RESIN

SUPPORTING DECISION – MAKING FOR RESILIENT CITIES

Climate Change Risk Assessment of Greater Manchester's Critical Infrastructure

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1. Introduction

Critical infrastructure is central to Greater Manchester's (GM) future. The achievement of the city's growth and public sector reform ambitions, as set out in the Greater Manchester Strategy[1], requires a resilient critical infrastructure network that is able to anticipate, respond to and recover from shocks and stresses. Climate change and extreme weather events such as flooding and heat waves pose a specific threat to critical infrastructure assets and the provision of related services. As a result, the EcoCities project identified adapting and building the resilience of critical infrastructure to climate change as a key task for GM[2].

Risk assessments are central to adapting and building resilience to climate change. The concept of risk is established within the climate change community, and climate change risk assessments are undertaken within the public and private sectors. For example, the UK government published climate change risk assessments in 2012 and 2017, and infrastructure providers (including utilities companies, Network Rail and Highways England) are required to prepare climate change risk assessments in response to the Climate Change Act of 2008.

This report contains the results of GM's first climate change risk assessment of critical infrastructure undertaken as part of the Horizon 2020 RESIN project. The risk assessment methodology drew on established approaches developed by high profile organisations including the Intergovernmental Panel on Climate Change and the UK Cabinet Office. It provides an evidence-based risk assessment informed by the best available data on the current occurrence of extreme weather and climate change hazards in GM, and on the direction of future climate change projections that will influence the frequency and intensity of these hazards locally. The report aims to:

- Improve understanding of the potential implications of climate change for critical infrastructure.
- Prioritise themes for adaptation and resilience strategy and action related to this sector.
- Support the targeting of capacity and resources to adapt and build the resilience of critical infrastructure to climate change.
- Identify key audiences and processes that will be supported by the risk assessment
- Set out a series of next steps which would allow GM to refine understanding of and spatially define the risks identified, and to better appreciate issues of residual risk.

The key themes emerging from this climate change risk assessment of GM's critical infrastructure are:

- Impacts associated with floods and storms present the highest risks to GM's critical infrastructure. Both of these hazard events are projected to become more frequent and intense with climate change, which in turn increases the associated risks to critical infrastructure.
- Extreme weather and climate change impacts on energy infrastructure represent the highest risks to GM's critical infrastructure.
- Five infrastructure sectors are present in the top 10 risks; energy, road; water supply and treatment, green infrastructure and social infrastructure. This suggests that the extreme weather and climate change poses a wide ranging threat to GM's critical infrastructure network.

The outcomes of this assessment are not a definitive statement of the climate risk to GM's critical infrastructure. This is a first step that provides evidence to guide decisions and inform the direction of future activity.

[1] https://www.greatermanchester-ca.gov.uk/ourpeopleourplace
[2] http://www.adaptingmanchester.co.uk/ten-minute-read

2. Risk Assessment Approach and Output

The thematic focus of this risk assessment is on extreme weather and climate change risks to GM's critical infrastructure. The goal of this risk assessment is to establish the most prominent risks in this context, not to identify all possible risks. Six extreme weather and climate change hazards fall within the scope of the risk assessment:

- Fluvial flooding
- Pluvial flooding
- High temperatures
- Water scarcity
- Storms (high winds and lightening)
- Geohazards (subsidence and landslides)

This matches the hazards covered within the critical infrastructure chapter of the UK Climate Change Risk Assessment 2017[3]. Within the GM assessment, however, pluvial and fluvial flooding have been considered as separate hazard themes. This is to reflect the different processes underlying these two forms of flooding, and variations in their occurrence in GM.

Urban critical infrastructure can be defined as: "An asset, system or part thereof located in an urban area which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in an urban area as a result of the failure to maintain those functions." This definition is adapted from the European Council Directive 2008/114/EC.

Taking this definition as a starting point, the critical infrastructure sectors covered within the GM risk assessment have been established with reference to the GM Spatial Framework (GMCA 2015), which identifies GM's critical infrastructure sectors as:

- Transport: air (Manchester Airport), rail, port (Salford) tram (metrolink), road, walking and cycling).
- Energy: gas, electricity, heat.
- ICT: digital connectivity.
- Water and waste water: water supply and water treatment.
- Social infrastructure: schools and education, health services, community facilities[4].
- Green infrastructure[5].

Within this assessment, we follow the risk-based approach developed by the Intergovernmental Panel on Climate Change (IPCC). This states that; "Risk is often represented as probability of occurrence of

[3] https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/uk-climate-change-risk-assessment-2017/ccra-chapters/infrastructure/

[4] Within this risk assessment, a focus is placed on social infrastructure buildings.

[5] The Greater Manchester Spatial Framework (GMCA 2016) notes that green infrastructure comprises of five strategic elements – trees and woodlands, the uplands, lowland wetlands, river valleys and canals and recreation areas including major parks and green spaces.

hazardous events or trends multiplied by the impacts if these events or trends occur" (IPCC 2014: 36). Further, the UK Climate Change Risk Assessment 2017 also assesses risk in this way (Dawson et al 2016). Using these existing approaches as a framework, the following risk 'function' is applied within the GM RESIN risk assessment to develop a risk score for a range of potential climate change impacts to GM's critical infrastructure:

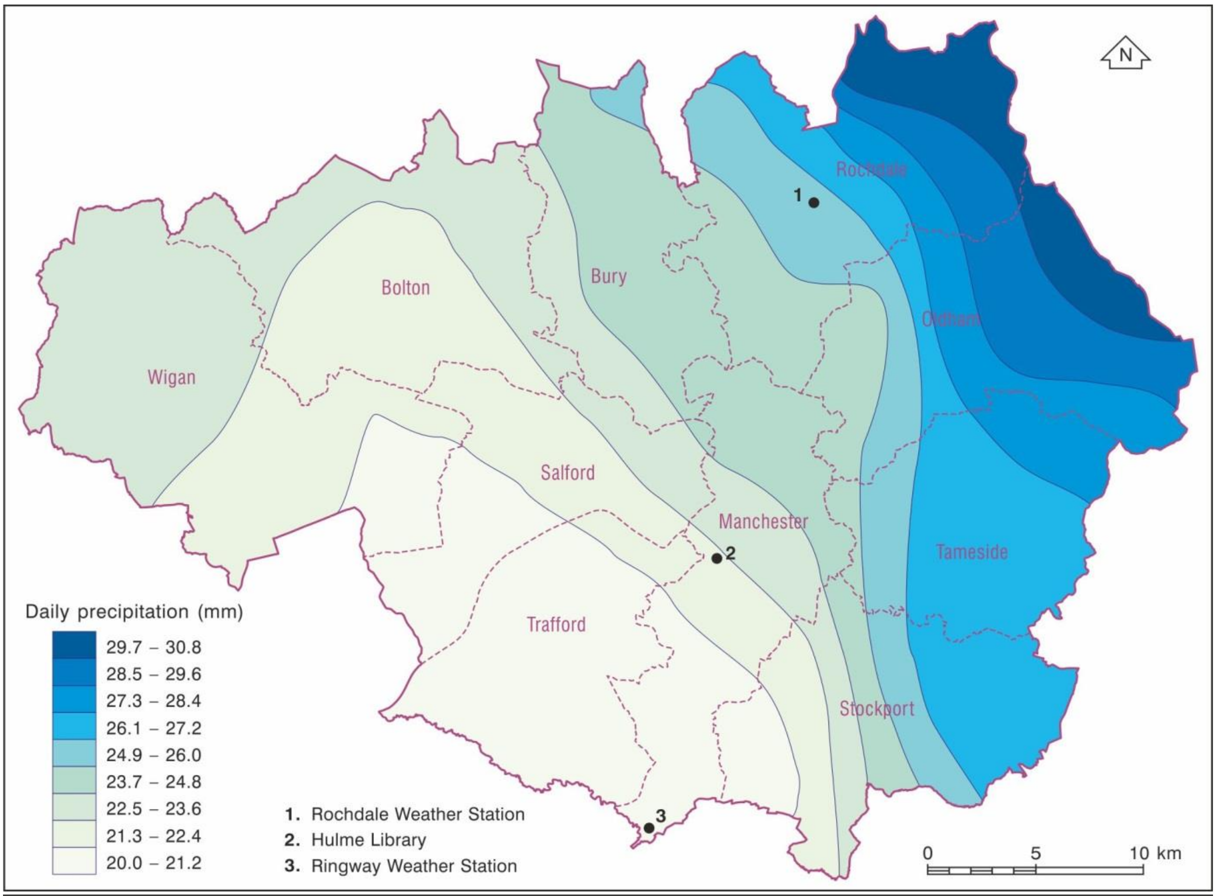
Risk = ***Probability*** of extreme weather and climate change impacts to GM's critical infrastructure occurring X ***Consequences*** of the impacts to GM's critical infrastructure should they occur

The consequences of extreme weather and climate change impacts on critical infrastructure will depend in part on how 'critical' the infrastructure is to GM. Based on the results of a questionnaire involving stakeholders with involvement in this sector in GM, a 'criticality' score is assigned to each of the critical infrastructure sectors included within the risk assessment. This is accounted for in the risk assessment process (by multiplying the risk score by the criticality score) and reflects that not all risks to critical infrastructure are equal. Ultimately, disruption to certain infrastructure will have greater implications for GM's residents and businesses than disruption to other infrastructure.

The risk assessment looks at extreme weather and climate change hazards at the GM scale, and infrastructure sectors rather than specific assets or networks. The assessment is not spatial in nature. This is because it was not possible to obtain spatial data for the full range of hazards and critical infrastructure sectors covered by the risk assessment, which would be need to undertake a spatial analysis of risk. Nevertheless, it is important to acknowledge the importance of location in the context of extreme weather and climate hazards. For example, figure 1 highlights that when looking at extreme precipitation events, which are a driving factor underlying pluvial flooding, the north and east of GM receives more rainfall than the south and west of the conurbation. In order to complement this broader multi-hazard and multi-sectoral risk assessment, a separate spatially informed assessment of flood risk to GM's transport infrastructure was undertaken within the RESIN project[6].

[6] http://www.resin-cities.eu/greatermanchester/

Figure 1 Contour map showing the precipitation gradient across Greater Manchester based on the 99th percentile daily precipitation in millimetres and including location of the Rochdale, Hulme and Ringway weather stations. Source: Smith and Lawson, 2011.



There are four key elements to the risk assessment approach followed within the GM case study which are now outlined:

1. Identify extreme weather and climate change impacts to critical infrastructure
2. Determine likelihood of extreme weather and climate change impact occurrence
3. Assess the consequences of extreme weather and climate change impacts for critical infrastructure
4. Assess extreme weather and climate change risk to critical infrastructure

2.1. Identify extreme weather and climate impacts to critical infrastructure

The starting point for the risk assessment was to identify a range of relevant extreme weather and climate change impacts that have the potential to affect GM's critical infrastructure. The UK Climate Change Risk Assessments, from 2012 and 2017, were key sources used to identify these impacts.

These large scale assessments, which involved input from numerous experts, included critical infrastructure as a constituent theme. They resulted in the identification of climate change impacts considered to be of particular importance to a range of critical infrastructure sectors. Drawing principally on the outputs of these assessments, in addition to locally focused input from a GM steering group set up to support the RESIN case study, 36 impacts were selected. These impacts cover the hazards and critical infrastructure sectors that form the basis of the GM risk assessment, and are listed in Table 1.

Table 1: Extreme weather and climate change impacts to GM's critical infrastructure

	Fluvial flooding	**Pluvial flooding**	**High temperatures and heat waves**	**Water scarcity**	**Storms (high winds and lightening)**	**Geohazards (subsidence and landslides)**
Transport	- Flooding of road network - Flooding of rail network - Road bridge failure due to scour - Rail bridge failure due to scour	- Flooding of road network - Flooding of rail network	- Rail buckling due to high temperatures		- Storm damage to road network - Storm damage to rail network	- Slope and embankment failure on road network - Slope and embankment failure on rail network
Energy (Gas and Electricity)	- Flooding of energy infrastructure (esp. substations) - Flooding of power stations	- Flooding of energy infrastructure (esp. substations)	- Increased energy demand for cooling - Damage to energy infrastructure from high temperatures	- Lack of cooling water for power generation	- Storm damage to energy infrastructure	
ICT (Digital Connectivity)	- Flooding of ICT infrastructure	- Flooding of ICT infrastructure			- Storm damage to ICT infrastructure	
Water Supply and Waste Water Treatment	- Flooding of water supply and waste water treatment infrastructure - Sewer flooding and combined sewer spills	- Flooding of water supply and waste water treatment infrastructure - Sewer flooding and combined sewer spills	- Increased demand for water	- Low groundwater levels and reduced recharge - Water supply and demand deficit (water scarcity) N.B. Also links to temp rise.		
Public Buildings	- Flooding of properties	- Flooding of properties	- Overheating of buildings	- Reduced water availability for buildings		- Subsidence
Green and Blue Infrastructure			- Loss of green and blue infrastructure functions	- Loss of green and blue infrastructure functions	- Tree fall	

2.2. Determine likelihood of extreme weather and climate impact occurrence

The next stage of the risk assessment required the likelihood of extreme weather and climate hazards that influence the occurrence of related impacts to critical infrastructure (identified in Table 1) to be assessed. Although this risk assessment was not spatially focused, it is acknowledged that the likelihood of certain hazard events is not equal across GM and will vary at finer spatial scales due to factors including land use and topography. For example, in the case of fluvial flooding from rivers and water courses, the likelihood of occurrence is not uniform across GM as only certain areas are located within flood zones.

In order to determine likelihood, GM data was analysed on the occurrence of hazard events over recent decades and on future climate change projections. Data on the occurrence of extreme weather and climate change hazard events drew on research outputs from the EcoCities project (Carter and Lawson 2011), which identified hazard events that impacted on GM between 1945 and 2008. Additional research was undertaken within the RESIN project to bring this study up to date (through to 2017). This enabled the differentiation between hazards based on their relative frequency of occurrence in GM. Table 2 summarises the findings of these studies and details the past occurrence of extreme weather and climate change hazard events across GM. This demonstrates that:

- Flooding is the principal hazard event occurring in GM, accounting for over half of events to have impacted on human health/well-being, infrastructure and services since 1994. Also, pluvial flooding now dominates, accounting for 50% of all floods since 1994.
- Storms account for over 20% of all events.
- Cold/snow related events have been steadily decreasing in frequency.
- Heat events are rare but have increased in frequency since 1994.
- Drought and water shortages are rare events in GM. Whilst they have increased in frequency since 1994, their occurrence relative to other hazards remains low.

Table 2. Past occurrence of extreme weather and climate change hazard events across GM.

Event	**1945-1969 Events**	**1970 – 1993 Events**	**1994 - 2017 Events**
Flood (all forms)	36 (44%)	24 (36%)	109 (52%)
~ Pluvial floods	~ 8	~ 8	~ 54
~ Fluvial floods	~ 17	~ 10	~ 27
~ Pluvial, Fluvial and Flash	~ 11	~ 6	~ 28
Storm	18 (22%)	24 (36%)	44 (21%)
Cold	17 (21%)	11 (16%)	27 (13%)
Heat	2 (2%)	4 (6%)	10 (5%)
Fog	8 (10%)	2 (3%)	15 (7%)
Drought (water shortages)	1 (1%)	2 (3%)	5 (2%)
TOTAL EVENTS	82	67	210

Notes on forms of flooding:

- Fluvial floods include flooding from rivers, streams and brooks.
- Flash flood events are included with pluvial events where evidence thereof is clear. However where evidence is ambiguous floods described as having been flash are included in the combined Fluvial + Pluvial + Flash category.
- Where the type of flood source is unclear it has been included in the Fluvial, Pluvial + Flash category

In addition to looking at the frequency of hazards, an assessment was made of the severity of these events. Although this is not directly linked to the risk assessment approach being followed, it is notable that the frequency of occurrence of severe wind and precipitation-related events impacting on GM since 1945 (those events which impacted on 100 or more properties, caused 100 or more emergency services call-outs, generated severe and prolonged disruption to services and severe injuries or deaths) appears to be increasing. Between 1945 and 1969 nine events were identified, between 1970 and 1993 eight events were identified and between 1994 and 2017 13 events were identified (with 9 nine of these occurring between 2010 and 2017).

Climate change projections data was used within the risk assessment to help account for how the frequency of hazard effects may change in the future. The GM risk assessment follows a 'reasonable worst case scenario' approach, as applied within the UK National Risk register (Cabinet Office 2017). Within the GM risk assessment, a reasonable worst case scenario is defined as one where the hazard event and resulting impacts to critical infrastructure are rare in terms of their frequency and severity, and have the potential to generate serious negative effects on GM, its people and the environment in which they live. In terms of future climate projections used to inform the risk assessment, the high greenhouse gas (GHG) emissions scenario for the 2050's (compared against baseline data for 1961-1990) was therefore selected. Here, the 90th percentile climate change projection was used, which represents the upper end of the range of available projections. This can be viewed as a 'reasonable worst case' climate change scenario for GM. Projections developed within the EcoCities project for GM's Mersey Basin zone (Cavan 2010) were used, with other sources also utilised where relevant.

Data used to inform the assessment of likelihood of extreme weather and climate change hazards generating impacts to GM's critical infrastructure is presented in Tables 3 and 4 below. These tables include an assessment of the relative frequency of occurrence of the hazard events in GM (Table 3), and of how climate change is anticipated to influence their frequency in the future (Table 4).

Table 3. Data on the recorded occurrence of extreme weather and climate events in GM.

	Flooding (fluvial, pluvial and flash)	**Flooding (fluvial)**	**Flooding (pluvial)**	**High temperatures – heat waves**	**Water scarcity – drought**	**Storms - high winds and lightening**
% of total extreme weather events recorded in GM (1945-2017)	51%	16% (N.B. a further 14% of events were combined fluvial, pluvial and flash)	21% (N.B. a further 14% of events were combined fluvial, pluvial and flash)	5%	2%	26%
% of total extreme weather events recorded in GM (1994-2017)	56%	14% (N.B. a further 14% of events were combined fluvial, pluvial and flash)	28% (N.B. a further 14% of events were combined fluvial, pluvial and flash)	5%	2%	23%
Current frequency of occurrence of the event in GM (relative to other hazards)	***Relatively high:*** GM's most common hazard and appears to be occurring more often.	***Relatively high:*** Events have become slightly less frequent over recent years.	***Relatively high:*** Events have become more frequent over recent years.	***Relatively low:*** Events linked to high temperatures are uncommon in GM.	***Relatively low:*** There are few records of drought related hazard events in GM.	***Relatively high:*** Storms are the second most common hazard facing GM.

Table 4. Data on the projected occurrence of extreme weather and climate events in GM.

	Flooding (fluvial, pluvial and flash)	**Flooding (fluvial)**	**Flooding (pluvial)**	**High temperatures – heat waves**	**Water scarcity – drought**	**Storms - high winds and lightening**
Projected climate change (EcoCities 2050's high GHG emissions scenario for GM's Mersey Basin zone. Change is from 1961-1990 at 90th percentile)	- Precipitation on wettest day in winter: + 31% - Precipitation on wettest day in summer: + 19% - Winter mean precipitation: +28% - Annual mean precipitation: +9%	- Precipitation on wettest day in winter: + 31% - Precipitation on wettest day in summer: + 19% - Winter mean precipitation: +28% - Annual mean precipitation: +9%	- Precipitation on wettest day in winter: + 31% - Precipitation on wettest day in summer: + 19% - Winter mean precipitation: +28% - Annual mean precipitation: +9%	- Summer mean daily maximum temperature: + 5.6°C - Warmest day in summer: + 6°C - Warmest night in summer: + 4.4°C	- Summer mean precipitation: - 36% - Summer mean daily maximum temperature: + 5.6°C	Projections data is not available for storms
Relevant additional literature	In the future, all sources of flooding with the potential to impact on GM are projected to increase (including fluvial, pluvial and groundwater flooding) (Sayers et al 2015).	In the future, all sources of flooding with the potential to impact on GM are projected to increase (including fluvial, pluvial and groundwater flooding) (Sayers et al 2015).	In the future, all sources of flooding with the potential to impact on GM are projected to increase (including fluvial, pluvial and groundwater flooding) (Sayers et al 2015).	A UK heatwave is defined by the Met Office as a period of two days where the max temp exceeds 30°C with a min temp exceeding 15°C in the intervening night. These events are projected to increase in central Manchester (Cavan 2010).	By the 2030s the northwest region is vulnerable to low water availability due to high population and reliance on surface water. The water deficit intensifies under projections for 2050 (HR Wallingford 2015). United Utilities forecast a reduction in water demand up to 2040 (United Utilities 2015).	Research suggests that under higher climate change scenarios, the frequency of storms increases (Robinson et al 2017, Zappa 2013), particularly over the central portion of the UK which incorporates GM (Robinson et al 2017).
Projected change in the occurrence of the hazard in GM by the 2050s under a high GHG emissions scenario	***Increasing:*** An increase in rainfall intensity is projected, particularly in the winter months. Winter mean precipitation is also projected to increase. Flooding may therefore increase in the winter and also at other times due to higher rainfall intensity across the year.	***Increasing:*** Over the period 1994-2017, 35% of recorded fluvial floods occurred during the winter, and a further 27% in the autumn. The intensity and volume of winter rainfall is projected to increase. Rainfall intensity is projected to increase across the year.	***Increasing:*** Rainfall intensity is projected to increase across the year so when extreme rainfall events do occur, they are projected to deliver a higher volume of water. Increased winter rainfall is also projected, raising the risk of pluvial flooding where the ground is more saturated.	***Increasing:*** Temps are projected to increase across all seasons, with heat wave events becoming more frequent. Projections for increases in temp extremes are particularly pronounced (e.g. the warmest day in summer).	***Increasing:*** Rising temps and lower summer rainfall raise the chance of water shortages. Population and economic growth will put more stress on resources in GM. Higher evapotranspiration due to higher temps will reduce water availability.	***Increasing:*** Until recently, future storm projections have been uncertain and inconclusive. However recent research points towards an increase in storm occurrence under high climate scenarios.

Additional work was undertaken within the RESIN project to build a picture of geohazard occurrence in GM. This hazard was not covered within the original EcoCities study (Carter and Lawson 2011). Virtually all surface geomorphological and landscape hazards are initiated, triggered or aggravated by extreme weather events. Examples include:

- Extreme rainfall raises soil pore water pressure which can induce landslides.
- Heavy rainfall and related high intensity river flows can trigger bank erosion and changes to river channels.
- Changes to groundwater levels can trigger subsidence events as well as activating either the collapse or heave of old mine workings.
- Exceptional rainfall can also cause the collapse of culverts and other drainage channels.

Recorded geohazard events in GM are relatively rare, and when they do occur tend to be localised in their impact and low in the severity of disruption that they cause. Recorded examples of events over recent years include landslips affecting road, rail, metrolink and residential properties, sinkholes affecting roads and residential properties, and river bank collapse affecting footpaths. There is currently not enough evidence to establish whether or not climate change will have a significant impact on the occurrence of geohazards in GM. For the purposes of this assessment, it is judged that the frequency of occurrence of geohazards will therefore remain unchanged.

Table 5 brings together data on the current frequency of occurrence of hazards in GM that have the potential to generate impacts on critical infrastructure, and on whether these hazards are anticipated to increase or decline in frequency from their current level by 2050 as a result of climate change. A resulting likelihood score is given for each hazard covered within the risk assessment, where 1 is low and 4 is high. These scores describe the likelihood of extreme hazard events occurring in GM during the 2050's time period (2035-2065) under a high greenhouse gas emission projection (at the 90^{th} percentile level). The likelihood assessment follows the 'reasonable worst case scenario' approach adopted within the UK National Risk register (Cabinet Office 2017). In the GM risk assessment, this relates to a hazard event and associated impacts to critical infrastructure that are rare both in terms of their frequency and severity, and would have serious negative effects on GM, its people and the environment in which they live. A definition of each likelihood score is provided below.

Table 5: Likelihood of extreme weather and climate change hazard events occurring in GM during the 2050's under a high greenhouse gas emission projection (at the 90^{th} percentile level).

	Hazard occurrence projected to increase in GM from the current level by 2050	**Hazard occurrence projected to remain unchanged or decline in GM from the current level by 2050**
Hazard is currently relatively common in GM	***Likelihood score – 4*** • Flooding • Storms	***Likelihood score – 2***
Hazard is currently relatively rare in GM	***Likelihood score – 3*** • Drought • High temperatures	***Likelihood score – 1*** • Geohazards

Key:

- ***Likelihood Score 1:*** Very unlikely that an extreme hazard event will occur.
- ***Likelihood Score 2:*** An extreme hazard event is as likely to occur as not.
- ***Likelihood Score 3:*** It is likely that an extreme hazard event will occur.
- ***Likelihood Score 4:*** It is virtually certain that an extreme hazard event will occur.

2.3. Assess the consequences of extreme weather and climate impacts for critical infrastructure

The next stage of the risk assessment involved evaluating, in a GM context, the consequences of extreme weather and climate change impacts to critical infrastructure (as listed in Table 1). A stakeholder-led evaluation of consequences was undertaken which involved the completion of a questionnaire. A pilot questionnaire was developed and tested with stakeholder input in order to refine the approach. Representatives from the following groups completed the questionnaire:

- Adaptation/resilience officers/experts
- Infrastructure owners/operators
- Academics working in the adaptation/resilience field
- GM planners/policy makers
- Consultants

In total, 40 people responded to the questionnaire, who were targeted via GM networks such as the Infrastructure Advisory Group and the Natural Capital Group, and contacts of the RESIN project team. The majority of respondents worked in the public sector (59%). Others came from the charitable sector (19%), private utilities companies (15%) and consultancies (7%). Most respondents worked at GM local authority or city-region scale, suggesting a familiarity with the challenges facing GM. The majority of respondents (78%) had been working on climate change adaptation issues for more than five years. Only 11% indicated that they had no familiarity of working on climate change adaptation or had less than two years of experience in this field. Although an effort was made to obtain a diversity of opinions to inform the risk assessment, the results of the questionnaire on the consequence of impacts to critical infrastructure are nevertheless based on the opinions of a certain group of people.

Initially the questionnaire respondents were asked to rate six infrastructure sectors based on their relative importance to GM's people and economy should there be widespread disruption within that infrastructure sector arising from a hazard event. Respondents ranked the relative importance of the six infrastructure types for GM on a scale of 1 to 10. All infrastructure types scored highly with all average ranks being more than 7 (Figure 2). There were only slight differences between them with water and waste water infrastructure (9.35) ranked of highest relative importance with green infrastructure of least relative importance (7.11). The response to this question is used within the risk assessment approach as a 'criticality score', which relates to the perceived importance of different critical infrastructure sectors in a GM context. This helps to account for the fact that extreme weather and climate change impacts to certain infrastructure sectors are potentially more damaging to GM.

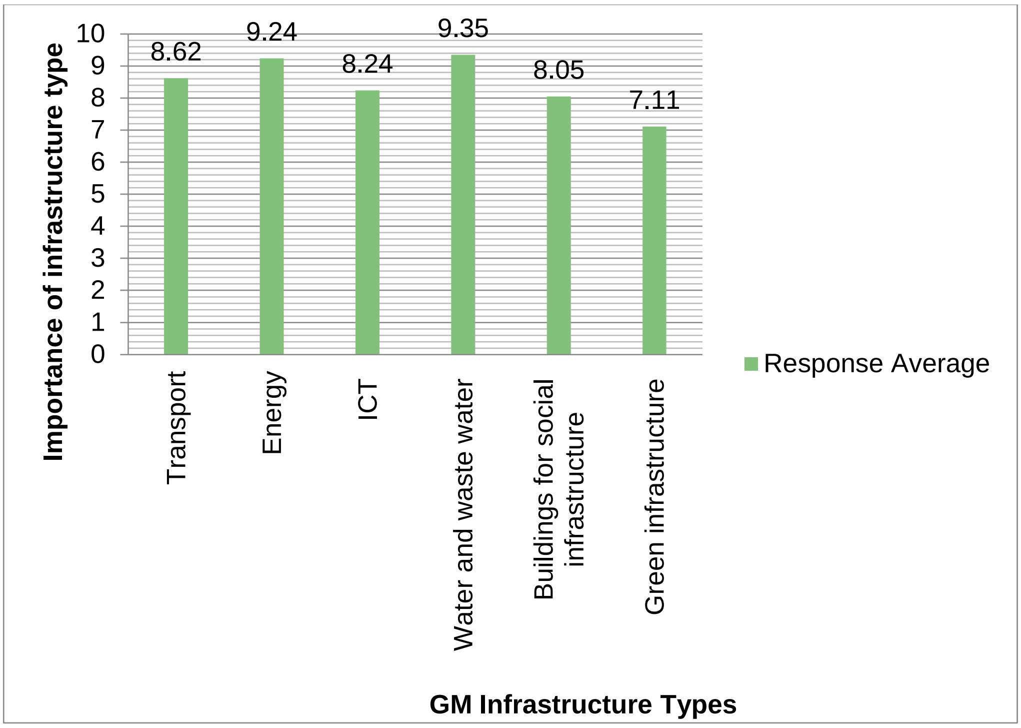
A key issue in designing the questionnaire was developing a scale against which the respondents could assess the consequences of extreme weather and climate impacts to critical infrastructure sectors. Three criteria were developed to assess the consequences of impacts, based on the National Risk Assessment Register's definition of an emergency arising from the Civil Contingencies Act (Cabinet Office 2017). The criteria, and related options offered to questionnaire respondents, were:

1. The impact on GM's economy (rather than the cost of repairs needed as a result of the climate impact to critical infrastructure assets and networks).
    - No negative impact on GM's economy
    - Limited negative impact on GM's economy
    - Moderate negative impact on GM's economy

- Severe negative impact on GM's economy
- I don't know

2. Social disruption, concerning loss or lack of access to health and social services, and to essential services such as water supply, food and fuel.
    - No disruption to daily life
    - Some short-term disruption to daily life
    - Moderate disruption to daily life
    - Serious and sustained disruption to daily life
    - I don't know
3. The severity of fatalities, illness and injury, both during the event and in its aftermath.
    - No illness, injury or fatalities
    - Some illness and injuries. No fatalities
    - Significant illness and injuries. No fatalities
    - Significant illness and injuries, including fatalities
    - I don't know

Figure 2: The relative importance of infrastructure types to GM's people and economy (the criticality score) where 1 is of least importance and 10 of highest importance. Total N = 38



The severity of the consequences of impacts to critical infrastructure will depend on the nature of the hazard event. Addressing this point, this assessment followed the 'reasonable worst case scenario' approach (Cabinet Office 2017), which was clarified in the stakeholder questionnaire. Questionnaire respondents assessed the consequences of the 36 extreme weather and climate change impacts (see table 1) for GM's critical infrastructure using the three criteria listed above. An average of the consequence scores provided for each criterion for each impact was then calculated. The resulting consequence scores (which have a maximum of 4) are given in Table 6.

Table 6: Consequences scores for the extreme weather and climate change impacts included in the risk assessment. The scores are ranked on the basis of 'total consequence', with the highest first.

Extreme Weather and Climate Change Impact	Economic Impact (Average score)	Social Disruption (Average score)	Illness and Fatalities (Average score)	Total Consequence Score
Fluvial flooding of energy infrastructure (esp. substations)	3.53	3.36	2.57	3.15
Water scarcity leading to reduced GI functionality	3.09	3.08	2.42	3.1
Geohazard leading to subsidence (social infrastructure)	2.5	3	3.6	3.03
High temperatures leading to reduced GI functionality	2.92	3	3	2.96
Fluvial flooding of power stations	3.23	3.07	2.54	2.95
Tree fall due to storms	2.67	2.58	3.6	2.95
Overheating of social infrastructure buildings	2.4	3	3.2	2.87
Impact of storm damage to energy infrastructure	2.85	2.85	2.82	2.84
Increased demand for cooling - energy infrastructure	2.85	2.62	3.09	2.74
Water supply and demand deficit (water scarcity)	2.8	2.8	2.6	2.73
Pluvial flooding of social infrastructure buildings	2.75	3	2.4	2.72
Fluvial flooding of road network	3	2.8	2.3	2.7
Impact of high temperatures on energy infrastructure	2.83	2.62	2.64	2.7
Pluvial flooding of energy infrastructure (esp. substations)	3.09	2.83	2.08	2.67
Reduced water availability in social infrastructure buildings	2.2	3	2.8	2.67
Fluvial flooding of water supply and treatment infrastructure	2.6	2.4	2.4	2.47
Fluvial flooding of social infrastructure buildings	2.4	2.8	2.2	2.47
Lack of water for cooling energy network	2.64	2.64	2.11	2.46
High winds and lightening on the road network	2.2	2.3	2.78	2.43
Low ground water levels and reduced recharge (water supply and treatment infrastructure)	2.6	2.2	2.4	2.4
Pluvial flooding of road network	2.6	2.6	1.9	2.37
Pluvial flooding of water supply and treatment infrastructure	2.4	2.4	2.2	2.33
Increased demand for water (water supply and treatment infrastructure)	2.6	2.2	2.2	2.33
Road bridge failure due to scour (fluvial)	2.4	2.4	1.83	2.21
Sewer Flooding and Combined Sewer Spills (fluvial)	2.4	2.2	2	2.2
Fluvial flooding of ICT infrastructure	2.5	2.5	1.5	2.17
Fluvial flooding of the rail network	2.3	2.44	1.67	2.14
Rail bridge failure due to scour (Fluvial)	2.4	2.44	1.56	2.13
Rail buckling (heatwave)	2.33	2.44	1.57	2.11
Slope and embankment failure on the road network	2.38	2.5	1.43	2.1
Sewer Flooding and Combined Sewer Spills (pluvial)	2.2	2.2	1.8	2.07
High winds and lightening on the rail network	2.3	2.2	1.57	2.02
Pluvial flooding of rail network	2.11	2.33	1.56	2
Storm damage to ICT infrastructure	2.25	2.25	1.5	2
Pluvial flooding of ICT infrastructure	2.25	2.25	1.25	1.92
Slope and embankment failure on the rail network	2	2.13	1.5	1.88

2.4. Assess extreme weather and climate risk to critical infrastructure

Once the likelihood and consequence scores for the extreme weather and climate impacts with the potential to affect GM's critical infrastructure had been determined, a risk score was produced by multiplying these two scores together. Some elements of the critical infrastructure network are perceived, by the questionnaire respondents who supported this risk assessment process, to be more 'critical' to GM than others (as reflected in Figure 2). In order to build this into the risk assessment process, each risk score is weighted by multiplying it with the 'criticality score' for the related infrastructure sector (taken from Figure 2). This produced a final risk score for each impact, which represent the final output of the risk assessment process. The final risk scores are provided in descending order within Table 6.

The key themes emerging from the outputs of this climate change risk assessment of GM's critical infrastructure are:

- Impacts associated with floods and storms present the highest risks to GM's critical infrastructure. Both of these hazard events are projected to become more frequent and with climate change, which in turn increases the associated risks to critical infrastructure.
- Extreme weather and climate change impacts on energy infrastructure represent the highest risks to GM's critical infrastructure.
- Five infrastructure sectors are present in the top 10 risks; energy, road; water supply and treatment, green infrastructure and social infrastructure. This suggests that the extreme weather and climate change poses a wide ranging threat to GM's critical infrastructure network.

The outcomes of this assessment are not a definitive statement of the climate risk to GM's critical infrastructure. This is a first step that provides evidence to guide decisions and inform the direction of further activity.

Table 6. Risk scores for extreme weather and climate impacts with the potential to affect GM's critical infrastructure.

Impact	Likelihood score	Consequence score	Risk Score	Criticality score	Final risk score
Fluvial flooding of energy infrastructure (particularly substations)	4	3.15	12.60	9.24	116.42
Fluvial flooding of power stations	4	2.95	11.80	9.24	109.03
Impact of storm damage to energy infrastructure	4	2.84	11.37	9.24	105.06
Pluvial flooding of energy infrastructure (particularly substations)	4	2.67	10.68	9.24	98.68
Fluvial flooding of road network	4	2.7	10.80	8.62	93.10
Fluvial flooding of water supply and treatment infrastructure	4	2.47	9.88	9.35	92.38
Pluvial flooding of water supply and treatment infrastructure	4	2.33	9.32	9.35	87.14
Pluvial flooding of social infrastructure buildings	4	2.72	10.88	8.05	86.94
Tree fall due to storms	4	2.95	11.80	7.11	83.90
High winds and lightening on the road network	4	2.43	9.72	8.62	83.79
Sewer Flooding and Combined Sewer Spills (fluvial)	4	2.2	8.80	9.35	82.28
Pluvial flooding of road network	4	2.37	9.48	8.62	81.72
Fluvial flooding of social infrastructure buildings	4	2.47	9.88	8.05	79.53
Sewer Flooding and Combined Sewer Spills (pluvial)	4	2.07	8.28	9.35	77.42
Water supply and demand deficit (water scarcity)	3	2.73	8.19	9.35	76.58
Road bridge failure due to scour (fluvial)	4	2.21	8.84	8.62	76.20
Increased demand for cooling - energy infrastructure	3	2.74	8.22	9.24	75.95
Impact of high temperatures on energy infrastructure	3	2.7	8.10	9.24	74.84
Fluvial flooding of the rail network	4	2.14	8.56	8.62	73.79
Rail bridge failure due to scour (Fluvial)	4	2.13	8.52	8.62	73.44
Fluvial flooding of ICT infrastructure	4	2.17	8.68	8.24	71.52
High winds and lightening on the rail network	4	2.02	8.08	8.62	69.65
Overheating of social infrastructure buildings	3	2.87	8.61	8.05	69.31
Pluvial flooding of rail network	4	2	8.00	8.62	68.96
Lack of water for cooling energy network	3	2.46	7.38	9.24	68.19
Low ground water levels and reduced recharge (water supply and treatment infrastructure)	3	2.4	7.20	9.35	67.32
Water scarcity leading to reduced GI functionality	3	3.1	9.30	7.11	66.12
Storm damage to ICT infrastructure	4	2	8.00	8.24	65.92
Increased demand for water (water supply and treatment infrastructure)	3	2.33	6.99	9.35	65.35
Reduced water availability in social infrastructure buildings	3	2.67	8.01	8.05	64.48
Pluvial flooding of ICT infrastructure	4	1.92	7.68	8.24	63.28
High temperatures leading to reduced GI functionality	3	2.96	8.88	7.11	63.13
Rail buckling (heatwave)	3	2.11	6.33	8.62	54.56
Geohazard leading to subsidence (social infrastructure)	1	3.03	3.03	8.05	24.39
Slope and embankment failure on the road network	1	2.1	2.10	8.62	18.1
Slope and embankment failure on the rail network	1	1.88	1.88	8.62	16.21

3. Using the risk assessment outputs

This report contains the results of GM's first climate change risk assessment of critical infrastructure. The risk assessment methodology drew on established approaches developed by high profile organisations including the Intergovernmental Panel on Climate Change and the UK Cabinet Office. It provides an evidence-based risk assessment informed by the best available data on the current occurrence of extreme weather and climate change hazards in GM, and on the direction of future climate change projections that will influence the frequency and intensity of these hazards locally. The assessment has been supported by over 40 individuals working in and around GM, the majority who have considerable experience (over 5 years) of working in associated fields. Care has therefore been taken to ensure that the data underpinning the risk assessment and the methodology employed enhance the robustness of the findings of this process.

The climate change risk assessment of GM's critical infrastructure offers the following benefits:

- *Awareness raising:* The risk assessment output identifies extreme weather and climate change risks to GM's critical infrastructure and can help to raise awareness of this issue.
- *Prioritisation:* The risk assessment outputs can support the prioritisation of risks to focus on as part of adaptation and resilience planning and action.
- *Resource allocation:* The risk assessment outputs enable available capacity and resources to be targeted towards locally significant issues.
- *Strategy and action development:* The risk assessment outputs can support adaptation and resilience strategy development and action delivery. Specific applications from a GM perspective are highlighted below.

3.1. Specific applications in GM

Over recent years, political awareness of and commitment to taking action on climate change adaptation and resilience in GM has increased. This risk assessment is potentially valuable to GM public sector organisations engaged in initiatives targeted towards delivering on this political commitment. The outputs can support on-going activity within the Low Carbon Hub (including its Natural Capital Group) and the Civil Contingencies and Resilience Unit. Specific applications of the risk assessment within these organisations include:

- The risk assessment output can inform the forthcoming GM Resilience Strategy being developed as part of the 100 Resilient Cities initiative.
- GM joined the UNISDR's 'Making Cities Resilient – My City's Getting Ready' campaign in 2014. GM has been recognised as a 'role model' city by the UNISDR due to its current work on resilience to general emergencies and disasters. The risk assessment output can be communicated in future reporting to the UNISDR to demonstrate activity linked to raising awareness of key risks to address as part of resilience building initiatives.
- GM's Climate Change and Low Emissions Implementation Plan 2016-2020 includes a target, to be achieved by 2020, to '…have a clear understanding of the main climate risks faced by Greater Manchester…' The risk assessment can form part of the evidence base needed to meet this target, and can inform adaptation and resilience strategy development in GM.
- The Covenant of Mayors for Climate and Energy, to which GM is a signatory, requires a climate change risk and vulnerability assessment to be published within 2 years of signing the covenant. This risk assessment can be used as part of the evidence base for this process.

- There is a set of ongoing actions and objectives targeted at local government in the UK's 2nd National Adaptation Programme, including a specific set of city commitments. Climate change adaptation also holds a prominent place in the government's own 25 year environment plan, which stresses that that all policies, programmes and investment decisions should account for the possible extent of climate change over the course of this century. GM reporting against this responsibility will be sought by DEFRA and the Committee on Climate Change. This GM risk assessment will enable an evidenced programme of climate change adaptation and resilience activity to be developed and communicated to GM's partners nationally and beyond.

3.2. Next steps

The risk assessment findings provide a springboard for further climate change adaptation and resilience activity in GM. As a first step, it would be useful to identify, with the input of GM stakeholders, which of the risks identified within this assessment require further activity in the short term and which can be assigned a 'watching brief' status. Further useful tasks link to developing a spatial perspective of prominent risk and better understanding levels of residual risk that remains following the implementation of ongoing or planned risk reduction measures.

The outputs of this risk assessment are not spatial in nature, and instead look at GM as a whole from a broad perspective. A spatial risk assessment of multiple extreme weather and climate hazards to multiple infrastructure sectors was beyond the scope of this project due to the lack of availability of related spatial data. A useful next step would be to undertake a focused spatial assessment of the highest risks emerging from this process, which in some cases may require the creation of new spatial data sets to inform this process. This would support the development of a more nuanced understanding of locally significant risk themes, particularly the impact of floods and storms to GM's energy infrastructure, which could subsequently inform more detailed adaptation and resilience strategy and action in this sector. A related study within the RESIN project has developed a spatial flood risk assessment of GM's transport infrastructure in collaboration with Transport for Greater Manchester. This was undertaken to support the implementation of the GM Climate Change Strategy. The method developed for this study could be used to inform risk assessments linked to other hazards and infrastructure sectors. This is available within the GM section of the RESIN project webpage: http://www.resin-cities.eu/cities/tier1/.

In addition to developing a spatially informed perspective of prominent extreme weather and climate change risks to GM's critical infrastructure, it would also be useful to explore the extent to which these risks are being addressed by current policy and practice. One of the key caveats associated with this risk assessment is that it does not account for activity that may be ongoing to mitigate extreme weather and climate change risks to GMs critical infrastructure. The risk that remains following the implementation of such measures is known as 'residual risk.' The outcomes of this risk assessment suggest that the impact of floods and storms to energy infrastructure represent the highest extreme weather and climate change impact to GM's critical infrastructure, and it would be valuable to better understand the extent to which this risk is already being managed. A useful follow up task would be to establish not only the nature of this particular risk spatially, but also the extent of residual risk remaining after related risk reduction measures are accounted for.

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