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

Sakamoto Ferranti, Emma; Chapman, Lee; Whyatt, Duncan

DOI:
10.1002/wea.2907

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

Emma Ferranti, Lee Chapman, Duncan Whyatt
e.ferranti@bham.ac.uk

On the 4th and 5th 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 5th 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 1,120 mm, with an average of 205 wet days per year (1977-2016; BADC, 2016). However, on the 4th and 5th 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 5th December and 09:00 GMT on the 6th December is the second highest on record (the highest being 8th 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 4th/5th 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). 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.

Flooding 5th/6th December

eIn 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 south Lancaster with north Lancaster and Morecambe; their closure, combined with the closure of M6 Junction 34 and flooding on local roads meant detours in the order of tens of miles just to cross the river (Figure 1a). It also meant the Rest Centre created for use by local inhabitants and operated by Lancaster City Council at Salt Ayre Sports Centre in North Lancaster was accessible only to those living north of the river.

Power Outage 5th – 7th December

However, the most devastating impact of the heavy rainfall occurred at approximately 22:30 on 5th December. Despite pumps, sand bags, extra emergency pumps, and the new defences built in 2007 and designed to withstand a 1-in-100 flood event, floodwater entered a major electricity substation on Caton Road (Figure 4). The flooding of the substation led to a power outage in approximately 61,000 homes in Lancaster and the neighbouring towns of Carnforth and Morecambe (Figure 1a). Flood waters inside the substation reached over 1 metre in height, restricting access for the maintenance teams until the water receded. The power outage on the Lancaster grid lasted from approximately 22:30 on Friday 5th December until 04:40 on Monday 7th December when emergency generators that were brought in to temporarily restore power could be connected (Lancaster City Council, 2016). At 16:00 on Monday there was another power cut to 45,000 homes lasting overnight; the power supply was then maintained via generators until the Lancaster grid was reconnected back to the mains supply later in the week.

The absence of electricity for over 30 hours led to a secondary wave of infrastructure failures and widespread disruption across Lancaster and the surrounding area (Figure 5). For example, without electricity to power routers and modems there was no home or public Internet services. Mobile phones were also inoperable; the base stations that transmit radio signals to and from mobile handsets and the wider telephone network require electricity and there was no back-up power source. Only landline phones using traditional (non-electric) handsets were operable, leading to long queues to use the public payphones in Lancaster. Without access to modern communication services such as the Internet, texting, emailing and social media, the residents of Lancaster relied on local radio services such as The Bay for information, who themselves were operating out of a makeshift upstairs office powered by a generator after their ground floor studio had flooded. By using their landline and sending a reporter to an area unaffected by the power outage they were able to broadcast updates provided by the emergency services and also infrastructure operators and owners such as Electricity Northwest and Highways England. For many residents of Lancaster, this was the main (and often only) source of updates and information. This loss of digital communications was traumatic for many in the local community, especially where family and friends could not check upon each other's safety (Lancaster City Council, 2016). The number of public payphones in the UK has rapidly declined in recent years due to a reduction in their usage however the loss of modern communication services during the power outage clearly demonstrates the importance of having an alternative to mobile phones for telecommunication.

Those roads unaffected by flooding were affected by power loss for there were no street lights or traffic lights at major junctions, and fuel was unavailable from station forecourts as there was no electricity to power the pumps. There were very few trains on the West Coast Mainline due to flooding along different sections of the track, particularly further north near Carlisle, and trains could only stop in Lancaster during daylight hours because there was no power at Lancaster Railway Station. The Royal Lancaster Infirmary and Morecambe Queen Victoria Hospital remained operational via their own diesel generators, but all routine outpatient appointments and non-urgent surgeries were cancelled, and military and mountain rescue teams helped transport staff to and from work on the flooded roads. On the 6th December Lancaster University made the decision to end term a week early and cancelled all lectures and exams. The students were advised to go home and free buses were organised to take people to Preston Bus Station as there was little public transport operational in Lancaster. Local schools were closed for two to three days which impacted not only the children, but also their parents and carers who needed to reorganise their work commitments. Vulnerable communities or those people that required the highest level of support were most impacted by the power loss. For example, many elderly or chronically ill people are supported by the health services within their own homes. Without power, essential home support systems such as personal alarms, stair lifts, oxygen therapy machines, or dialysis machines could not work (Kemp, 2016). With many communication services down, it was more difficult for carers to contact the people they needed to support. The homeless community felt particularly vulnerable in a city without lights; those with no fixed abode depend particularly on their mobile phones to contact others, and to receive regular information (Kemp, 2016).

A Perfect Storm?

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

Flood risk management

It therefore seems reasonable that prolonged wet periods combined with heavy rainfall events will happen again in the future. As such the focus needs to be on ameliorating the impact that they may have on urban areas and their critical infrastructure. Following the flooding in December 2015 new flood defences have been proposed along the east bank of the Lune between the M6 motorway and Skerton Bridge (Figure 1a and 3). Funding is not assured, and although the details are still being developed it is likely the defences would be an enhancement of the flood embankment, or flood walls. Hard, 'grey' defences such as these form the cornerstone of traditional flood management (Environment Agency, 2009). They are designed to withstand a specific flood-risk, such as the 1-in-100 event, and are often used to protect businesses and properties in urban areas. Other grey flood defences in Lancaster include the new underground storm water drains near the bus station which were completed in March 2015 (£18 million), and the 1-in-100 flood defences completed in 2007 to protect the substation on Caton Road. Both of these defences were overwhelmed on the 5th/6th December. Regionally, other new flood defences also designed to withstand 1-in-100 flood events also failed in December 2015 in Carlisle (£38 million; completed 2010), Cockermouth (£4.4 million; completed 2013), and Keswick (£6 million; completed 2012). Each of these defences were built to specifications drawn up following flooding events in the past decade, suggesting either that their design was insufficient or that there is a limit to the effectiveness of hard, 'grey', barrier defences.

In either case, alternative approaches to manage flood-risk are urgently needed to minimise the impact from the likelihood of future wet winters of successive storms. In Lancaster, the benefits of introducing more areas of green infrastructure should be explored. Green infrastructure, for example street trees, green roofs and walls, or parks, can reduce surface run off by increasing infiltration and also slowing down the rate at which rainfall reaches the ground via interception (Forest Research, 2010). Green roofs can significantly reduce the amount of surface run off (Mentens et al., 2006) and could be particularly effective along the east bank of the Lune or in Lancaster city centre where impervious surfaces dominate and there is limited opportunity for new parks or street trees. Reviewing the management of the rural Lune catchment upstream of Lancaster is also essential; working with natural processes, reforesting flood plain areas, and introducing other 'soft-engineering' solutions such as log jams can significantly reduce the flood risk downstream by reducing surface run off and therefore reducing the amount and speed of water reaching urban areas (Dixon et al., 2016; Environment Agency, 2010).

Systems-of-systems

Managing future flood risk is essential, but it is unrealistic to assume that new grey and green flood defences, and better upstream catchment management can entirely prevent flooding events in the future. Minimising the impact of future flooding is therefore equally important, and understanding the interdependencies between our infrastructure systems is central to this. Our infrastructure should not be considered as a series of disconnected assets, but instead a system-of-systems with cross-sectoral issues, challenges and interdependencies (Hall et al., 2013). For example, electric trains need an energy supply to operate; alternatively, a railway embankment may also act as a flood defence for farmland or urban areas. Where there are interconnected infrastructure systems there is the potential for a fault or failure to cascade across multiple infrastructure sectors. This is particularly true for urban areas which combine dense populations of people and highly-evolved, interdependent critical infrastructure (Chapman et al., 2013). The case of Lancaster exemplifies this; several critical infrastructure networks (electricity, communications, water supply) depended on one substation that was located in a floodplain (Figure 5). Had an alternative electricity supply for the Lancaster grid been available more rapidly, the period without power would have been shorter. If the base stations for the mobile phone network had an alternative power supply, communities affected by the flooding or power outage could have more readily accessed basic information such as the extent of the flooding, details on road closures or public transport networks, updates on the renewal of power supply, or advice on where food (especially hot food) and other provisions could be obtained. The case of Lancaster also clearly demonstrates our dependence on electricity and modern communication services; in the past a greater number of houses would have gas stoves or ovens, landline phones and analogue radios, thus reducing the impact of power loss at individual household level.

The case of Lancaster also shows how our infrastructure assets may now be used to provide a modern infrastructure service for which they were not necessarily designed. The location of Lancaster's electricity substation on the Lune floodplain is a legacy of Lancaster's industrial past, not modern best practice. The substation was built on the site of a former power station, in a historically industrial part of the city when the Lune was used for water transport and steam power (Kemp, 2016). This is also similarly true of other road, rail, energy and communication infrastructure assets across the UK. For example, much of our railway infrastructure was built 100 years ago, and was not designed for the current levels of passengers and freight. Also on our railways, heat-sensitive modern telecommunication equipment is stored in poorly ventilated lineside boxes designed for older less heat-sensitive assets which can lead to heat-related failures even at relatively mild temperatures (Ferranti et al., 2016). In 2014 there was 36 million cars using the road network compared to 4.2 million in 1951 (DfT, 2016); road length has increased by only a third in the same time period and consequently 'hard shoulder running' and 'all lane running' are becoming increasingly used to increase capacity on critical sections of the GB motorway network. When our infrastructure is operating at or close to the maximum capacity it is more vulnerable to any issues that may arise.

Forward look

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

Acknowledgements

The authors are grateful to Lancaster City Council and Lancashire Fire and Rescue Service for providing information on the impacts of the heavy rainfall on 5th/6th December 2015, and also for the constructive comments provided by the reviewers. Meteorological data came from the Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current) available from the NCAS British Atmospheric Data Centre. This research was undertaken under the NERC-funded Knowledge Exchange Fellowship: **MEDIATE**: Overcoming barriers to **M**aximis**E** **D**ata potential for better blue-green-grey **I**nfr**A**s**T**ructur**E** (NE/N005325/1).

References

BADC. (2016). *UK Meteorological Office. Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current), [Internet].NCAS British Atmospheric Data Centre, 2012, Accessed 1 February 2016. [Available from http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas]*

Barker, L., Hannaford, J., & Parry, S. (2016). Briefing note. Severity of the December 2015 floods- preliminary analysis. http://www.ceh.ac.uk/news-and-media/blogs/briefing-note-severity-december-2015-floods-preliminary-analysis.

Burt, S., McCarthy, M., Kendon, M., & Hannaford, J. (2016). Cumbrian floods, 5/6 December 2015. *Weather, 71*(2), 36-37. doi:http://dx.doi.org/10.1002/wea.2704.

Burt, T. P., & Ferranti, E. J. S. (2012). Changing patterns of heavy rainfall in upland areas: a case study from northern England. *International Journal of Climatology, 32*(4), 518-532. doi:http://dx.doi.org/10.1002/joc.2287.

Chapman, L., Azevedo, J. A., & Prieto-Lopez, T. (2013). Urban heat & critical infrastructure networks: A viewpoint. *Urban Climate, 3*, 7-12. doi:http://dx.doi.org/10.1016/j.uclim.2013.04.001.

DfT. (2016). Road use statistics: 2016 report. Department for Transport, UK. https://www.gov.uk/government/statistics/road-use-statistics-2016.

Dixon, S. J., Sear, D. A., Odoni, N. A., Sykes, T., & Lane, S. N. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*. doi:http://dx.doi.org/10.1002/esp.3919.

EDINA. (2015a). OS Terrain 5 [ASC geospatial data], Scale 1:10000, Tiles: sd46se, Updated: 9 October 2015, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <http://digimap.edina.ac.uk>, Downloaded: 2016-02-01 11:32:52.214.

EDINA. (2015b). OS VectorMap® Local [SHAPE geospatial data], Scale 1:10000, Tiles: sd46se, Updated: 1 October 2015, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <http://digimap.edina.ac.uk>, Downloaded: 2016-02-01 11:32:52.214.

Environment Agency. (2009). Flooding in England: a national assessment of flood risk. Environment Agency, Bristol, UK. https://www.gov.uk/government/publications/flooding-in-england-national-assessment-of-flood-risk.

Environment Agency. (2010). Working with Natural Processes to Manage Flood and Coastal Erosion Risk. A Guidance Document – March 2010. EnvironAgency, Bristol, UK. . https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk-a-research-and-development-framework.

Ferranti, E., Chapman, L., Lowe, C., McCulloch, S., Jaroszweski, D., & Quinn, A. (2016). Heat-Related Failures on Southeast England's Railway Network: Insights and Implications for Heat Risk Management. *Weather, Climate, and Society, 8*(2), 177-191. doi:doi:10.1175/WCAS-D-15-0068.1. http://journals.ametsoc.org/doi/abs/10.1175/WCAS-D-15-0068.1.

Forest Research. (2010). Benefits of green infrastructure. Report by Forest Research. Forest Research, Farnham, UK.

http://www.forestry.gov.uk/pdf/urgp_benefits_of_green_infrastructure.pdf/$FILE/urgp_benefits_of_green_infrastructure.pdf.

Fowler, H. J., & Ekström, M. (2009). Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *International Journal of Climatology, 29*(3), 385-416. http://dx.doi.org/10.1002/joc.1827.

Hall, J. W., Henriques, J. J., Hickford, A. J., & Nicholls, R. J. (2013). Systems-of-systems analysis of national infrastructure. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability, 166*(5), 249-257. doi:http://www.icevirtuallibrary.com/doi/abs/10.1680/ensu.12.00028.

Huntingford, C., Marsh, T., Scaife, A. A., Kendon, E. J., Hannaford, J., Kay, A. L., . . . Parry, S. (2014). Potential influences on the United Kingdom's floods of winter 2013/14. *Nature Climate Change, 4*(9), 769-777. doi:http://dx.doi.org/10.1038/nclimate2314.

Jenkins, G. J., Perry, M. C., & Prior, M. J. (2009). The climate of the United Kingdom and recent trends. Met Office Hadley Centre, Exeter, UK. http://www.ukcip.org.uk/wp-content/PDFs/UKCP09_Trends.pdf.

Jones, M. R., Fowler, H. J., Kilsby, C. G., & Blenkinsop, S. (2013). An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *International Journal of Climatology, 33*(5), 1178-1194. doi:http://dx.doi.org/10.1002/joc.3503.

Kemp, R. (2016). Living without Electricity. Royal Academy of Engineering Report, May 2016. London, UK. www.raeng.org.uk/livingwithoutelectricity.

Lancaster City Council. (2016). The Impacts of Storm Desmond and Eva. Report of Chief Officers Regeneration and Planning/Health and Housing/Environment/Resources. 20th April 2016. https://committeeadmin.lancaster.gov.uk/ieListDocuments.aspx?CId=298&MId=6798&Ver=4.

LFRS. (2016). Dealing with Desmond - Experiences from the Front Line. Lancashire Fire and Rescue Service online video available at: https://www.youtube.com/watch?v=zkbB-DMgRPs [Accessed 4th August 2016]. -

Maraun, D., Osborn, T. J., & Gillett, N. P. (2008). United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006. *International Journal of Climatology, 28*(6), 833-842. doi:http://dx.doi.org/10.1002/joc.1672.

Matthews, T., Murphy, C., Wilby, R. L., & Harrigan, S. (2014). Stormiest winter on record for Ireland and UK. *Nature Climate Change, 4*(9), 738-740. doi:http://dx.doi.org/10.1038/nclimate2336.

Mentens, J., Raes, D., & Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning, 77*(3), 217-226. doi:http://dx.doi.org/10.1016/j.landurbplan.2005.02.010.

Met Office. (2015). UK actual and anomaly maps. Met Office, UK. http://www.metoffice.gov.uk/climate/uk/summaries/anomacts. [Accessed. 1 February 2016].

Osborn, T. J., Hulme, M., Jones, P. D., & Basnett, T. A. (2000). Observed trends in the daily intensity of United Kingdom precipitation. *International Journal of Climatology, 20*(4), 347-364. doi:http://dx.doi.org/10.1002/(SICI)1097-0088(20000330)20:4<347::AID-JOC475>3.0.CO;2-C.

Parry, S., Barker, L., Prosdocimi, I., Lewis, M., Hannaford, J., & Clemas, S. (2016). Hydrological summary for the United Kingdom: December 2015. Wallingford, UK, NERC/Centre for Ecology & Hydrology, 12pp. (CEH Project no. C04954). http://nora.nerc.ac.uk/512654/1/HS_201512%20v2.pdf.

Royal Society. (2014). Resilience to Extreme Weather. The Royal Society Science Policy Centre report 02/14 Issued: November 2014 DES3400. Royal Society, London. UK. https://royalsociety.org/~/media/policy/projects/resilience-climate-change/resilience-executive-summary.pdf.

Slingo, J., Belcher, S., Scaife, A., McCarthy, M., Saulter, A., McBeath, K., . . . Hannaford, J. (2014). The recent storms and floods in the UK. http://www.metoffice.gov.uk/research/news/2014/uk-storms-and-floods.

United Nations. (2012). World urbanization prospects: The 2011 revision. New York: United nations department of economic and social affairs/population division. *UN Proceedings*. http://www.un.org/en/development/desa/population/publications/pdf/urbanization/WUP2011_Report.pdf.

van Oldenborgh, G. J., Otto, F. E. L., Haustein, K., & Cullen, H. (2015). Climate change increases the probability of heavy rains like those of storm Desmond in the UK – an event attribution study in near-real time. *Hydrol. Earth Syst. Sci. Discuss., 2015*, 13197-13216. doi:10.5194/hessd-12-13197-2015. http://www.hydrol-earth-syst-sci-discuss.net/12/13197/2015/.

Wilby, R. L., & Barker, P. A. (2016). Wettest December in the Lake District for over 200 years. *Weather, 71*(3), 76-76. doi:http://dx.doi.org/10.1002/wea.2711.

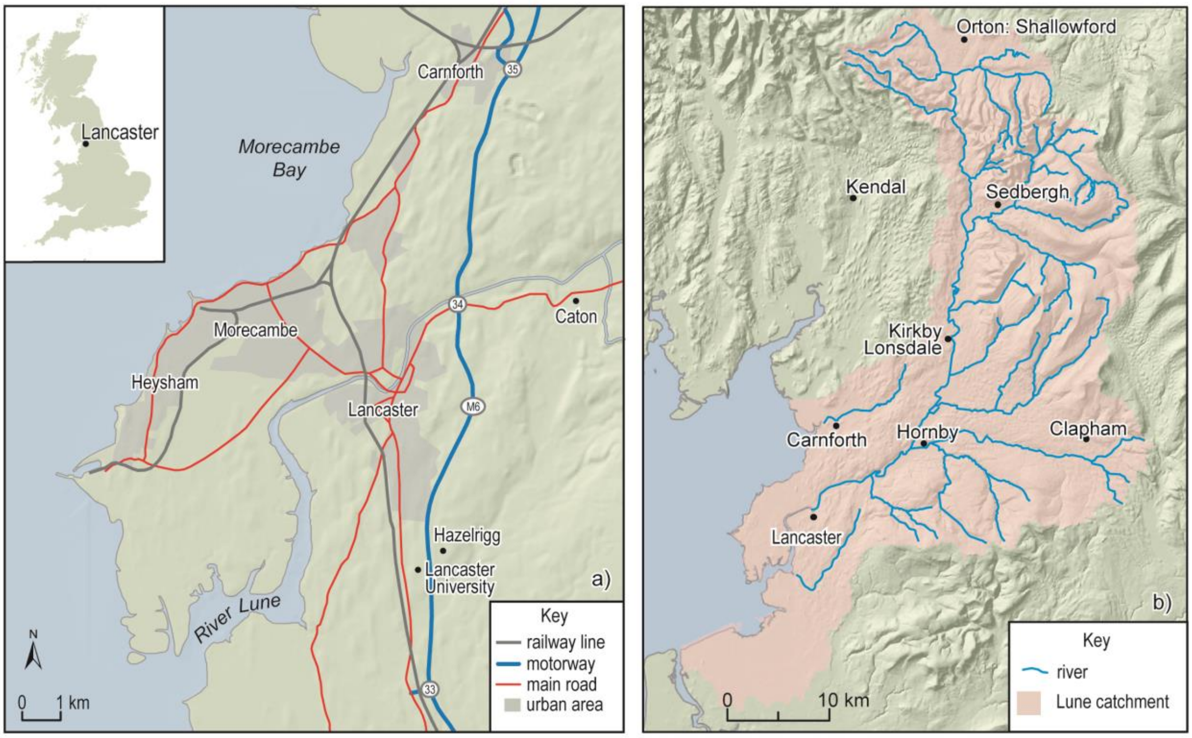

Figure 1: a) Lancaster and the surrounding area; and, b) the Lune catchment.

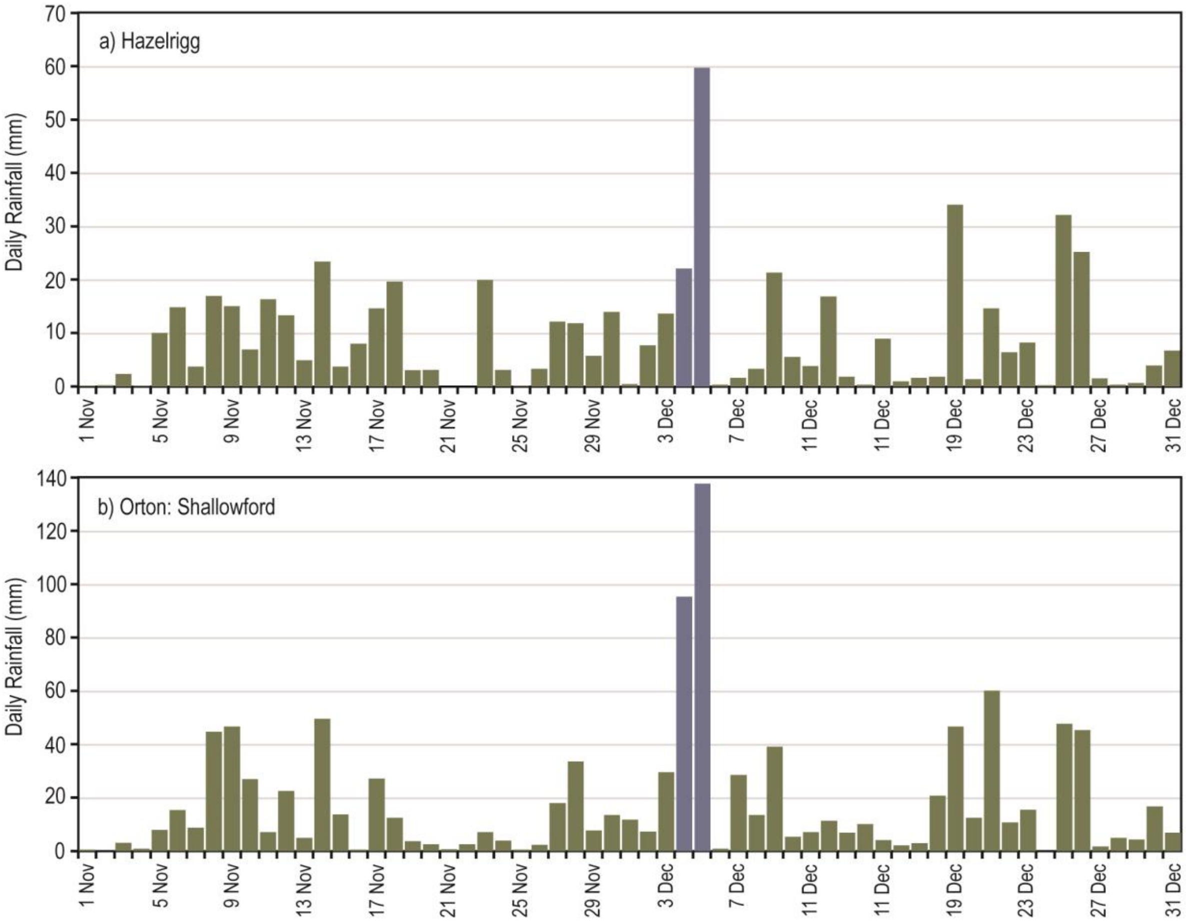

Figure 2: Daily rainfall amounts recorded at a) Hazelrigg, and b) Orton, in November and December 2015. The two-day rainfall event is highlighted in blue (Data from BADC, 2016)

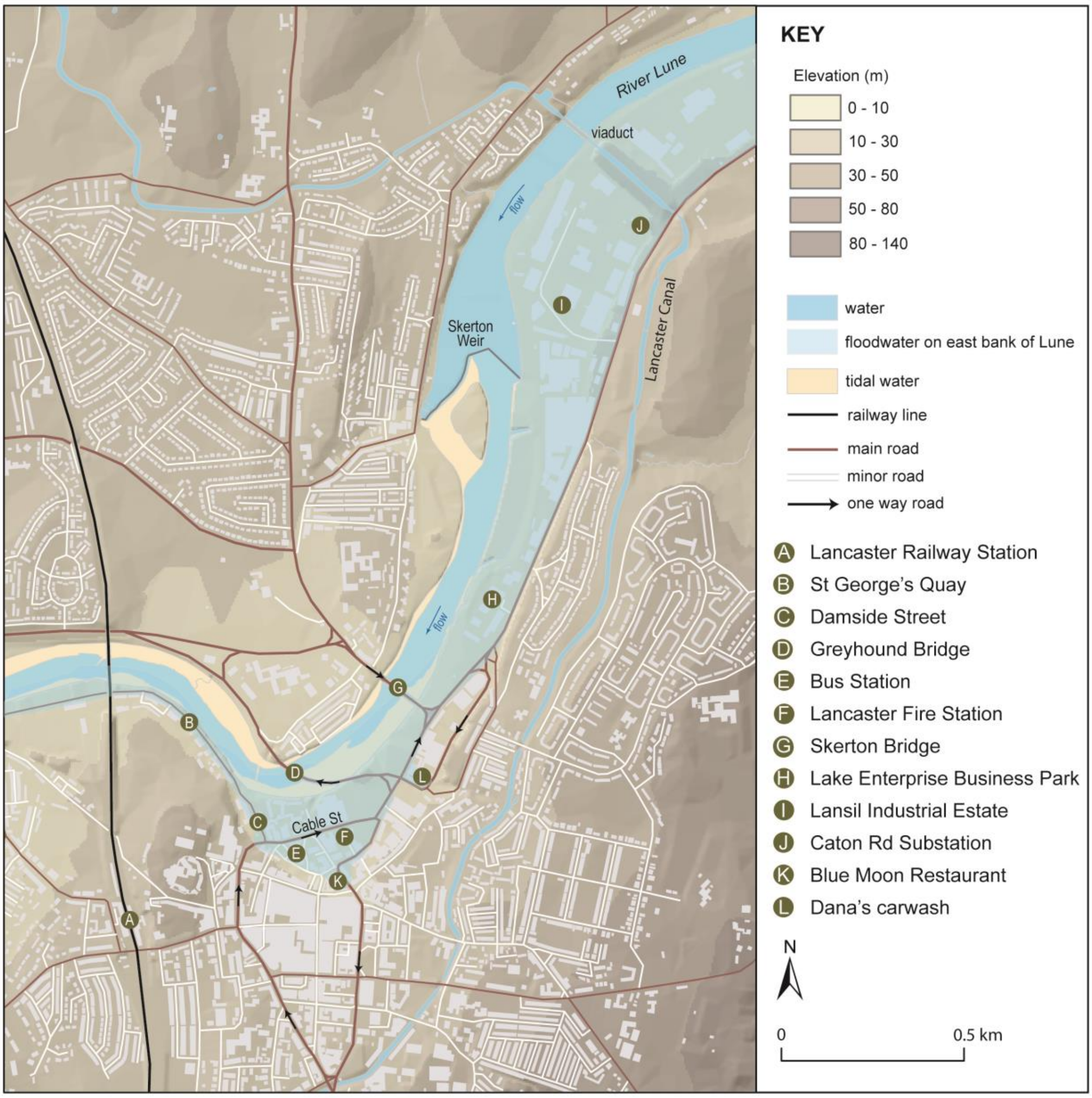

Figure 3: The River Lune and the centre of Lancaster. Places mentioned in the main text are shown by the letters A to L. The map was produced using data from EDINA Digimap Ordnance Survey Service (EDINA, 2015a, 2015b).

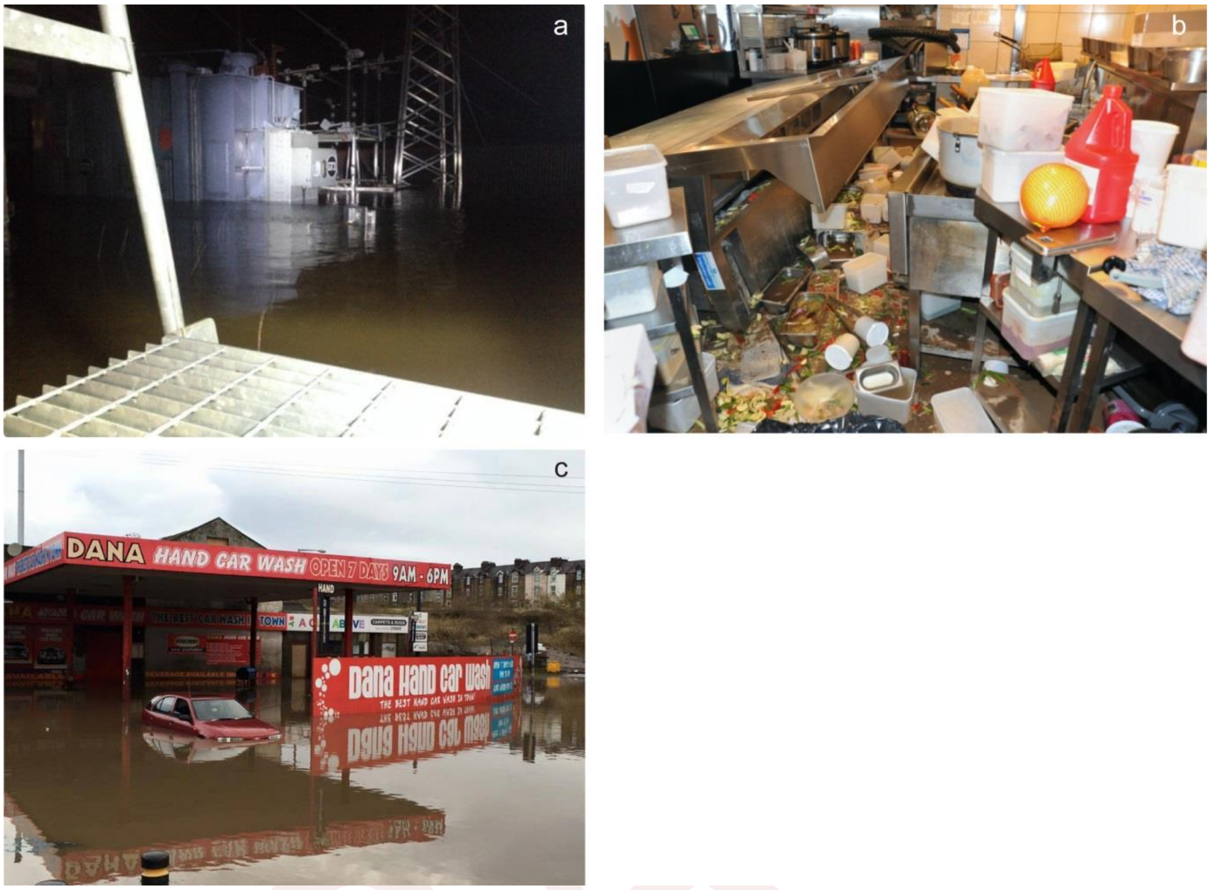

Figure 4: (a) The substation on Caton Rd at approximately 23:00 on 5th January (*Electricity North West*); (b) Flood damage to the Blue Moon Thai Restaurant (*Lancaster Guardian*) (Figure 3: K); (c) Flooding on the one way system (*The Bay Radio* Figure 3: L).

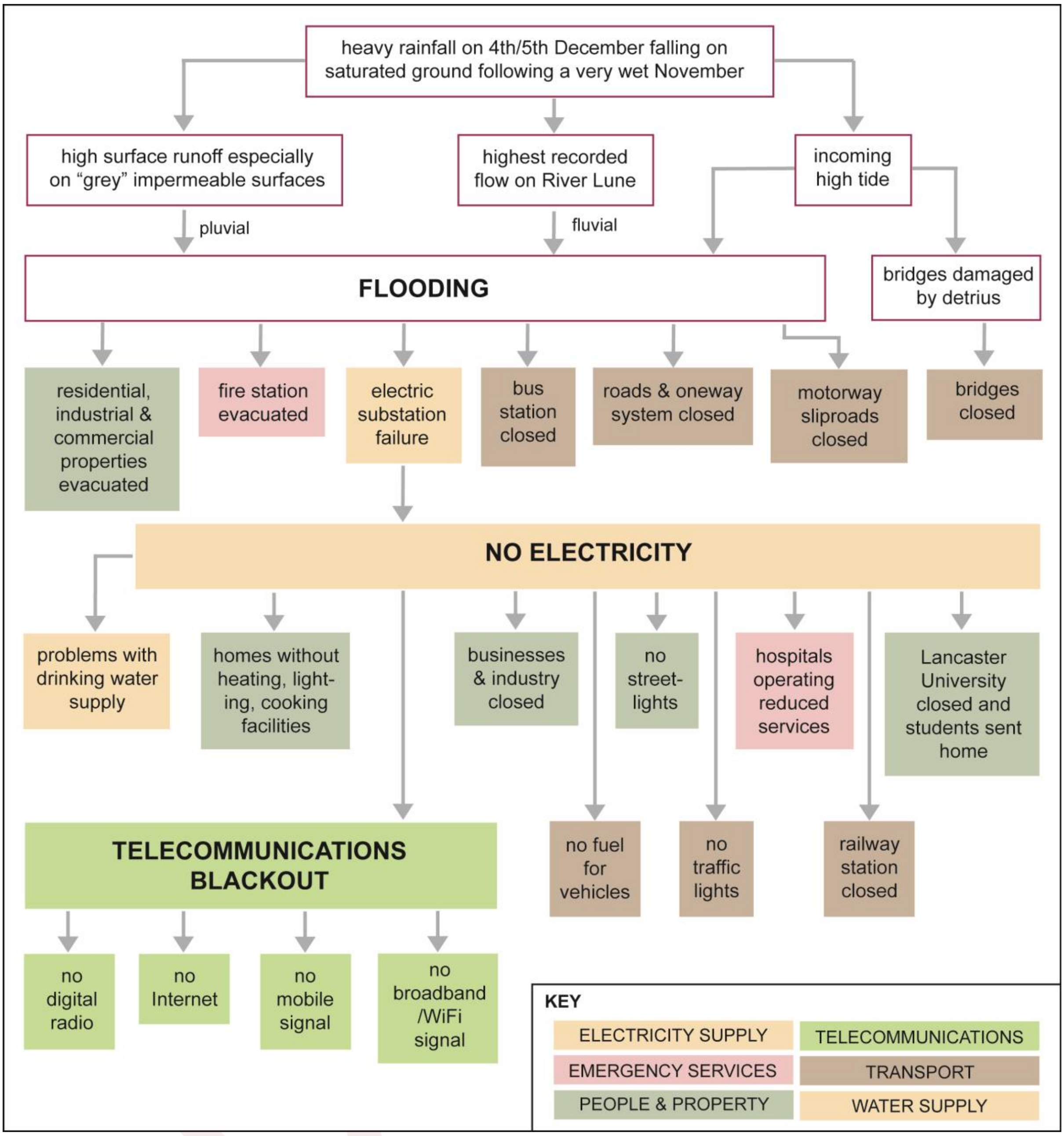

Figure 5: Flow chart summarising the collapse of Lancaster's critical infrastructure networks following the heavy rainfall on 4th / 5th December 2016.