

# A Perfect Storm? The collapse of Lancaster's critical infrastructure networks following intense rainfall on 4th/5th in December 2015

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**A Perfect Storm? The collapse of Lancaster's critical infrastructure networks following intense rainfall on 4th/5th in December 2015**

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**Title:**

A Perfect Storm? The collapse of Lancaster's critical infrastructure networks following intense rainfall on 4<sup>th</sup>/5<sup>th</sup> in December 2015

**Authors:**

Emma Ferranti, Lee Chapman, Duncan Whyatt

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**Running head:**

Impact of Storm Desmond on Lancaster

**Abstract:**

On the 4<sup>th</sup> and 5<sup>th</sup> December 2015 a slow moving frontal system associated with the extratropical cyclone Storm Desmond brought record-breaking levels of rainfall to Lancaster. Both high ground and low-lying areas were already saturated following the wettest November on record and on the evening of the 5<sup>th</sup> December the River Lune flooded into the city. Critical road and rail transport networks ground to a halt and the city and the surrounding areas were left without mains power for two days after a key substation flooded, consequentially leaving the majority of communication services inoperable. Was this a 'Perfect Storm', or a glimpse of what the future may hold for our cities as they face more frequent extreme weather events, set against the backdrop of urban population growth, and increasingly interdependent critical urban infrastructure systems?

### Meteorological background

Lancaster is located approximately 5 km inland from Morecambe Bay on the coast of northwest England (Figure 1a) and is exposed to the prevailing south-westerly winds that bring mild, moist air from across the Atlantic Ocean. Daily observations have been made continuously at the Lancaster University weather station at Hazelrigg since 1976 and the annual average rainfall is 1,108 mm (1981-2010), with an average of 205 wet days per year (BADC, 2016). However, on the 4<sup>th</sup> and 5<sup>th</sup> December 2015 (09:00 04/12/2015 – 09:00 06/12/2015), a two-day rainfall total of 82 mm was recorded. This is the highest two-day value in the station history, and the rainfall amount of 60 mm which fell between 09:00 GMT on the 5<sup>th</sup> December and 09:00 GMT on the 6<sup>th</sup> December is the second highest on record (the highest being 8<sup>th</sup> December 1983; 69 mm). This record-breaking two day event followed the wettest November on record at Hazelrigg which had more than twice the monthly average rainfall (250 mm; 213% of average), and also marked the end of an exceptionally wet five-week period that contained only five dry days (Figure 2a).

Regionally, November 2015 was also an exceptionally wet month in northwest England with Lancashire and the Pennine hills receiving more than twice the 1981-2010 monthly average rainfall (Met Office, 2015). Indeed it was fourth wettest November in 200 years (Wilby & Barker, 2016). This above average rainfall caused the soils in many regional catchments including the Lune (Figure 1b) to be saturated by the beginning of December, therefore reducing their capacity to store rainfall. The two-day rainfall event on the 4<sup>th</sup>/5<sup>th</sup> December led to exceptional flow levels on the River Lune, with a new peak flow record of 1,700 cubic metres per second being recorded at the Lune gauging station in Caton (Figure 1), where records date from 1968 (Barker et al., 2016). Similar amounts were measured on the Rivers Eden and Tyne and these are the highest ever flows recorded in England and Wales (Parry et al., 2016). For comparison, Figure 2b shows rainfall from the gauge at Orton in the upper Lune Catchment (Figure 1), where there was only one dry day recorded in November 2015. A two-day rainfall total of 233 mm was recorded at Orton on the 4<sup>th</sup> and 5<sup>th</sup> December 2015 (09:00 04/12/2015 – 09:00 06/12/2015); the annual average rainfall at Orton is 1,568 (1981-2010; BADC, 2016).

### Flooding 5<sup>th</sup>/6<sup>th</sup> December

In many parts of the city the persistent heavy rainfall overwhelmed the surface drainage networks, including the new underground storm water drains located by the bus station and completed in March 2015, causing significant levels of surface run off and localised flooding. Business and residential properties were flooded along the east bank of the Lune from St George's Quay and the one-way system around the Bus Station and Cable Street, through to the Lake Enterprise Business Park, the Lansil Industrial Estate (Figures 3 and 4), and the Holiday Inn hotel opposite Junction 34 of the M6 motorway (Figure 1a). Road transport was severely disrupted: the one-way system, the key route round Lancaster city centre by bus and car was forced to close due to flooding in several locations (e.g. Figure 3: Cable Street, E, C, L; Figure 4), including around the bus station where flood waters reached over 1 metre in depth. The slip road exits to the M6 at junction 34 were closed due to flooding (Figure 1a), and the Greyhound and Skerton bridges (Figure 3: D, G) over the River Lune were closed as a precaution after they were struck by a shipping container and other debris floating down the river during the high water levels (Lancaster City Council, 2016). The Lune bridges connect

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3 south Lancaster with north Lancaster and Morecambe; their closure, combined with the closure of  
4 M6 Junction 34 and flooding on local roads meant detours in the order of tens of miles just to cross  
5 the river (Figure 1a). It also meant the Rest Centre created for use by local inhabitants and operated  
6 by Lancaster City Council at Salt Ayre Sports Centre in North Lancaster was accessible only to those  
7 living north of the river.  
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### 10 11 12 **Power Outage 5<sup>th</sup> – 7<sup>th</sup> December** 13

14 However, the most devastating impact of the heavy rainfall occurred at approximately 22:30 on 5<sup>th</sup>  
15 December. Despite pumps, sand bags, extra emergency pumps, and the new defences built in 2007  
16 and designed to withstand a 1-in-100 flood event, floodwater entered a major electricity substation  
17 on Caton Road (Figure 4). The flooding of the substation led to a power outage in approximately  
18 61,000 homes in Lancaster and the neighbouring towns of Carnforth and Morecambe (Figure 1a).  
19 Flood waters inside the substation reached over 1 metre in height, restricting access for the  
20 maintenance teams until the water receded. The power outage on the Lancaster grid lasted from  
21 approximately 22:30 on Friday 5<sup>th</sup> December until 04:40 on Monday 7<sup>th</sup> December when emergency  
22 generators that were brought in to temporarily restore power could be connected (Lancaster City  
23 Council, 2016). At 16:00 on Monday there was another power cut to 45,000 homes lasting overnight;  
24 the power supply was then maintained via generators until the Lancaster grid was reconnected back  
25 to the mains supply later in the week.  
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30 The absence of electricity for over 30 hours led to a secondary wave of infrastructure failures and  
31 widespread disruption across Lancaster and the surrounding area (Figure 5). For example, without  
32 electricity to power routers and modems there was no home or public Internet services. Mobile  
33 phones were also inoperable; the base stations that transmit radio signals to and from mobile  
34 handsets and the wider telephone network require electricity and there was no back-up power  
35 source. Only landline phones using traditional (non-electric) handsets were operable, leading to long  
36 queues to use the public payphones in Lancaster. Without access to modern communication services  
37 such as the Internet, texting, emailing and social media, the residents of Lancaster relied on local  
38 radio services such as The Bay for information, who themselves were operating out of a makeshift  
39 upstairs office powered by a generator after their ground floor studio had flooded. By using their  
40 landline and sending a reporter to an area unaffected by the power outage they were able to  
41 broadcast updates provided by the emergency services and also infrastructure operators and owners  
42 such as Electricity Northwest and Highways England. For many residents of Lancaster, this was the  
43 main (and often only) source of updates and information. This loss of digital communications was  
44 traumatic for many in the local community, especially where family and friends could not check  
45 upon each other's safety (Lancaster City Council, 2016). The number of public payphones in the UK  
46 has rapidly declined in recent years due to a reduction in their usage however the loss of modern  
47 communication services during the power outage clearly demonstrates the importance of having an  
48 alternative to mobile phones for telecommunication.  
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54 Those roads unaffected by flooding were affected by power loss for there were no street lights or  
55 traffic lights at major junctions, and fuel was unavailable from station forecourts as there was no  
56 electricity to power the pumps. There were very few trains on the West Coast Mainline due to  
57 flooding along different sections of the track, particularly further north near Carlisle, and trains could  
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3 only stop in Lancaster during daylight hours because there was no power at Lancaster Railway  
4 Station. The Royal Lancaster Infirmary and Morecambe Queen Victoria Hospital remained  
5 operational via their own diesel generators, but all routine outpatient appointments and non-urgent  
6 surgeries were cancelled, and military and mountain rescue teams helped transport staff to and  
7 from work on the flooded roads. On the 6<sup>th</sup> December Lancaster University made the decision to end  
8 term a week early and cancelled all lectures and exams. The students were advised to go home and  
9 free buses were organised to take people to Preston Bus Station as there was little public transport  
10 operational in Lancaster. Local schools were closed for two to three days which impacted not only  
11 the children, but also their parents and carers who needed to reorganise their work commitments.  
12 Vulnerable communities or those people that required the highest level of support were most  
13 impacted by the power loss. For example, many elderly or chronically ill people are supported by the  
14 health services within their own homes. Without power, essential home support systems such as  
15 personal alarms, stair lifts, oxygen therapy machines, or dialysis machines could not work (Kemp,  
16 2016). With many communication services down, it was more difficult for carers to contact the  
17 people they needed to support. The homeless community felt particularly vulnerable in a city  
18 without lights; those with no fixed abode depend particularly on their mobile phones to contact  
19 others, and to receive regular information (Kemp, 2016).  
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### 27 **A Perfect Storm?**

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29 There were no fatalities directly associated with the rainfall on 4<sup>th</sup>/5<sup>th</sup> December or the  
30 consequential power loss, but over the two day period Lancashire Fire and Rescue Service received  
31 450 calls, and attended 350 incidents; 163 properties were flooded and 2 bridges were closed (LFRS,  
32 2016). Figure 5 depicts the impact of the two-day rainfall event on Lancaster's infrastructure. All  
33 critical infrastructure networks – road, rail, electric, communication, emergency services, and water  
34 supply, were affected either directly by flooding, or indirectly by the failure of the substation on  
35 Caton Road.  
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39 So was this a 'Perfect Storm'? The two-day rainfall total from 4<sup>th</sup>/5<sup>th</sup> December is remarkable within  
40 the 40 year record from Hazelrigg. However, this rainfall event in isolation did not cause the flooding  
41 of Lancaster; instead it was the combination of heavy rainfall following the wettest November on  
42 record that led to the record-breaking flows on the Lune, which in turn were exacerbated by an  
43 incoming tide. Could this combination of events that led to the collapse of Lancaster's critical  
44 infrastructure happen again? Various metrics of winter rainfall have all consistently shown an  
45 increasing trend in observational data in the winter in northern and western areas (Burt & Ferranti,  
46 2012; Jones et al., 2013; Maraun et al., 2008; Osborn et al., 2000). Moreover, extreme rainfall events  
47 are expected to become increasingly frequent in a future warmer climate (Fowler & Ekström, 2009;  
48 Jenkins et al., 2009); indeed climate change is probably making precipitation events like Storm  
49 Desmond about 40 % more likely (van Oldenborgh et al., 2015). Looking regionally, Lancaster was  
50 not the only city to suffer major flooding in December 2015: other towns, villages and cities across  
51 Lancashire, Cumbria, Northumberland and South Scotland were also impacted on 5<sup>th</sup>/6<sup>th</sup> December.  
52 Later in the month the rainfall associated with a low pressure system following Storm Eva led to  
53 flooding in Lancashire, West Yorkshire and Greater Manchester on Boxing Day; and Storm Frank  
54 caused flooding predominantly in Scotland at the end the year. In each case, flooding resulted not  
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3 just from a heavy rainfall event, but from heavy rainfall falling on saturated land that had little  
4 capacity to store any further moisture. Parallels can also be drawn with 2013/2014, considered to be  
5 the 'stormiest winter in 143 years' (Matthews et al., 2014) where successive low pressure systems  
6 caused many catchments to be saturated by mid-December. Subsequent rainfall triggered tidal  
7 surges, high flow levels on major rivers including the Thames, extensive floodplain inundations, and  
8 flooding in southern England (Huntingford et al., 2014; Slingo et al., 2014).  
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### 11 12 13 **Flood risk management**

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15 It therefore seems reasonable that prolonged wet periods combined with heavy rainfall events will  
16 happen again in the future. As such the focus needs to be on ameliorating the impact that they may  
17 have on urban areas and their critical infrastructure. Following the flooding in December 2015 new  
18 flood defences have been proposed along the east bank of the Lune between the M6 motorway and  
19 Skerton Bridge (Figure 1a and 3). Funding is not assured, and although the details are still being  
20 developed it is likely the defences would be an enhancement of the flood embankment, or flood  
21 walls. Hard, 'grey' defences such as these form the cornerstone of traditional flood management  
22 (Environment Agency, 2009). They are designed to withstand a specific flood-risk, such as the 1-in-  
23 100 event, and are often used to protect businesses and properties in urban areas. Other grey flood  
24 defences in Lancaster include the new underground storm water drains near the bus station which  
25 were completed in March 2015 (£18 million), and the 1-in-100 flood defences completed in 2007 to  
26 protect the substation on Caton Road. Both of these defences were overwhelmed on the 5<sup>th</sup>/6<sup>th</sup>  
27 December. Regionally, other new flood defences also designed to withstand 1-in-100 flood events  
28 also failed in December 2015 in Carlisle (£38 million; completed 2010), Cockermouth (£4.4 million;  
29 completed 2013), and Keswick (£6 million; completed 2012). Each of these defences were built to  
30 specifications drawn up following flooding events in the past decade, suggesting either that their  
31 design was insufficient or that there is a limit to the effectiveness of hard, 'grey', barrier defences.  
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37 In either case, alternative approaches to manage flood-risk are urgently needed to minimise the  
38 impact from the likelihood of future wet winters of successive storms. In Lancaster, the benefits of  
39 introducing more areas of green infrastructure should be explored. Green infrastructure, for  
40 example street trees, green roofs and walls, or parks, can reduce surface run off by increasing  
41 infiltration and also slowing down the rate at which rainfall reaches the ground via interception  
42 (Forest Research, 2010). Green roofs can significantly reduce the amount of surface run off  
43 (Mentens et al., 2006) and could be particularly effective along the east bank of the Lune or in  
44 Lancaster city centre where impervious surfaces dominate and there is limited opportunity for new  
45 parks or street trees. Reviewing the management of the rural Lune catchment upstream of Lancaster  
46 is also essential; working with natural processes, reforesting flood plain areas, and introducing other  
47 'soft-engineering' solutions such as log jams can significantly reduce the flood risk downstream by  
48 reducing surface run off and therefore reducing the amount and speed of water reaching urban  
49 areas (Dixon et al., 2016; Environment Agency, 2010).  
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### 55 56 **Systems-of-systems**

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3 Managing future flood risk is essential, but it is unrealistic to assume that new grey and green flood  
4 defences, and better upstream catchment management can entirely prevent flooding events in the  
5 future. Minimising the impact of future flooding is therefore equally important, and understanding  
6 the interdependencies between our infrastructure systems is central to this. Our infrastructure  
7 should not be considered as a series of disconnected assets, but instead a system-of-systems with  
8 cross-sectoral issues, challenges and interdependencies (Hall et al., 2013). For example, electric  
9 trains need an energy supply to operate; alternatively, a railway embankment may also act as a flood  
10 defence for farmland or urban areas. Where there are interconnected infrastructure systems there is  
11 the potential for a fault or failure to cascade across multiple infrastructure sectors. This is  
12 particularly true for urban areas which combine dense populations of people and highly-evolved,  
13 interdependent critical infrastructure (Chapman et al., 2013). The case of Lancaster exemplifies this;  
14 several critical infrastructure networks (electricity, communications, water supply) depended on one  
15 substation that was located in a floodplain (Figure 5). Had an alternative electricity supply for the  
16 Lancaster grid been available more rapidly, the period without power would have been shorter. If  
17 the base stations for the mobile phone network had an alternative power supply, communities  
18 affected by the flooding or power outage could have more readily accessed basic information such  
19 as the extent of the flooding, details on road closures or public transport networks, updates on the  
20 renewal of power supply, or advice on where food (especially hot food) and other provisions could  
21 be obtained. The case of Lancaster also clearly demonstrates our dependence on electricity and  
22 modern communication services; in the past a greater number of houses would have gas stoves or  
23 ovens, landline phones and analogue radios, thus reducing the impact of power loss at individual  
24 household level.  
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31 The case of Lancaster also shows how our infrastructure assets may now be used to provide a  
32 modern infrastructure service for which they were not necessarily designed. The location of  
33 Lancaster's electricity substation on the Lune floodplain is a legacy of Lancaster's industrial past, not  
34 modern best practice. The substation was built on the site of a former power station, in a historically  
35 industrial part of the city when the Lune was used for water transport and steam power (Kemp,  
36 2016). This is also similarly true of other road, rail, energy and communication infrastructure assets  
37 across the UK. For example, much of our railway infrastructure was built 100 years ago, and was not  
38 designed for the current levels of passengers and freight. Also on our railways, heat-sensitive  
39 modern telecommunication equipment is stored in poorly ventilated lineside boxes designed for  
40 older less heat-sensitive assets which can lead to heat-related failures even at relatively mild  
41 temperatures (Ferranti et al., 2016). In 2014 there was 36 million cars using the road network  
42 compared to 4.2 million in 1951 (DfT, 2016); road length has increased by only a third in the same  
43 time period and consequently 'hard shoulder running' and 'all lane running' are becoming  
44 increasingly used to increase capacity on critical sections of the GB motorway network. When our  
45 infrastructure is operating at or close to the maximum capacity it is more vulnerable to any issues  
46 that may arise.  
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### 53 **Forward look**

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56 The heavy rainfall on 4<sup>th</sup>/5<sup>th</sup> December and the subsequent impacts on Lancaster's critical  
57 infrastructure has shown how unexpectedly vulnerable our cities can be to extreme weather.  
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3 Lessons must be learned from the case of Lancaster in order to prevent similar cascade failures  
4 occurring in larger, more populous urban areas that would cause far greater impact and disruption.  
5 Across the UK, legacy infrastructure assets are used in a context or loading for which they were not  
6 designed. Moreover urbanisation is rapidly increasing, and by 2040, 67% of the world population  
7 and 86% of the UK population will live in towns or cities (United Nations, 2012). Moving forward, as  
8 extreme weather events become increasingly frequent under a future warmer climate, cross-  
9 disciplinary co-ordination and a systems-of-systems approach to infrastructure is imperative to limit  
10 cascade failures in order to build resilience to extreme weather in our urban areas (Hall et al., 2013;  
11 Royal Society, 2014). This holistic approach must include greater co-ordination and knowledge  
12 exchange between infrastructure operators, owners, and regulators, and must consider the more  
13 sustainable solutions that green (i.e. trees, grass roofs, catchment planting) and blue (sustainable  
14 water management) infrastructure offer to grey infrastructure problems such as urban drainage. The  
15 rainfall on the 4<sup>th</sup>/5<sup>th</sup> December was exceptional; rainfall totals across the upper Lune catchment  
16 were in the order of 100 to 200 mm or more, and the 24-hour (341.4 mm), and two rainfall days  
17 (405 mm) records for the UK were broken in Cumbria (Burt et al., 2016). However, this was no  
18 "Perfect Storm", but instead a harbinger of what the future may hold unless we build climate  
19 resilience in our urban areas.  
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28  
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35 potential for better blue-green-grey **InfrAsTructurE** (NE/N005325/1).  
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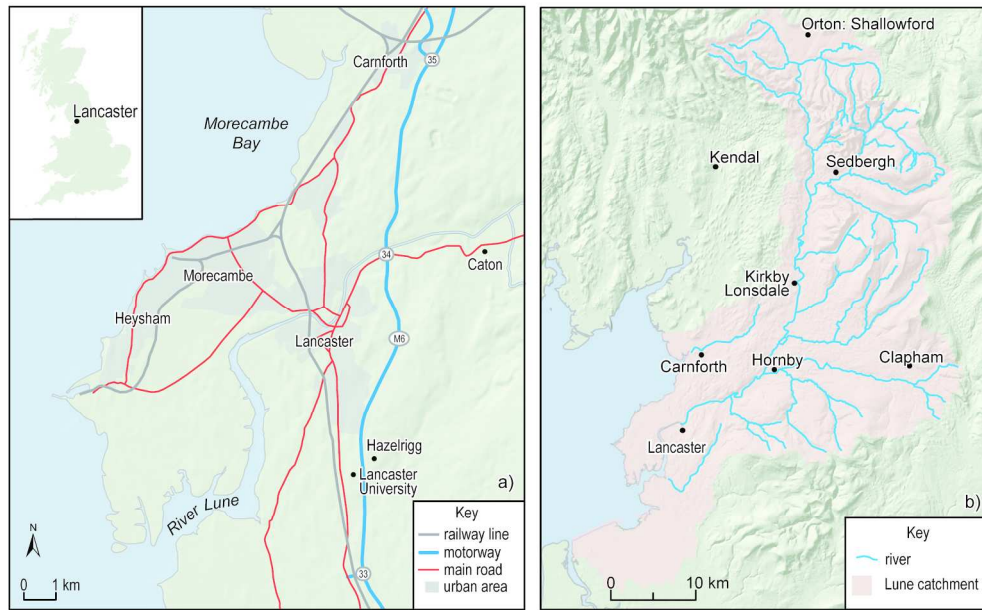


Figure 1: a) Lancaster and the surrounding area; and, b) the Lune catchment (983 km<sup>2</sup>).

197x122mm (300 x 300 DPI)

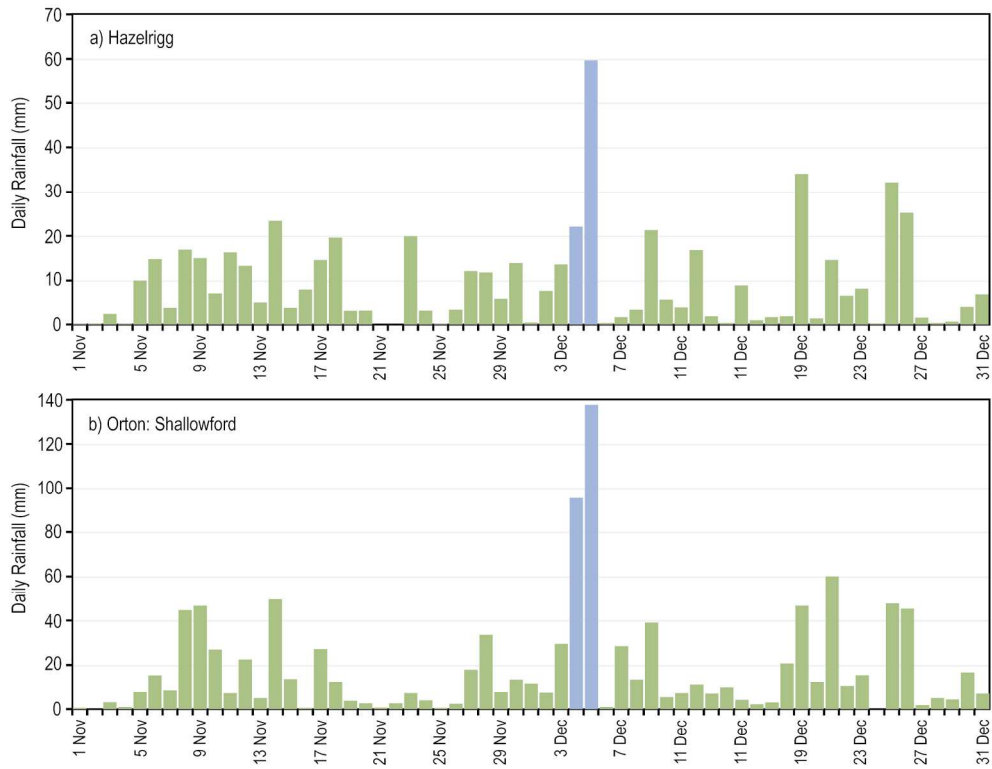


Figure 2: Daily rainfall amounts recorded at a) Hazelrigg, and b) Orton, in November and December 2015. The two-day rainfall event is highlighted in blue (Data from BADC, 2016) . Note the difference y-axis scales.

184x147mm (300 x 300 DPI)

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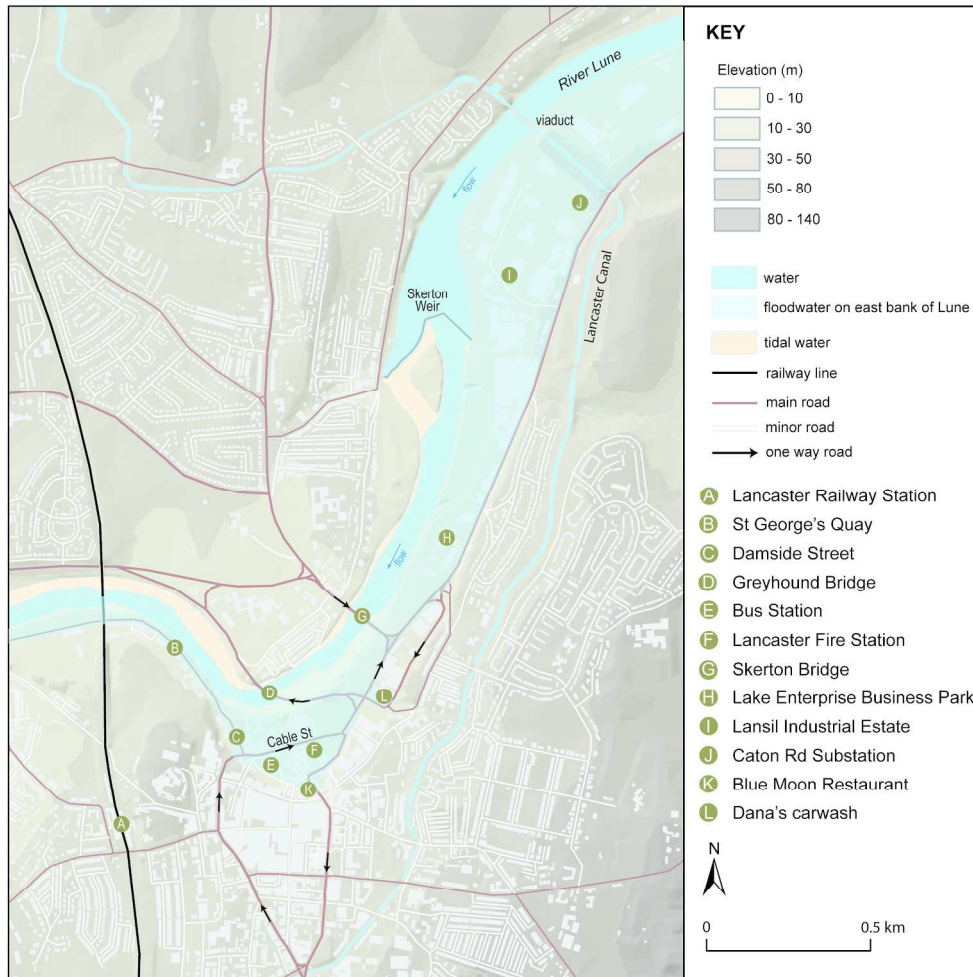


Figure 3: The River Lune and the centre of Lancaster. Places mentioned in the main text are shown by the letters A to L. The map was produced using data from EDINA Digimap Ordnance Survey Service (EDINA, 2015a, 2015b).

219x218mm (300 x 300 DPI)



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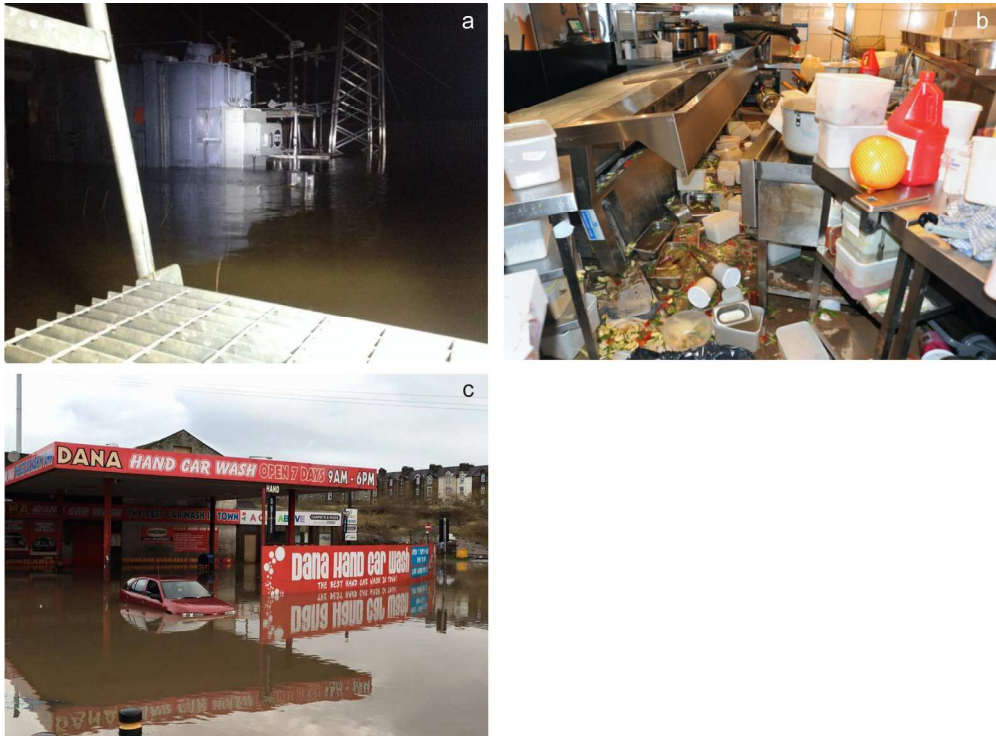


Figure 4: (a) The substation on Caton Rd at approximately 23:00 on 5th January (Electricity North West); (b) Flood damage to the Blue Moon Thai Restaurant (Lancaster Guardian) (Figure 3: K); (c) Flooding on the one way system (The Bay Radio Figure 3: L).

183x134mm (300 x 300 DPI)



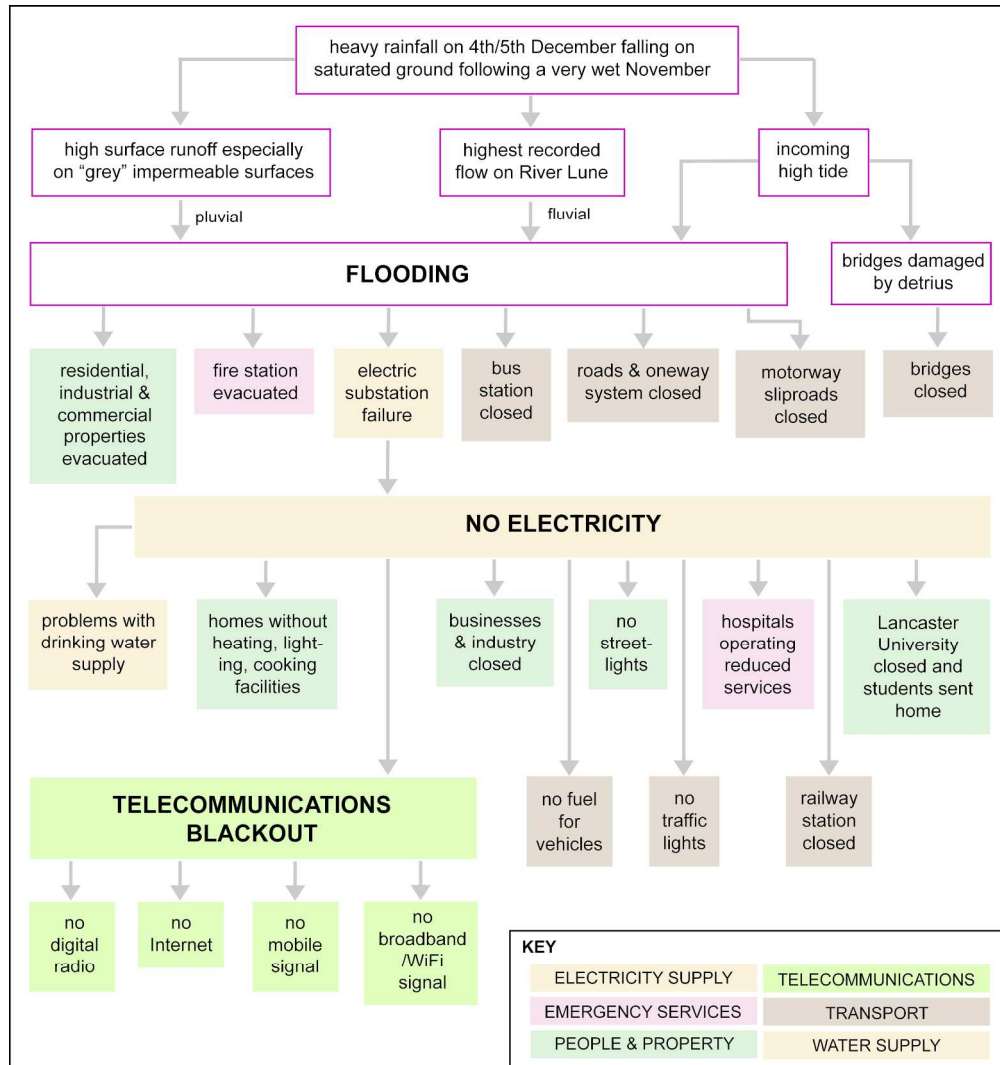


Figure 5: Flow chart summarising the collapse of Lancaster’s critical infrastructure networks following the heavy rainfall on 4th / 5th December 2016.

210x224mm (300 x 300 DPI)