RESIN

SUPPORTING DECISION – MAKING FOR RESILIENT CITIES

Research and Data for Climate Change Adaptation and Resilience

A Baseline Assessment for Greater Manchester

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1. Executive Summary

The key goal of this assessment of research and data, and of the RESIN project more generally, is strengthening capacity to adapt and build resilience to climate change. Knowledge of climate change related research and data increases adaptive capacity in several ways, including by raising awareness of related issues and providing information to assess climate risk. This can in turn help to generate political commitment, and potentially support the allocation of resources. Allied to this, research and data can help to inform and target adaptation and resilience decisions and actions to generate more effective outcomes in practice. This is one of three complementary baseline reports produced within the RESIN project, with the others considering the stakeholder and policy landscape influencing urban climate change adaptation and resilience in Greater Manchester (GM) (Connelly et al 2017, Ellis et al 2017).

This assessment has been undertaken for several reasons, not least because an overview of existing research and data relevant to adaptation and resilience in GM is currently unavailable. The aims are:

- To identify resources to inform the GM RESIN case study, particularly the design and implementation of a method to assess weather and climate risks to GMs critical infrastructure.
- To identify gaps in current research and data that the RESIN project (or other future studies) could help to address.

In addition to supporting the RESIN project, this assessment aims to inform ongoing and future activities in GM that are linked, directly or indirectly, to climate change adaptation and resilience.

This assessment has established that no systematic analysis has been undertaken to date of climate risks to the multiple critical infrastructure themes and sectors that serve GM. Given the importance of critical infrastructure to GM, and the potential for negative impacts associated with the changing climate, the RESIN project is filling a gap in the knowledge base. Although GM stakeholders do have access to a range of sources that can support the assessment of weather and climate risks to critical infrastructure, there are several key issues and gaps concerning available research and data that present challenges. They include:

- Although future weather and climate projections do exist, the capacity may not be available within organisations such as local authorities to process and analyse this data in order to better understand related risks.
- GM benefits from a range of locally focused research and data outputs. Some fine scaled hazard data is available, such as flood maps and urban heat island mapping. These are the exceptions, however, and the majority of local data remains at a relatively course scale for reasons including the challenges associated with downscaling hazard and projections data.
- Research and data tends to address defined critical infrastructures and spatial scales in isolation and does not consider the implications of climate change risks to infrastructure from a broader systems perspective. However, due to the methodological and data complexities associated with cascading effects between infrastructures, such assessments currently are rare.
- The research and data that is available to support the assessment of climate risk in GM represents what could be described as a 'first generation' resource. It is relatively simple, there is little insight into interdependencies and cascading effects, data is often at a course spatial scale and hazards such as wind storms are not covered. Further, it may not always be in a format that can be readily applied by 'end users.'
- A 'second generation' research and data resource to support extreme weather and climate change research and practice in GM would be less purely research-driven and more closely aligned to the needs of climate change policy makers and practitioners.

2. Introduction

The key goal of this assessment of research and data, and of the RESIN project more generally, is strengthening capacity to adapt and build resilience to climate change. Knowledge of climate change related research and data increases adaptive capacity in several ways, including by raising awareness of climate change and providing information to assess climate risk. This can in turn help to generate political commitment to take action, which may lead to the allocation of resources. Allied to this, research and data can help to inform and target adaptation and resilience decisions and subsequent actions to generate more effective outcomes in practice. This is one of three complementary baseline reports produced within the RESIN project, with the others considering the stakeholder and policy landscape influencing urban climate change adaptation and resilience in Greater Manchester (GM) (Connelly et al 2017, Ellis et al 2017).

2.1. Aims

This assessment has been undertaken for several reasons, not least because an overview of existing research and data sources of relevance to climate change adaptation and resilience in GM is currently unavailable. The aims are:

- To identify resources to inform the GM RESIN case study, particularly the design and implementation of a method to assess weather and climate risks to GMs critical infrastructure.
- To identify gaps in current research and data that the RESIN project (or other future studies) could help to address, or that might influence the GM case study approach.

In addition to supporting the RESIN project, this assessment also has the potential to inform the development of ongoing and future GM activities linked directly or indirectly to climate change adaptation and resilience.

2.2. Approach to the baseline assessment

Climate change adaptation, risk and resilience agendas cover multiple sectors, stakeholders and spatial scales. This baseline assessment is not focused on analysing all available data on the full range of different aspects of weather and climate risks in GM. The goal is to assess the nature and scope of available research and data related to the assessment of weather and climate risks to GM's critical infrastructure. Several criteria were used to identify resources to include in the assessment. These were that the resources included within the baseline assessment should:

- Focus, spatially, on issues related to the generation and assessment of climate risk to GM's critical infrastructure. In some cases, this may encompass issues that operate beyond the GM scale given the cross-boundary nature of critical infrastructure.
- Incorporate research and data connected, thematically, to critical infrastructure (as defined within the RESIN GM case study) and specifically to the assessment of climate-related risks to critical infrastructure.

Using these criteria as a guide, an online literature search identified resources. Additional resources were accessed through the knowledge and contacts available within the GM RESIN team. The resources reviewed for this assessment are detailed in Appendix 1.

Climate-related risk is central to the RESIN project. The risk concept informed this element of the baseline assessment, particularly at the analysis stage. Following the approach taken by the

Intergovernmental Panel on Climate Change (IPCC) (IPCC 2014), climate risk is related to the occurrence of weather and climate hazards, the degree to which a 'receptor' (e.g. a person, infrastructure asset, economic sector) is exposed to a hazard and the receptor's vulnerability to the hazard should it be exposed. This builds on and connects to the 'classic' approach to assessing risk, which relates to the probability of an event occurring and the consequences associated with the event should it occur. Concepts associated with risk and risk assessment are explored in more detail, in the context of climate change adaptation and resilience, within a supporting RESIN report (Connelly et al 2016). The IPCC's risk themes of hazard, exposure and vulnerability helped to guide and structure this assessment of research and data.

2.3. Caveats

This assessment does not claim to be exhaustive and there will be some studies that have been missed. There are several further caveats to note:

- Some of the research and data included in this assessment may have been informed by information that is now out of date or has since been superseded, for example related to data inputs such as flood maps, land use patterns or census data.
- This assessment has not gone into specific detail of individual infrastructure sectors, networks and assets that provide functions to GM. This is due to the breadth of issues that this covers, and because related data may not be consistently available. Once the risk assessment focus and methodology has been finalised, relevant infrastructure data will be gathered to support related work.
- Some data needed to support a risk based assessment (based around the IPCC's approach) may not be available, for example due to commercial sensitivity (e.g. relating to the vulnerability of critical infrastructure) or simply because it does not exist.
- The assessment did not consider legislation, policies and strategies to reduce climate-related risk to critical infrastructure, which is an important aspect of adaptive capacity. This was addressed in a separate section of the baseline assessment (Connelly 2017).

3. Baseline assessment results

Figure 1 visualises the studies included in the baseline assessment, situating these according to their date of publication or completion, their spatial scale of investigation and their thematic focus. This provides an insight into the research and data 'landscape' that informs an understanding of climate risk in GM, with particular reference to critical infrastructure. The outputs of the assessment of research and data are now considered in more detail. This is organised around a risk based approach, looking at hazards and exposure and vulnerability to hazards, which are the three core elements linked to understanding and assessing weather and climate risk.

3.1. Weather and climate-related hazards

Although there are numerous hazards[1] with the potential to impact on cities and urban areas, from industrial accidents to disease outbreaks, the focus of this report (and the RESIN project) is on weather and climate hazards. Weather and climate hazards occur as a result of the interaction between a range of different themes, including climate variables (principally temperature and precipitation) and socio-economic and biophysical factors (e.g. land use patterns, legislation, topography). Prominent hazards with the potential to affect GM include flooding, high temperatures and heat waves, storms and high winds, droughts and water stress. Sea level rise and storm surge hazards affect some areas, but are not relevant to GM due to its location. Although cold weather events can be disruptive, they are not considered here as climate change projections suggest that they are likely to become less frequent and intense in GM. This does not mean, however, that cold events will cease to be a problem for the city.

Cities experience different weather and climate hazards as a result of numerous factors including their location, biophysical character, topography and land use patterns. As a result, two cities that are relatively close to each other many have quite different hazard profiles. Research and data is therefore needed to increase awareness of related issues locally, including which events are most common in any particular city, and which events are projected to intensify in the future under climate change. Developing these insights may be challenging in some cases due to issues including a lack of systematic recording of weather and climate events, and limited access to or capacity to interpret future climate change projections data. However, for GM, there is a range of relevant research and data on this topic.

[1] This report follows the definition of a hazard set out by the IPCC: 'The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources.'(IPCC 2014a: 560)

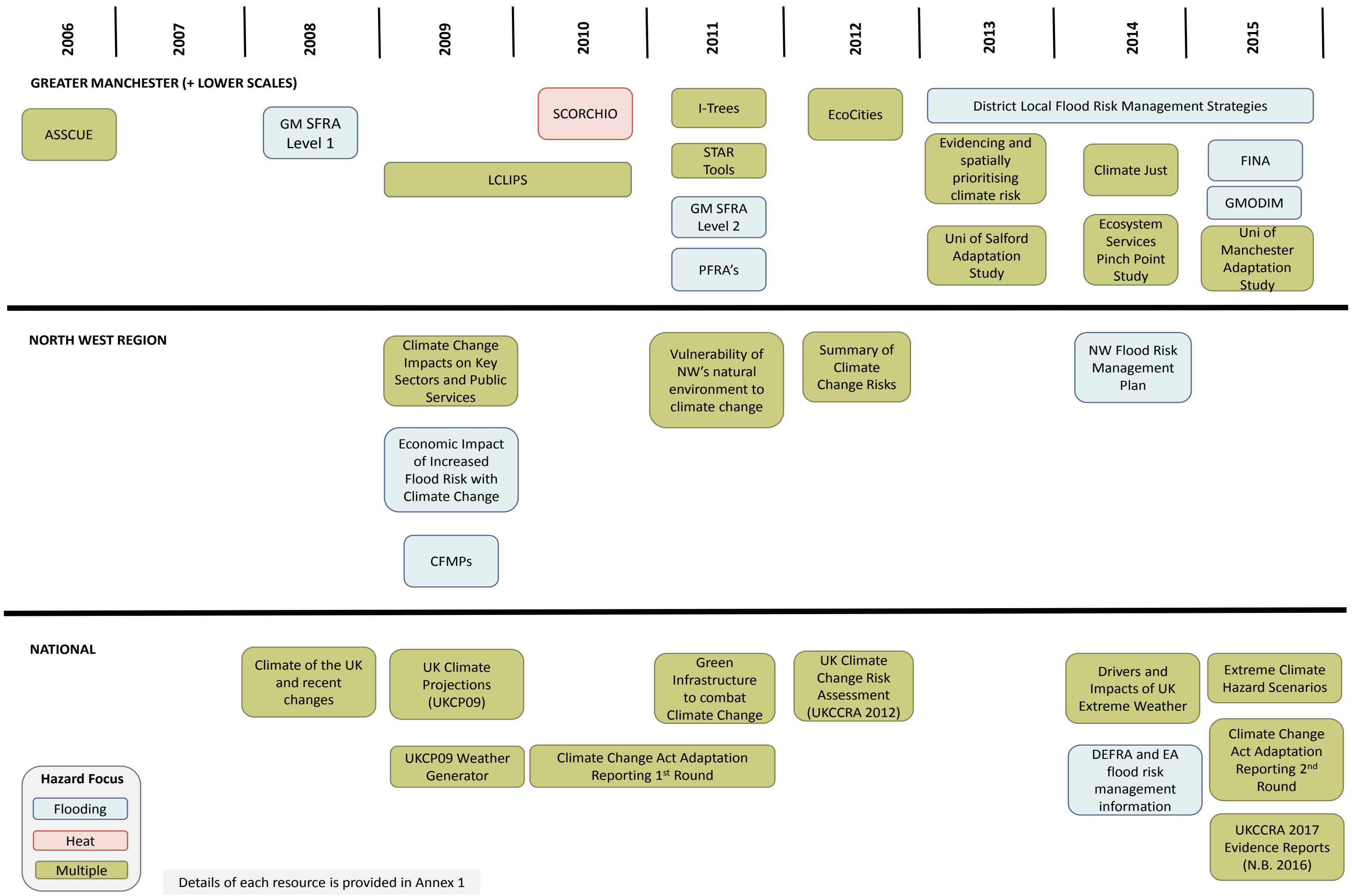

Figure 1: Greater Manchester's climate change research and data 'landscape' (Source: Authors)

Due to a national programme of climate change research (led by the Met Office) and related research activity in local universities, there is relatively good access to weather and climate hazard data relating to GM. Concerning current hazards, a study conducted within the EcoCities project identified 377 hazard events that affected GM between 1945 and 2008 (Table 1). To date, this represents the most comprehensive historic review of GM's weather and climate hazard events. A key highlight of this research is that flooding is GM's key current hazard, with pluvial (or surface water) flooding becoming more common over recent decades. This research support can support an assessment of the likelihood of weather and climate hazards in the present day.

Event/Time period	1945-1960	1961-1990	1971-2000	2001-2008	1945-2008
Fluvial Flood	10	22	25	19	76
Pluvial Flood	3	17	16	30	66
Unclassified Flood	5	9	5	7	26
Storm	12	25	26	22	85
Heat	3	4	8	7	22
Drought	0	2	3	3	8

Table 1: Recorded incidence of extreme weather and climate events across Greater Manchester for different time periods (Source Carter and Lawson 2011).

Over recent years, it has increasingly been acknowledged that the climate is changing and looks set to influence the frequency and severity of weather and climate hazards going forwards. Projections for future change to temperature and precipitation in GM are available for three distinct zones; the Pennine uplands, the Pennine fringe and the Mersey Basin (Cavan 2010). This research utilised climate projection outputs from the UK Climate Impact Programme developed in 2009 (known as UKCP09)[2]. Projections for precipitation and temperature variables in GM are summarised below. In each case data is provided for the 2050's in comparison to a baseline figure covering the period 1961-1990. The central estimate (50th percentile) for a high greenhouse gas emission scenario is given.

- Average summer precipitation is projected to decline by 20%
- Average winter precipitation is projected to increase by 16%
- Rainfall volumes during the wettest day in winter are projected to increase by 14.6%
- Mean annual temperature is projected to increase by 2.5°C.
- Warmest day in the summer is projected to increase by 3.4°C.

[2] Further information on GM's current and projected future climate is available here (Carter and Lawson 2011).

- Coldest night in the winter is projected to increase by 2.4°C.

The UK Climate Projections (UKCP) 'Weather Generator' enables users to develop projections for a range of weather variables and extremes for different time periods and climate change scenarios. These are produced at a 5km² scale (downscaled by the Weather Generator from projections produced at a 25km² scale) and cover precipitation and temperature variables. This tool offers the potential to undertake additional climate projections studies for specific locations in and around GM. Although climate variables can give a sense of the extent to which GM's climate is projected to change over the coming decades, this type of data – percentage changes in precipitation and degrees of temperature increase - can remain quite abstract and difficult to appreciate for non-specialists. Understanding how these changes may influence the frequency and severity of specific hazard events, floods for example, can make climate variable projections data more meaningful.

Certain extreme hazard events are projected to become more frequent and intense over the coming decades. This is significant as some of the most harmful impacts associated with weather and climate change are generated by extreme events. Extreme events, which are of a magnitude that is rare for a particular location, can include floods, droughts or heatwaves. Available data on extreme events in GM is limited, particularly concerning future projections. The Weather Generator tool includes a 'Threshold Detector' that enables users to assess the number of times that a given temperature or precipitation threshold (e.g. related to heatwave or precipitation events that have led to flooding in the past) are breached for selected locations, future time periods and climate change scenarios. There has been some limited use of this tool for GM, including research that looked at changes to heatwave and precipitation extremes in Manchester city centre, both of which were projected to increase (Cavan 2010). There is scope to apply the Weather Generator to better understand potential changes to weather and climate extremes in other parts of GM.

The surface temperature and runoff (STAR) tools, developed by Mersey Forest and the University of Manchester within the EU Interreg IVC GRaBS project, enable impacts of greening and land cover change on local climate to be assessed. They can therefore support the assessment of future hazards in GM as changes to temperature and runoff levels under different climate and land cover scenarios can be modelled using the STAR tools. The STAR tools recognise that the climate and land use interact to influence the frequency and severity of extreme weather and climate hazards. Although they are not produced directly by the STAR tools, maps can be created based on its outputs. The neighbourhood scale is recommended as ideal for STAR tools runs, which could potentially be used for tasks such as understanding issues such as how land use change around a critical infrastructure asset may influence heat and rainfall related hazards locally. The STAR tools can be accessed here[3].

3.1.1. Hazard maps

Over recent years, two online platforms housing spatial data on weather and climate hazards developed by local universities, consultancies and public sector bodies, have been created to support planning and decision making in GM.

- *The EcoCities project spatial portal:* This online resource, developed as part of the University of Manchester led EcoCities project, contains a range of spatial data sets connected to weather and climate change in GM. Future temperature and rainfall projections data is included for three climate zones in GM; the Pennine uplands, Pennine fringe and Mersey Basin. Other hazard data layers include maps of GM's heat island, the occurrence of drought

3 http://maps.merseyforest.org.uk/grabs/

conditions for grass and surface water runoff. Fluvial and pluvial flooding maps are also included, although these have since been superseded by more recent outputs from the Environment Agency. The interactive spatial portal, which displays data sets onto a map of Greater Manchester, can be accessed via the adaptingmanchester[4] website.

- *The GM Open Data Infrastructure Map (GMODIN):* This online resource is an ongoing initiative led by New Economy and Salford City Council. It has been developed to display public and private sector open data linked to various forms of infrastructure, and also on constraints related to infrastructure development. It includes the latest fluvial flooding mapping outputs from the Environment Agency. These indicate current flood extent, and are based on the national assessment of flood risk for England. The maps presents data on the chance (very low, low, medium and high) of flooding calculated at a 50m² scale. They are publically available, and can be accessed here[5].

In addition to these online resources, hazard maps relating to different forms of flooding (including fluvial, pluvial, reservoir and groundwater flooding) have been produced to support various flood risk assessments and flood risk management plans that have been produced by GM and its districts, often with input from consultancies. These include strategic flood risk assessments (SFRA's), local flood risk management strategies, and GM's surface water management plan. Although these reports are publically available, this is not always the case for the spatial data underpinning the hazard maps, which may nevertheless be accessible via licence. The Environment Agency also have an evolving programme of flood risk mapping work, covering both fluvial and pluvial flooding in the present day and accounting for climate change uplift. Although spatial data outputs are not publically available, they can be accessed for research purposes via licence.

Spatial data is not available for all weather and climate hazards with the potential to impact on GM. For example, there are no maps of future storms and high wind hazards, reflecting the difficulties associated with assessing this hazard spatially. Also, future heat stress maps are not available although GM's heat island map can be used as a proxy because locations currently exposed to high temperatures (relative to other areas in the city) are likely to be those that continue to be exposed under future climate change conditions. However, there will be gradual changes in GM's urban form which will influence the nature and extent of the heat island.

3.1.2. Hazard research and data - analysis

The aim of this assessment has not been to present data on the range of different hazards facing GM. This is available, in a GM context, through the outputs of research projects including EcoCities (Carter and Lawson 2011). Instead, GM-relevant hazard research and data outputs have been identified and signposted in Figure 1 and Annex 1, which summarise and provide links to research projects and data sources where specific hazard data can be obtained. Each individual activity, project or planning process that has a focus on adapting and building resilience to climate change, or that incorporates climate change as a decision factor, will require specific hazard data suited to its particular requirements. These requirements will differ according to issues including thematic and sectoral focus, spatial coverage and time horizon. For example, an assessment of extreme weather and climate risks to a specific planned or existing infrastructure asset (e.g. a train station or stretch of motorway) would benefit from detailed data on weather and climate hazards at a fine spatial scale. Conversely, a process focused on developing an adaptation strategy for a city, or district within a city, would be able

[4] http://www.adaptingmanchester.co.uk/home
[5] http://mappinggm.org.uk/gmodin/

to proceed effectively with less spatially detailed weather and climate data. Here, high level data on current and potential future hazards may be enough to develop a strategic policy framework, although the implementation of this framework locally (e.g. relating to individual development decisions) would ideally require more detailed data.

GM does have access to data on current and projected hazards either as outputs from previous research projects and sources such as UKCP09. However there are several issues with this data, issues that are shared with other weather and climate variable and hazard data sets, which should be acknowledged when using this data in practice. They relate to spatial resolution and uncertainty.

- ***Spatial resolution:*** Where weather and climate variable and hazard data does exist, it is often available at a broad spatial resolution. For example, UKCP09 climate change projections are delivered at a 25km² grid, in addition to other outputs at broader scales including regions and Water Framework Directive River Basin Districts, although the UKCP09 Weather Generator can produce projections data at a 5km² scale. Other hazard data sources, such as those produced to support the 2017 UK Climate Change Risk Assessment, are also course in scale. For example, a study of future water availability led by HR Wallingford produced outputs at the scale of water utility company boundaries, which generally cover large areas (HR Wallingford 2015). The value of hazard data produced at broader spatial scales will depend on the context within which it is being used.

- ***Uncertainty:*** Much attention is paid to climate change projections when developing climate change adaptation and resilience responses. However, projections are beset by considerable uncertainty, and in many cases this uncertainty is unlikely to be lessened due to complexity in the climate system and associated challenges linked to modelling future climates. This is why a range of future climate scenarios are usually presented, to reflect a range of different potential climate futures. This uncertainty cascades down into the outcomes of exercises focused on developing future hazard projections, relating to themes such as flooding and water availability. However, it is important to note that uncertainty in future climate projections should not be taken as a reason for inaction. This also raises the issue of which climate change scenarios to draw on within the RESIN project. Ideally, more than one scenario should be considered in order to reflect different possible climate futures and related risks.

3.2. Exposure of critical infrastructure to climate-related hazards

Exposure, in the context of climate risk, is often regarded as a spatial issue (for example by the IPCC). It concerns whether a receptor (e.g. a railway station or electricity sub-station) may be exposed to a climate hazard as a result of its location. For a specific asset, for example a sub-station, spatial mapping approaches (drawing on available hazard maps) can determine whether the asset is within an area that could potentially be exposed to a hazard or not. Where the receptor is a larger area (e.g. a greenspace) or a linear asset (e.g. a train line), as these infrastructures may not be entirely contained within the hazard area. Here, exposure may be reflected as the percentage of an area or line potentially exposed to a hazard. To assess exposure in this way, hazard maps are needed such as those available for GM via the EcoCities Spatial Portal and GM Open Data Infrastructure Map. In addition, spatial data on the location of the receptors is also required. Alternatively, research outputs may be available that provide the results of previous assessments on the exposure of GM's critical infrastructure to weather and climate hazards. Research and data linked to these two aspects - receptor location and exposure assessments - are considered below.

3.2.1. Receptor location

To assess the potential for critical infrastructure to be exposed to weather and climate hazards, data is needed on the location of related networks and assets. Spatial data on critical infrastructure is available for GM via the two online resources noted above:

- ***The EcoCities project spatial portal****:* Transport infrastructure contained within the spatial portal relates to the rail and metrolink network, including lines and stations, although the recent expansion of the metrolink network is not covered. Other critical infrastructure covered within the spatial portal includes assets linked to electricity supply, water supply and wastewater treatment, waste management and telecommunications.

- ***The GM Open Data Infrastructure Map (GMODIN)****:* Various critical infrastructure data sets are accessible via this online platform, and can be visualised onto a map of Greater Manchester. They include communications, energy, transport, waste and water supply and wastewater treatment infrastructure assets and networks. There are certain closed layers on the platform that are not available to the public for reasons including commercial sensitivity.

There is relatively good coverage of and access to 'hard' critical infrastructure spatial data via the EcoCities and GMODIN platforms. Within the RESIN project (and locally within Manchester) green infrastructure (GI) is also regarded as critical infrastructure. Spatial data on GI type and location is available from several sources, with some datasets included on the EcoCities spatial portal and the GMODIN platform. Dedicated work on mapping GM's GI resources has been undertaken by organisations including the GM Ecology Unit, Red Rose Forest (now City of Trees) and the Mersey Forest, and collectively they provide a strong spatial data resource on GM's GI.

Although data on GM's critical infrastructure is currently available, the city's infrastructure 'landscape' is continually evolving as new investments are made and infrastructure assets become obsolete or are replaced. Equally, GM's GI resource evolves driven by urbanisation processes. As a result, existing data reflects a current 'snapshot' of the situation, which is subject to change.

3.2.2. Existing exposure assessments

Previous studies provide insights into the exposure of some elements of GM's critical infrastructure to weather and climate hazards. Relevant examples include:

- A study undertaken within the EcoCities project looked at the risk of flooding to infrastructure in Greater Manchester. The report is available to download here (Kazmierczak and Kenny 2011). It presents the results of an assessment of the exposure of different forms of critical infrastructure, including transport, water, electricity, waste management and telecommunications, to five fluvial and pluvial flooding scenarios, which are listed below.

    1. Surface flooding exceeding 1m depth (JBA Consulting data, 2009).
    2. Surface flooding exceeding 0.1m depth (JBA Consulting data, 2009).
    3. Flood Zone 3, representing a 1 in 1000 years event (Environment Agency data).
    4. Flood Zone 2, representing a 1 in 100 years event (Environment Agency data).

5. A combination of the extreme spatial extent of both river and surface water flooding (Flood Zone 2 and surface flooding exceeding 0.1m depth) (Environment Agency and JBA Consulting data, 2009).

- The Flooding of Transport and Infrastructure Networks and Assets (FINA) project included an assessment of flooding events to different aspects of GM's transport infrastructure network. This project focused on previous flood events, and mapped where these impacted on GM's highways network (motorways and principal A-roads) and rail network. This demonstrated where transport infrastructure assets have been exposed to flooding in the past. The final project report is available from GM's Civil Contingencies and Resilience Unit.
- A Defra funded project, which focused on evidencing and spatially prioritising climate change risks in Greater Manchester, included some exposure analysis undertaken as part of a broader risk assessment. The critical infrastructure assets and networks included in this assessment were elements of GM's current and planned transport infrastructure network, waste water treatment works and electricity sub-stations. The exposure assessment covered fluvial and pluvial flooding and high temperatures. The report can be downloaded here (Carter and Kazmierczak 2013).
- The GM Surface Water Management Plan (Stage 1) includes the results of an assessment into critical infrastructure exposure to surface and sewer flooding in GM and its ten districts. The plan is available for download here (JBA Consulting 2012).
- The EcoCities spatial portal and the GM ODIN platform both contain certain weather and climate hazard data sets and details of critical infrastructure location, therefore enabling an assessment of critical infrastructure hazard exposure to take place.

3.2.3. Exposure research and data - analysis

There are several issues to acknowledge when considering data that could potentially be used to underpin exposure assessments, and equally the outcomes of existing exposure assessments.

- In some cases existing exposure assessments may have relied on data (e.g. on hazard extent or infrastructure location) that has since been superseded. Existing exposure assessments reflect the situation at the time of the study, using the data available at that time.
- Aside from flooding, there is limited availability of data to assess future exposure to extreme weather and climate change hazards.
- Potential exposure to a climate hazard, such as a flood, does not always materialise in practice. This depends on whether a receptor is actually exposed. This will not always occur for reasons including the existence of flood defences (e.g. around a substation). 'Ground truthing' may be needed in order to establish whether an infrastructure asset would actually be exposed in the event of a hazard occurring.
- Some hazards, particularly fluvial flooding, have a 'footprint' that can be defined spatially via hydrological modelling. Other hazards such as heatwaves and windstorms are more difficult to map spatially, particularly at finer scales, which can complicate spatially oriented exposure assessments.

- As spatial data on the full range of weather and climate hazards facing GM is not available, and equally not all critical infrastructure can be mapped, an assessment of the exposure of GM's critical infrastructure to these hazards will only ever be partial. Also because critical infrastructure systems evolve over time, as does understanding of weather and climate hazard, any assessment of exposure only reflects a snapshot of the current situation and knowledge available at the time.

3.3. Critical infrastructure vulnerability to climate-related hazards

Vulnerability, in the context of extreme weather and climate change, can be defined as: "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." (IPCC 2014a). According to the IPCC, vulnerability encompasses two elements, sensitivity and adaptive capacity. Sensitivity concerns a receptor's susceptibility to harm from a hazard. Adaptive capacity relates to a receptor's ability to adjust or adapt in order to minimise damages or take advantage of any opportunities that may be presented by extreme weather and climate change. Risk may therefore be low if a receptor is not vulnerable to a hazard, even if it is exposed. This emphasises the value of looking beyond hazards when assessing weather and climate risk. In order to build vulnerability into the RESIN risk assessment, relevant data relating to critical infrastructure is needed. Examples of sensitivity and adaptive capacity indicators of relevance to critical infrastructure are identified and discussed below.

3.3.1. Sensitivity

Indicators of critical infrastructure's sensitivity to (or susceptibility to harm from) extreme weather and climate change relate to themes concerning its characteristics and role. The focus here is on the sensitivity of the critical infrastructure assets and networks, not on the users or beneficiaries of the infrastructure. Examples include:

- Infrastructure characteristics and quality, e.g. age, design, type, condition, maintenance.
- Extent of interdependence between different critical infrastructure systems.
- Degree of criticality of infrastructure services for the functioning of a city.

3.3.2. Adaptive capacity

Indicators of adaptive capacity of relevance to critical infrastructure networks and assets cover themes related to emergency planning and preparedness, and concern infrastructure sectors and the wider public sector emergency response functions. Examples include:

- Existence and quality of governance frameworks, e.g. business continuity plans, emergency response plans.
- Existence (and implementation) of legislation and regulations on adapting and building the resilience. This issue is covered in the policy baseline assessment (Connelly et al 2017).
- Capacity of emergency responders.

- Presence of collaboration and information sharing networks between relevant stakeholder groups.

The list of potential sensitivity and adaptive capacity indicators provided above is not exhaustive. Further indicators will be identified, and associated data gathered, during the risk assessment depending on its thematic focus. At this point, the available literature on vulnerability indicators will be consulted. The RESIN state of the art report on vulnerability will provide a starting point (Connelly et al 2015). However, the indicators identified above do give a sense of the issues with the potential to influence the vulnerability of GM's critical infrastructure to extreme weather and climate change. These relate to the design, operation and management of critical infrastructure. Undertaken as part of the GM RESIN risk assessment of critical infrastructure, further work will focus on understanding the characteristics and measurement of critical infrastructure vulnerability. This process will be influenced by the thematic objectives of the risk assessment and the availability of information and resources. The theme of vulnerability will also be picked up within the GM case study at the stage of considering options to adapt and build resilience. Here options that reduce vulnerability, and therefore risk, will be considered.

4. Analysis of results

This assessment of available research and data has established that no systematic analysis has been undertaken to date of climate risks to the multiple critical infrastructure themes and sectors that serve GM. Given the importance of critical infrastructure to GM, and the potential for negative impacts associated with the changing climate, the RESIN project is filling a gap in the knowledge base. Further, there is an increasing move towards more devolved and local control and influence over an interconnected range of critical infrastructures, for example related to transport in a GM context. In some cases this will include responsibilities for funding, commissioning of investment and asset management. This increases the potential value of the GM RESIN risk assessment for local stakeholders.

This assessment has demonstrated that GM stakeholders have access to a range of sources that can support the assessment of risks to critical infrastructure connected to extreme weather and climate change. Some of this has been produced as a result of statutory processes, for example in response to the Climate Change Act of 2008, the Flood and Water Management Act of 2010. A significant proportion of the GM focused resources have been developed by academic institutions and consultancy firms, generally via commissions from GM authorities or as an outcome of academic research projects. This places GM in a relatively strong position in comparison to other cities and urban areas that may not have the same amount of locally-relevant information in place to inform climate change adaptation and resilience activities. Nevertheless, there are areas where data is limited. This is understandable given the cross cutting nature of understanding and assessing climate risk to critical infrastructure, which touches on multiple issues and processes. There are several key areas where there are issues and gaps with available research and data. They include:

Weather/climate theme

Flooding is the most well researched hazard in a GM context, particularly concerning current flood risk. This reflects that flooding is the most frequent and damaging hazard currently facing the conurbation. It is notable that the source of flood risk in England has changes over recent years, with surface water flooding and latterly reservoir flooding becoming more prominent (White 2014). It is necessary to acknowledge that the nature of flood risk may change further over time with climate change and socio-economic pressures. Future precipitation projections are available for GM, but until recently (with flood risk mapping from the Environment Agency that incorporates climate change uplift) these have not been translated into future flood risk projections. As a result, where they do exist, existing exposure assessments generally relate to current flood risk. Some data is available on temperature (current and projected) although this is generally not as spatially refined as flooding data. Aside from the SCORCHIO project, heat stress has not been covered comprehensively at a GM scale. Looking beyond flooding (and precipitation) and temperature, other weather and climate themes are relatively poorly covered in terms of GM-specific hazard data. Further, although future weather and climate projections do exist, the capacity may not be available within organisations such as local authorities to process and analyse this data in order to better understand related risks.

Data redundancy

There are issues concerning the data available to support the GM risk assessment, which may be redundant or at threat of becoming redundant. This relates to hazard data, which may be strengthened as climate science and modelling evolves. It also concerns data relating to critical infrastructure assets and networks which change over time as new investments are made and as the condition of existing assets fluctuates. As a result, some existing exposure assessments are now out of date due to new flooding data becoming available, for example. It will be important to acknowledge this at the risk assessment stage, and to highlight where there may be any related issues with data sets used to undertaken the assessment. This also emphasises that the risk assessment will represent a snapshot of the current situation based on the data that is available at the time.

Vulnerability indicators and data

Research and data that can support the assessment of climate risk to GM's critical infrastructure is relatively well developed in respect of certain locally relevant hazards and exposure to these hazards. However, accessing data on the vulnerability of critical infrastructure, the third element of the IPCC's risk based approach, appears to be more challenging. This is due to issues including the difficulty in accessing data sources on certain vulnerability indicators (e.g. related to the age and condition of infrastructure), and because there are uncertainties over which indicators may be most appropriate for assessing critical infrastructure vulnerability. A further assessment of options for determining the vulnerability of GM's critical infrastructure to extreme weather and climate change will be undertake during the risk assessment phase of the RESIN case study.

Spatial issues

GM benefits from a range of locally focused research and data. Some fine scaled hazard data is available, such as flood maps from the Environment Agency and urban heat island mapping from the University of Manchester. These are exceptions, and the majority of local data remains at a relatively course scale for reasons including the challenges associated with downscaling hazard and projections data. Regional and national studies provide additional insights into climate risk issues. National level climate change trends and projections data from UKCIP is a valuable resource, and some GM studies have built on this better understand weather and climate themes locally. Regional scale research has become less common over recent years with the abolition of the regional tier of governance and planning in England.

Although data is available to support an assessment of climate risks to critical infrastructure at the GM scale, hazards affecting other parts of the country may have a significant impact on GM and the infrastructure services that it relies upon. This is clear in respect of transport, water and energy infrastructure for example, which operate within a network that extends far beyond GM's administrative boundaries. Hazard events at scales beyond the conurbation may be more disruptive to critical infrastructure and the services it provides than the implications of climate change locally. This will need to be recognised within the GM RESIN case study, particularly at the risk assessment and adaptation/resilience options stage.

Complex and cascading effects

The research and data identified within this baseline assessment tends to address defined critical infrastructures and spatial scales in isolation and does not consider the implications of climate change risks to infrastructure from a broader systems perspective. For example, the consequences for GM's residents and businesses of disruption to critical infrastructure networks that extend beyond the boundaries of the conurbation have not been assessed. Further, cascading impacts caused by climate hazards (e.g. between multiple critical infrastructures such as energy and water), or across sectors (e.g. energy and health care), have not been addressed. However, due to the methodological and data complexities associated with cascading effects, such assessments currently are rare.

Utility in practice

The research and data that is available to support the assessment of climate risk in GM represents what could be described as a 'first generation' resource. It is relatively simple, there is little insight into interdependencies and cascading effects, data is often at a course spatial scale and hazards such as wind storms are not covered. Further, it may not always be in a format that can be readily applied by 'end users.' Given the challenges associated with research and data development in this context, these characteristics are common to climate research and data resources that are available for other locations. Indeed, due to the complex, wide ranging and cascading effects of extreme weather and climate change to critical infrastructure, it is not possible to gather data to support a quantitative assessment of all aspects of climate risk to GM's critical infrastructure. Some qualitative assessments will need to be made, informed by expert judgement, on issues such as the vulnerability of critical infrastructure. These issues will be explored in more detail within the GM RESIN case study.

It is also notable that the utility of existing research and data can be relatively low and not meet the needs of decision makers. The context for local decision makers, within local authorities for example, has changed significantly over recent years. Successive rounds of cuts to local authority budgets have led to a stripping back of environment and sustainability departments and the functions that they provide. The capacity does not exist in such departments in order to analyse and interpret research and data linked the changing climate, which can act to limit the use of related intelligence in practice. A 'second generation' of research and data to support extreme weather and climate change research and practice in GM would be less purely research-driven and more closely aligned to the needs of climate change policy makers and practitioners. Steps are being taken in this direction with flagship research programmes such as the European Union's Horizon 2020 programme encouraging the development of more collaborative approaches between researchers, policy makers and practitioners. The RESIN project, which is funded via this programme, aims to do so with the development of outputs 'co-produced' with potential end user urban practitioners and policy makers.

5. Annex A: Data and research covered within the baseline assessment of climate risk to critical infrastructure in GM

Project/study	Focus	Author/project leader	Date	Spatial scale	Climate hazard(s)	Timescale	Spatial data	Other relevant information
Adaptation Strategies for Climate Change in the Urban Environment (ASCCUE)	Development of a risk based approach to urban climate change adaptation.	University of Manchester	2006	GM	Flooding, heat	Future	GM urban morphology types map (1997 data) GM heat related risk.	Journal papers house key project outputs. Particular focus on the role of green infrastructure in GM for reducing climate risk.
Sustainable Cities: options for responding to climate change impacts and outcomes (SCORCHIO)	Development of adaptation data and tools, particularly linked to heat and human comfort.	University of Manchester	2010	GM (+ other cities)	Heat	Future	Heat island map for GM.	SCORCHIO focused principally at the building scale. Journal papers provide details of the key project outputs.
EcoCities	The development of data and tools	University of	2012	GM	Particular focus on	Recent, current and	A 'spatial portal' projects	Data on historic climate-related events impacting

	to support adaptation planning and action in GM.	Manchester			flooding and heat	future	data onto a map of GM, including a heat island map, flood maps, critical infrastructure.	on GM. Provides future climate projections for GM. Report on risk of flooding to GM infrastructure.
I-Trees	The investigation and demonstration of the adaptation benefits of green cover.	University of Manchester	2011	GM	Flooding, heat, air quality, water quality	Future	No	I-Trees led to a range of related PhD research that has produced journal papers linked to the adaptation role of green infrastructure in GM.
Surface Temperature and Runoff (STAR) tools	The STAR tools enable impacts of greening and land cover change on local climate to be assessed.	The Mersey Forest and University of Manchester	2011	GM	Temperature and precipitation	Future	No, but maps based on STAR tools outputs could be created. The neighbourhood scale is recommended as ideal for STAR tools runs.	The STAR tools were developed within the GRaBS project. Changes to temperature and runoff characteristics under different climate and land cover scenarios can be modelled using the STAR tools.
Evidencing and spatially prioritising	Assessment of climate-related	University of Manchester	2013	GM	Flooding and heat	Future	Assessment of flooding and	The risk assessment covers housing

Climate Change in GM	risks to the GM Strategy.						heat risk to selected key GM economic development locations.	development areas, GM's regional centre and eight town centres, strategic employment locations and future transport development sites.
University of Salford Climate Change Adaptation Study	Climate risks and adaptation responses to 3 buildings and public realm on the campus.	Buro Happold	2013	Building	Flooding and heat	Current and future	No	Although the principal focus of this report is on adaptation responses to flooding and heat stress, there is some useful data provided on hazards at the building scale.
ClimateJust	The provision of evidence to support local action to reduce climate related inequality and disadvantage.	University of Manchester with input from other partners	2014	National	Flooding and heat	Current and future	The Map Tool presents the opportunity to visualise climate hazard and vulnerability data at a local scale.	Some of the spatial data that can be mapped is of a course resolution (e.g. the heat exposure layer is a 25km grid) reducing its utility for local scale planning.
University of Manchester: extreme weather	Assessment of risk from flooding and heat stress	University of Manchester	2015	Neighbourhood and	Flooding and heat	Current and future	Flood risk and heat stress maps for the	Provides insights into how to assess climate risk the neighbourhood

and climate change risks and adaptation responses	to buildings on the University campus.			building			campus are provided.	and building scales. Given the significance of the University for the city's economy, it provide useful insight into related risks.
Flooding of Transport and Infrastructure Networks and Assets (FINA)	Understanding of flooding to GM's transport networks and assets to strengthen responses to related risks.	University of Manchester	2015	GM	Flooding	Recent trends	Mapping of patterns of recent flood events to the road network and heavy rail. Mapping of rail and Metrolink stations in flood zones.	The project focused on roads and heavy rail, sectors where historical flood data was available. Records suggest that flooding to the Metrolink network is uncommon.
The climate of the UK and recent changes	Assessment of changes to the UK's climate over recent decades.	UK Met Office	2008	National	Climate variables particularly temperatur e and rainfall	Historic trends	Trends data is provided at the regional scale. Maps of the UK are provided visualising changes in certain climate variables.	Changes in GM's climate over recent decades can be interpreted from the maps provided in this report.
UK Climate	The development	UK Met Office	2009	NationalReg	Climate	Future	Customisable	The UKCP09 projections

Projections	of a range of future climate change scenarios for the UK.			ional	variables, particularly temperature and rainfall		maps can be produced at a 25km² grid scale representing different scenarios and probabilities for selected climate variables.	are produced at a relatively course spatial scale. The EcoCities projections provide a slightly more refined picture for GM, but for a smaller number of climate variables, scenarios and probabilities.
UK Climate Projections Weather Generator	Enables users to create customised outputs on future weather variables. Can be used to assess changes in extremes.	University of East Anglia and Newcastle University (for UKCP09)	2009	User selects location	Climate variables, particularly temperature and rainfall	Future	Outputs produced for a single location, from a 5 km² grid or larger area up to 1000 km²	The Weather Generator also includes a 'Threshold Detector' allowing users to process Weather Generator outputs to calculate how often a selected climate variable threshold (e.g. daily precipitation volume) is breached.
UK Climate Change Risk Assessment (UKCCRA 2012)	Assessment of climate risk to 5 priority themes, and insights into actions to reduce risks, as required by the Climate	Defra	2012	National	Various weather and climate hazards	Future		Identification of risks associated with climate change to 5 themes - Agriculture and Forestry; Business, industries and Services; Health and Wellbeing; Natural

	Change Act of 2008.							Environment and Buildings and Infrastructure.
UK Climate Change Risk Assessment 2017 Evidence Reports (UKCCRA Evidence Reports)	The Climate Change Act of 2008 requires a UK government assessment of climate risk every 5 years. This collection of evidence is targeted at informing the 2017 assessment.	Defra	2016	National	Various weather and climate hazards	Current and Future	Some spatially oriented projections and mapped outputs are included in 4 new assessments developed for the evidence report. This is generally at large scales, including regions (inc. GM, Merseyside and Cheshire) and water company footprints.	The evidence base reviews published data on a range of different themes including infrastructure, business and global security. The evidence base also contains 4 new assessments focusing on future projections for flood risk, water availability, impacts on the UK's natural assets and extreme climate change scenarios.
Drivers and impacts of extreme seasonal weather in the UK	Assessment of connections between recent extremes and	Met Office	2014	National	Climate variables, particularly temperatur	Trends and future p	UK scale maps display climate variable anomalies for	Temperature and precipitation anomalies for recent extreme events, including the

	climate change, and of future prospects.				e and rainfall		selected recent extreme events.	2003 heat wave and the wet summer of 2012 can be extracted for GM.
Developing extreme climate scenarios for various climate hazards	The report focuses on extreme scenarios, termed H++, which fall outside the range presented by UKCIP09.	Met Office, CEH, University of Reading	2015	National	Various weather and climate hazards	Future	No	Extreme scenarios can be used to support analysis of low probability high impact events. Report covers heat waves, cold snaps, low and high rainfall, droughts, floods, windstorms. The scenarios will be used to support the second UKCCRA. The first UKCCRA did not use H++ scenarios.
A Summary of Climate Change Risks for North West England	A regional assessment to support the UKCCRA.	ClimateUK	2012	NW region	Various weather and climate hazards	Future	No	High level regional overview of key climate-related risks to the 5 themes covered by the UKCCRA.
Climate Change Impacts on Key Sectors and Public Services in	Assessment of climate risks to 18 themes within the public and	ARUP	2009	NW Region	Various climate variables and	Future	No	Utilises climate change data from UKCP09, and UKCIP's BACLIAT tool. Sector specific

Northwest England	private sectors.				hazards			awareness raising and briefing materials are available. GM is considered as a sub-region.
Economic impacts of increased flood risk associated with climate change in Northwest England	Assessment of economic impacts of flood risk under a changing climate.	URS Corporation Ltd	2009	NW region	Flooding	Future	No	Although the report does not focus specifically on GM, it does provide a regional insight into flooding costs to key business sectors and helps to build the case for action.
Greater Manchester Ecosystems Services Pinch Point Study	Understanding and mapping GM's priority Ecosystem Services (ESS), and assessing ways to progress this agenda.	Red Rose Forest and Countryscape	2014	GM	Various themes including flooding and cooling	Current	Mapping of priority GM ESS.	Many of the priority ESS connect to climate change adaptation and resilience. The report identifies 'pinches', some of which are spatial, that are critical to maximising the potential contribution of GM's ESS.
Green Infrastructure to Combat Climate Change	Provides a framework for organisations in NW England to	The Mersey Forest	2011	NW Region	Various adaptation and resilience	Current	Spatial data related to certain climate-related risks	GM is considered as one of five sub-regions within the NW.

	deliver GI responses to achieve adaptation goals.				themes		that could be addressed via GI responses	
North West Flood Risk Management Plan (Consultation draft)	Set out where and how to manage flood risk for the benefit of communities and the environment.	Environment Agency and Lead Local Flood Authorities	2014	NW Region	Flooding	Current	Connects to the Environment Agency's interactive online flood maps	Highlight the flood hazards and risks from rivers, the sea, surface water, groundwater and reservoirs. The impact of climate change is considered. Final draft is imminent. GM and its districts are covered by some flood analysis.
Vulnerability of North West's natural environment to climate change	Assessment of the vulnerability of National Character Areas (NCAs) to climate change.	Natural England	2010	NW Region	Various weather and climate hazards	Future	Mapping, at the regional scale, of NCA's vulnerability to climate change	The spatial scale of this study is relatively course. There are 29 NCAs in the region, several of which are included partially or wholly in GM.
Greater Manchester Open Data Infrastructure map (GMODIN)	Provides infrastructure and housing data across GM on a	GM Combined Authority	2015	GM	Flooding	Current	Provides an online map of physical, social and green	The map enables EA flood zones to be overlaid with infrastructure data. The map will be updated as

	single map.						infrastructure.	further data is accessed and becomes available.
Level 1 GM Strategic Flood Risk Assessment (GM SFRA)	Assesses flood risk from all sources, looking across GM and its districts.	Scott Wilson (consultancy firm)	2008	GM and its districts	Flooding	Current and future	The SFRA is spatial in nature and include maps of locations at risk of flooding.	This initial city region wide SFRA, developed collaboratively by GMs 10 districts, has subsequently been built on at the GM and districts scales (Level 2).
Level 2 Strategic Flood Risk Assessments	Produced by GM's districts, sometimes jointly, to assess flood risk from all sources.	JBA and Scott Wilson (consultancy firms)	2011	District	Flooding	Current and future	SFRAs are spatial in nature and include maps of locations at risk of flooding.	These SFRAs provide a more detailed view of this hazard in GM's districts than the Level 1 assessment. They also provide a more comprehensive view of climate change effects.
District Local Flood Risk Management Strategies	These strategies are focused on managing flood risk, and provide local assessments of flood risk.	Lead Local Flood Authorities	2013-2015	District	Flooding	Current	Strategies include maps of different forms of flooding.	These strategies have been produced in response to requirements within the Flood and Water Management Act of 2010. They have been approved by GM districts between 2013 and 2015.

Preliminary Flood Risk Assessments (PFRAs)	PFRAs identify flood risk areas where floods have happened in the past and may do in the future	PFRAs have been produced by consultancy firms for lead local flood authorities	2011	District	Flooding	Historic and future	A range of spatial data related to flooding and flood risk areas is mapped.	PFRAs for the North West River basin district, which contains GM, can be downloaded here. PFRAs cover fluvial, pluvial and groundwater flooding.
Catchment Flood Management Plans (CFMPs)	CFMPs provide an overview of flood risk and strategies to manage this risk over the coming decades	Environment Agency	2009	River catchments	Flooding	Current and future	Some mapping is provide, although CFMPs are more focused on developing policy frameworks to manage flood risk.	CFMPs can be downloaded here.
Local Climate Impacts Profiles (LCLIPs)	LCLIPs identify past extreme weather events and assess their impacts on the area of focus.	Local Authorities, University of Manchester	2009-2010	GM and its districts	Various weather and climate hazards	Historic events	Generally, LCLIP results are not mapped.	9 out of 10 of GM's districts had completed LCLIPS by 2009/2010. An LCLIP for GM was produced by the University of Manchester within EcoCities, the key findings of which are summarised here.

Flood risk management: information for flood risk management authorities, asset owners and local authorities	Guidance to support the assessment of flood risk and the development of responses by lead local flood authorities.	Defra and the Environment Agency	Last update 2014	Various	Flooding	Current and future	Reservoir flood maps have been made available to Local Resilience Forums. Climate change information for the NW River Basin District is available here.	This resource collects together relevant guidance, and is focused on supporting the implementation of the Flood and Water Management Act of 2010.
Climate Change Act Adaptation Reporting	The Climate Change Act of 2008 requires organisations, principally infrastructure providers, to publish climate risk assessments.	Infrastructure companies	2010-2016	Various	Various weather and climate hazards	Future	The risk assessments are often underpinned by spatial analysis, the results of which are generally made available e.g. number of sub-stations in different flood zones.	Reports produced during the first (2010-2011) and second (2015-2016) rounds of this cycle are available from Defra. These reports provide insights into the extent of extreme weather and climate risk faced by infrastructure companies that provide critical services to urban areas.

6. References

Carter, J.G. and Kazmierczak, A. 2013. Evidencing and spatially prioritising weather and climate change risks in Greater Manchester. University of Manchester.

Carter, J. G. and Lawson, N. (2011). *Looking back and projecting forwards: GM's weather and climate*. Manchester: The University of Manchester. Retrieved from http://media.adaptingmanchester.co.uk.ccc.cdn.faelix.net/sites/default/files/Recent_changes_and_trends_GM_climate.pdf

Cavan, G. 2010. Climate change projections for Greater Manchester. EcoCities Project, University of Manchester, Manchester, UK.

Committee on Climate Change. 2016. UK Climate Change Risk Assessment 2017: Evidence Report Chapter 4 on Infrastructure. Committee on Climate Change, London.

Connelly, A., Carter, J.G. and Handley, J. 2015. Vulnerability Assessment: Definitions, Indicators and Existing Assessment Methods. RESIN Project.

Connelly, A., Carter, J.G. and Handley, J. 2016. Undertaking Climate Risk Assessments: Definitions, Approaches and Methods. RESIN Project.

Connelly, A., Carter, J.G and Ellis, M. 2017. Climate Change Adaptation and Resilience Policy – a Baseline Assessment for Greater Manchester. RESIN Project.

Ellis, M., Carter, J.G and Connelly, A. 2017. Climate Change Adaptation and Resilience Stakeholders – a Baseline Assessment for Greater Manchester. RESIN Project.

HR Wallingford. 2015. CCRA 2 – Updated projections for water availability for the UK. HR Wallingford, Wallingford.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. contribution of working group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

IPCC, 2014a: Annex II: Glossary [Mach, K.J., S. Planton and C. von Stechow (eds.)]. In: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, pp. 117-130.

JBA Consulting. 2012. Greater Manchester Surface Water Management Plan – Stage 1: A Strategic Assessment of Flood Risk. JBA Consulting, Warrington.

White, I. (2014) 'Castles in Sand: The Shifting Sources of Flood Risk and the Implications for Governance', in Glavovic, B. and Smith, G. (eds) *Adapting to Climate Change: Lessons from Natural Hazards Planning*, Springer, 101-121.