stations is generally at least 3 days regular supply. The failure
probability of each link was calculated using the following equation:

\[ P_{ij} = 1 - e^{-\lambda d} \]  

(4)

Where, \( P_{ij} \) is the failure probability of link \( ij \), \( \lambda \) is the rate of failure of link \( ij \) for more than 3 days [times/month], and \( d \) is time duration [month]. \( d \) is equal to one for the monthly failure probability.

Estimated link failure probability is shown in Figure 5. The value indicates the probability that each link will be closed for more than 3 days at least once in a month. The links are divided into 3 groups according to the estimated probability: blue ranges from 0-20%, orange from 20%-50%, and red from 50%-80%. These values are to be used in the evaluation of link importance and vulnerability as discussed previously.

Figure 5 Monthly link failure probabilities
3. Results

3.1 Estimation of the 2010-11 Flood Impact

The 2011 GIS flood extent was overlaid on the road network and the locations of petroleum depots and petrol stations. Road closure data for the period of the floods was checked to ground-truth this approach. Figure 6 shows the locations of flooded roads, petrol stations, and petroleum depots. Although other petrol stations were not flooded, some petrol stations were cut-off due to flooded roads and were inaccessible for the delivery of petroleum products. All the ‘inaccessible’ petrol stations and petroleum depots and ‘flooded’ petrol stations and petroleum depots due to the 2011 flood are shown in Figure 6.

Figure 6 Flooded and Inaccessible Petrol Stations and Fuel Depots due to Road Closure
Table 1: Flooded Impact on Petrol Demand

<table>
<thead>
<tr>
<th>Petrol Stations</th>
<th>#Cars</th>
<th>7 days (1000 Liters)</th>
<th>14 days (1000 Liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Petrol</td>
<td>Diesel</td>
</tr>
<tr>
<td>Flooded</td>
<td>26</td>
<td>107,403</td>
<td>1,801</td>
</tr>
<tr>
<td>Inaccessible</td>
<td>110</td>
<td>473,648</td>
<td>7,940</td>
</tr>
<tr>
<td>Total</td>
<td>136</td>
<td>581,051</td>
<td>9,741</td>
</tr>
</tbody>
</table>

From the analysis we estimate 26 petrol stations were in ‘flooded’ locations and 110 petrol stations became inaccessible (using our definitions) for resupply of petroleum fuels. Table 1 summarizes the impact of the 2011 flood on petroleum fuel demand. As 136 petrol stations were flooded or became inaccessible, we estimate around 580,000 vehicles were impacted. These vehicles would have required around 9.7 million, 5.1 million, and 0.6 million liters of Petrol, Diesel, and LPG respectively for 7 days, and 19 million, 10 million, and 1.2 million liters of Petrol, Diesel, and LPG respectively for 14 days.

If 580,000 impacted vehicles had to find new petrol stations instead of the flooded or inaccessible ones, and assuming they travel to their nearest ‘available’ petrol station, Figure 7 shows the increase in demand of petroleum fuel at each of the accessible petrol stations in South-East Queensland, where over 70 per cent of Queensland’s population resides. In order to avoid confusion, this figure shows only the petrol stations expected to have more customers.

Similarly, the accessibility from petroleum depots to petrol stations is also impacted by flooding. Two depots were either in flooded locations or inaccessible; forcing impacted petrol stations to find new supply depots, or to seek supply from the nearest available supply depots regardless of the brand owner. As a result, some depots receive more demand during such an event. Figure 8 shows the increased requirement of petroleum fuel demand at each of the accessible depots estimated by our methods. Similarly, only the depots expected as having more demand are presented. Based on the analysis results, in many locations in South-East Queensland, petroleum depots would potentially need to increase their fuel supplies by 80% of the expected increased demand as a countermeasure.
3.2 Vulnerability of fuel supply

Next, key road links were analyzed for the impact of its closure on the fuel demand, for different periods of time, to test system vulnerabilities under possible flooding scenarios. A focus was placed on the key north-south highways shown in historical data to be regularly closed by flooding events, or that have major impacts during less frequent events. This includes the Bruce Highway as well as inland routes. Links were closed one by one and in combination, recognizing that single link-removal analyses are limited (Demirel et al. 2015). We sought the amount of demand expected to be impacted by the closure. The analysis results calculated using Equation (2) are presented in Figure 9. The thicker red links indicate the higher importance of the link on the fuel supply chain. The results indicate that the Cape York area in far north Queensland is dependent on a single access link with major vulnerabilities. In addition, the Bruce highway along the coast line is a crucial link for the petroleum fuel supply chain, with some key vulnerabilities.

When adjusting the link importance with the failure probability using Equation (3), we obtain the results shown in Figure 10. The links which are both important for supply and likely to be disrupted are presented in the thicker red lines. Similar to the previous result, the road in far north Queensland and some sections of Bruce highway have a high vulnerability considering the historical failure. These links will need to be improved in order to prevent supply shortage for large regions of the state. Though Cape York is sparsely populated, cuts to the Bruce Highway in central Queensland can have much more greater impact on populations.
Figure 9 Link importance to fuel supplies
4. Conclusion

The results show this approach and methods for exploring vulnerability to petroleum supplies in the aftermath of disasters at the provincial/regional scale are feasible. The methods not only assess vulnerability of the entire system, harnessing both demand and supply-side factors, but they produce mapping outputs that are useful to government and industry in terms of identifying vulnerabilities and moving forward with investment and management strategies.
that may reduce vulnerability and increase resilience. This is the first such assessment for an Australian state region, and it highlights the many vulnerabilities that are at play in the (particularly) disaster-prone state of Queensland.

However, being the first attempt at this approach using an Australian dataset, there are a number of limitations. Firstly, resource and data constraints meant we could only look at one mode, and one commodity. A more holistic vulnerability assessment would include key commodities that may need to flow in to affected communities following a disaster (i.e. potable water, foodstuffs, equipment and personnel, as well as fuels) plus the commodities that need to flow out, such as perishable agricultural produce that will otherwise spoil.

Secondly, we did not incorporate four-stage modelling to look at changes in travel times or transport costs. And through we drew on historical flooding data more expansive probability modelling would assist for those seeking to build up a better representation of flooding risk. A well-resourced research effort could go on to explore this more multi-dimensional problem.

Thirdly, commodity flow data is extremely poor in Australia compared to nations where national census of logistics flows occur, such as Japan, or where taxation of goods requires capture of such data. This evaluation method can be applied to other types of commodities but this requires commodity flow information at disaggregate levels, for which Australia has very little publicly available data. Our interest moving forward is looking at cash crops with limited shelf-life such as bananas which are an important agricultural commodity in Northern Queensland.

Next, we did not seek to take the analysis further to consider what would be required to make use of real-time flood sensor data to make it useful for disaster logistics response, but a more refined and expanded framework such as this could conceivably reach that point. Preliminary assessment suggests that this is a long way from being feasible, but the potential is certainly there. An entire sequence of models is required to transform a projected flood event into longer lead times for freight forwarding, and more effective response. Without effective commodity flow models, however, which are just not possible in Australia except perhaps within the tight confines of private industry for parts of the system, any response triggered by flood sensor levels will be sub-optimal. A set of more rudimentary preparedness settings based on likely disaster impact models are likely to have more value for both industry and government in the meantime. As such, systematic disaster impact forecasting and improved vulnerability assessments for road and for rail networks remain the priority.

Finally, some possible flood countermeasures can be suggested with links identified as both highly importance and vulnerable to fuel supply receiving a higher priority. Countermeasures may include raising or strengthening road structures against flooding, using water blockades including automatic blocks on road, installing anti-scouring measures for bridges, and armorizing road and bridge abutments with rubble or rip-rap. In addition, in some regions such as far north Queensland, the fuel supply relies upon a single link which causes the link to be particularly vulnerable, although the failure probability of the link might not be very high. Increasing redundant links to the region may be a viable countermeasure to reduce the importance of a single link. The petrol stations or petroleum depots located in the vulnerable area should also be prepared for sudden increased demand after a disaster such as increasing supply storage to provide for increased durations after flooding events.

References

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