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A deeper understanding of climate induced risk to urban infrastructure: case studies of past events in Greater Manchester

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Abstract

A detailed knowledge of past events is sometimes used to help understand and manage potential future risks. Flood risk management is one area where this has been particularly true, but the same ideas could theoretically be applied to other potential climate induced impacts in urban areas such as subsidence, sewer collapse and land movement. Greater Manchester, as the world's first industrial city, provides an ideal case study of how such events have affected the urban infrastructure in the past. This paper reviews some of the evidence which can be gleaned from past events and also shows how the realisation of some climate-related risks in heavy modified urban environments can only be fully understood through a consideration of sub-surface as well as surface characteristics.

Key words

flood, subsidence, risk assessment, Greater Manchester

Introduction

Urban areas have always been prone to climate-related risks as a result of their ability to modify physical processes such as drainage and heat exchange and their high concentration of people and property. Over recent years there has been a perception of increasing risks in the urban environment. This perception has been fuelled by reports of rises in quasi-tangible measures of risk such as insurance claims, and due to a number of well publicised extreme events, such as the 2005 Carlisle flood and the 2003 European heat wave. One analysis of insurance claims made in relation to weather-related risk suggested that such claims have doubled from 1993-8 to 1998-2005 with predictions of a further tripling by the 2050s (Dlugolecki 2004). Similarly, subsidence claims have risen from average levels of around £100 million per year in the 1980s to nearer £300 million per year by the end of the 1990s (Forster and Culshaw 2004). The reasons for these trends are complex and have both physical and societal drivers, not least the development of a more risk-aware society. To explore these reasons in more detail it is useful first to unpick what is meant by the idea of risk.

The notion of risk is subject to many different interpretations (Brooks 2003). One line of argument is that risk is a function of hazard, exposure and vulnerability. Using this conceptualisation, risk can only be realised if an element (e.g. a building or person) is exposed to a hazard which is capable of inflicting damage. In turn, damage can only result if there is an inherent vulnerability associated with the element which is exposed. It follows, therefore, that unless there is a connection between all three risk components, there can be no risk. Using these terms, drivers of changing patterns of risk can be seen to be as much associated with expressions of vulnerability (such as the use of inappropriate building materials or lack of community resource to deal with exposure to hazard) and the characteristics of exposure (such as building in floodplains) as they are associated with the characteristics of hazards themselves. Nevertheless, there is increasing evidence that at least one of the underlying reasons for apparently increasing levels of risk is a genuine change in the frequency and/or severity of weather-related hazards across the UK (Pilling and Jones 1999; Prudhomme et al 2002; Hall et al 2005). The recognition of changes in all of the aforementioned drivers of risk has lead to increased interest in improving the information base to support climate conscious planning in UK towns and cities.

The EPSRC/UKCIP funded Adaptation Strategies for Climate Change in the Urban Environment (ASCCUE) project has developed a screening risk assessment methodology for application to the related goals of adaptation and risk minimisation. The methodology was developed at the conurbation scale in order to be able to make a city-wide and inherently spatial assessment of risk both for current conditions and future scenarios. Examples of the methodology as applied to heat-related health risk and flooding are available in the wider literature (Lindley et al 2006; Lindley et al 2007; Gwilliam et al 2006). Risk was assessed through a GIS-based analysis using a geographical framework of discrete urban morphology units. The units were initially developed from the visual interpretation of aerial photography and subsequently verified through expert knowledge from local planning offices and a range of additional datasets (Lindley et al 2006; Gill et al 2007). Importantly, the units represent parcels of land with similar biophysical properties which can, for example, be readily characterised in terms of their built and evapotranspiring surfaces (Figure 1).

The screening risk assessment methodology was conceived as part of a wider risk management framework (Figure 2). Part of the risk management framework emphasises the role of an analysis of past events. Indeed, an analysis of past events can also be used as the basis of risk assessment, although this is generally more frequently used in research employing a 'natural hazards' definition of risk (i.e. associated with hazard and exposure). This paper documents past events in the Greater Manchester conurbation with a particular emphasis on flooding and subsidence. Through a consideration of the characteristics of past events and some of their drivers, suggestions are made for how such risks may be mitigated and managed in the future.

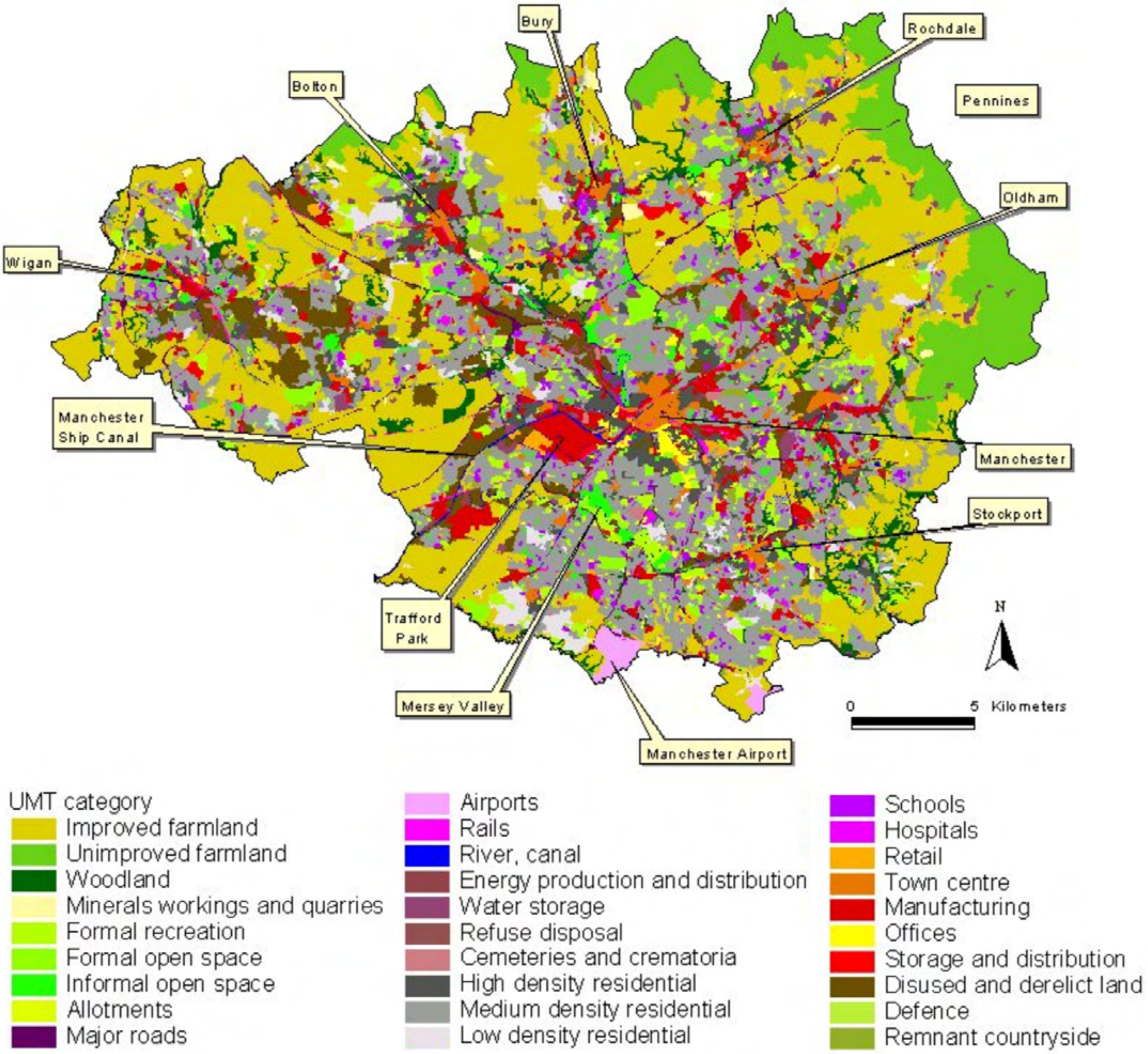

Figure 1: Urban morphology in Greater Manchester (after Handley et al, 2007).

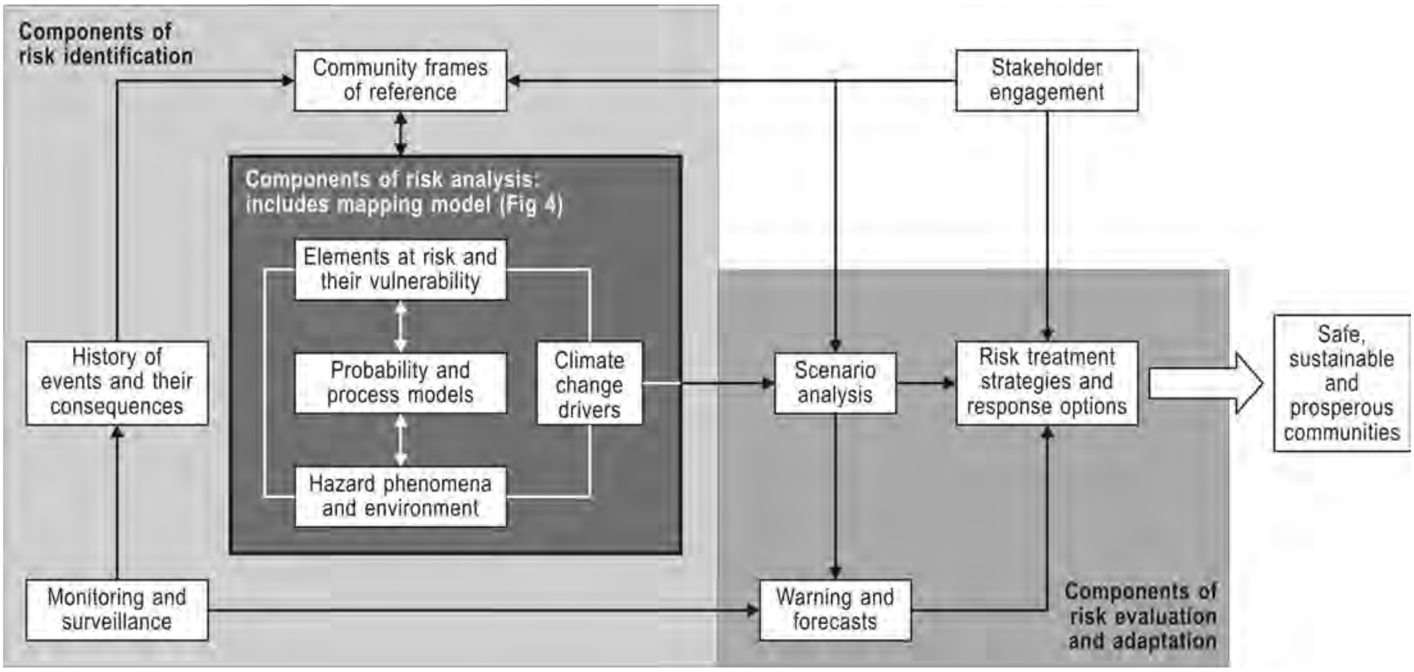

Figure 2: The risk management process (after Granger, 2001)

Flood risk and the Greater Manchester conurbation

Manchester is the archetypal industrial city. It is surrounded to the north and east by peat covered hills which catch the wet westerly airstreams from the Atlantic and is traversed by three rivers with fan-shaped catchments, the Irwell, Roch and Mersey. Average annual rainfall in the Peak District in the upper catchments of the Mersey is in the order of 1,450mm per annum, dropping to approximately 825mm in the city centre. River regimes are flashy, and as far back as 1715 the writer, journalist and traveller Daniel Defoe noted:

> *"The River Irwell runs close by this town, and receives the little River Irke just above the town, on the north and north east side. There is a very firm, but antient stone bridge over the Irwell, which is built exceedingly high, because this river, though not great, yet coming from the mountainous part of the country, swells sometimes so suddenly, that in one night's time they told me the waters would frequently rise four or five yards, and the next day fall as hastily as they rose".*
>
> (A Tour through the Whole Island of Great Britain, p. 265)

Since Defoe's day the main river channels have been straightened and canalised to accelerate the flow of water, but water levels rise quickly when peak flows enter narrowed sections with reduced capacity and can overtop embankments. In a city such as Manchester, it is also important to recognise the legacy of rapid industrial expansion and constant redevelopment on the drainage systems and how this affects both the causation and the magnitude of climatically induced flood events. Natural flood plains have been urbanised and urban infilling has increased runoff whilst also reducing the amount of gardens and open land available to infiltration. Much of Manchester is still drained by old combined sewers designed to cope with foul water and road runoff which flood by backing up when river levels are high. Many modified small streams, brooks and culverts are now hidden below ground and their condition is deteriorating; they become blocked with debris and are the cause of much localised flooding during peak events.

Records of historical flood events

The Environment Agency has compiled a list of 255 reported flood events in Greater Manchester since 1886. The degree to which this dataset might be used as the basis for developing a model of future flood risk is affected by a number of issues. First, evidence from other sources, such as newspapers and local archives, suggests that the records are far from complete. Second the data are primarily restricted to riverine flood events and tend to provide fewer details for floods associated with other causes. Third, flood management has been ongoing since records began, resulting in continued modification to river channels and other flood prevention methods. Finally, whilst the Agency's records indicate the size of the area flooded, they do not comment on either the depth or the duration of the inundation. Despite these limitations, the records do nonetheless provide some interesting insights into specific past events and closer inspection can often be used to draw out a better appreciation of flood causes and effects at more localised spatial scales.

Table 1: Major flood events in Greater Manchester. (Source: Compiled by Ian Douglas and Nigel Lawson from Municipal and Environment Agency records, the press and literature reviews.)

Year	Location	Cause	Effect
1616	Irwell in Salford	*No data*	*No data*
1649	Irwell in Salford	*No data*	*No data*
1662	Mersey	*No data*	Cut Chester and London Roads.
1750	Mersey	*No data*	Cost many lives.
1767	Mersey	*No data*	Washed away bridge at Stretford.
1799	Mersey	Banks burst	*No data*
1828	Mersey	*No data*	*No data*
1799-1852	Irwell – 10 events	Siltation	*No data*
1866	Irwell	*No data*	*No data*
1868	Irwell	Siltation by urban debris	*No data*
1871	Irwell	Loss of channel capacity	*No data*
1880	Irwell	*No data*	Severe damage to city centre riverbank properties.
1881	Irwell	*No data*	Severe flooding in Lower Broughton.
1886	Irwell at Salford	Channel capacity exceeded (No raised Defences)	800 ha with crowded tenements in Lower Broughton flooded up to 2m in depth.
1896	Mersey	*No data*	Floods in many parts, including Stockport.
1923	Mersey and Irwell	*No data*	Flooding in Lower Broughton and along Mersey.
1930	Mersey	*No data*	Flooding and severe bank erosion at Ashton in Mersey.
1940	Mersey and Irwell	Snowfall and Snowmelt	Severe flooding.
1946	Irwell	Channel capacity exceeded	Severe flooding in Salford, 5,300 properties and 243 ha in Lower Broughton.
1954	Irwell	Channel capacity exceeded	600 properties in Lower Kersal and Lower Broughton.
1964	Irwell, Mersey and Beal	Overtopping of banks at Northenden and Douglas Green, Salford	350 properties evacuated in Shaw. Didsbury widespread flooding of fields and property.
1965	Roch	*No data*	*No data*
1973	Mersey	*No data*	Flooding in Stockport.
1980	Irwell	Riverine and sewer flooding	Severe flooding, particularly in Lower Kersal.
1981	Chorlton and Sinderland Brooks	South Manchester 75 mm rain over 3 hours in early August	Widespread flooding along the Chorlton and Sinderland Brook catchments.
1995	Irwell, Roch and culverts	*No data*	60 houses and 21 industrial units flooded.
2000	Mersey, Irwell Irk, Roch and culverts	Banks overtopped, blocked culverts	Widespread flooding.
2002	Irwell, Roch and culverts	Overtopping of Irwell, backing up drains in Rochdale	11 properties flooded in Irwell Vale.
2004	Netherley, Shaw, Cringle and Chorlton brooks. Heywood	2nd wettest August on record, surface water, blocked culverts (Cringle Brook) pumping station breakdown	Cheadle: 22 properties and 2 industrial units affected. M60 motorway near Whitefield closed for 7 hours. Heywood: back-up sewage flooding in a number of homes.
2006	Heywood	July storm (33.2mm rainfall in 1 hour); culvert and sewer overflows	200 homes flooded, 40 homes evacuated.

Riverine flooding

Flood protection from major rivers is the responsibility of the Environment Agency which continuously seeks to reduce the risk of flooding, according to the risk scales expressed in Table 2. In spite of the Agency's efforts, levels of protection to the Mersey, Irwell and Roch, the three major rivers draining Greater Manchester, vary considerably. Much of the Mersey Valley is now low risk with protection to 1:200 years or more following the development in the 1970s of temporary flood storage basins on park land and golf courses in the natural flood plain. Bypass channels, channel adjustments, bank reinforcements, storm-water tanks and increased drainage and sewerage capacity intend to protect the River Roch in Rochdale and Littleborough to a standard of 1:100 years. However, Lower Kersal and Lower Broughton, the two areas in Greater Manchester to have suffered most from flooding in the past, will only have 1:75 year protection even after the 2005 completion of a 650,000m³ flood storage basin at Littleton Road. Furthermore, no provision has been made for future climate change despite the Department for the Environment, Food and Rural Affairs (Defra) recommending that, as a precaution, increases in peak flows up to 20% should be taken in to account. In the Lower Irwell Valley in Salford, this corresponds to an increase in flow of 110m³/s and a potential increase of 1.0m at Littleton Road Basin and 0.4m at Adelphi Weir (Environment Agency, 2005).

Table 2: Environment Agency classifications of flood severity.

Severity	Return period
Significant	Greater than 1:75 years
Moderate	Less than 1:75 years but greater than 1:200 years
Low	Less than 1:200 years

The impacts of sewers and culverts

The flood risk posed by sewers and culverts is a function of their hydraulic capacity and how this is affected by their condition, sedimentation, blockages and the interaction between them and other urban watercourses. The old sewers and urban drainage systems in Manchester were traditionally designed to cope with flood flows with a return period of less than 1 in 5 years and over the years a considerable effort has been made to improve the old combined systems by screening inputs, increasing the size of the actual sewers and by the provision of storage tanks. However, it was not until the 1970s–1980s that separate sewerage and runoff systems were incorporated in to new urban developments. In Manchester, where some 38% of the approximately 2,500 km of sewers built before 1984 are over 120 years old and are in need of reconstruction (Read, 1986), the potential disruption and cost means that it is impossible to provide a separate city wide sewerage system.

Since privatisation of the water industry in 1989 the sewerage system is the responsibility of the utility company whereas ordinary watercourses and surface water are the responsibility of Local Authorities (LA). Culverts come under the auspices of the LA Highways Departments where they are crossed by roads but when they are under buildings they remain the responsibility of the riparian landowner. There is only limited information on the capacity, age, routes and condition on the majority of culverts where the only source of information is from old maps, plans in Local Authority archives, other historical records and empirical knowledge. Ashworth (1987) mapped most of these hidden rivers in Manchester using evidence derived from local histories, newspapers, City Engineers and Surveyors, Court Leet Records and personal on foot surveys. Ashworth's work has been extended and verified using Ordnance Survey maps from the 1840s and 1890s and current on-line OS sources (Figure 3). Figure 3 clearly demonstrates the existence of a series of small river catchments, now largely culverted, which are part of the hidden underground drainage system of the city. As has been noted, such hidden rivers may prove particularly susceptible to floods from extreme climate events, not least due to their potential to become blocked by debris and fly-tipped waste. Local scale consideration of such pressure points in the culverted network can therefore add a further dimension to city-scale flood risk assessment.

Flooding case studies

A characteristic faced by many cities such as Manchester which grew exponentially during the 19th century is the inability of the drainage system to respond to severe storm events and this is evidenced by the repetitious nature of localised flooding in several areas of the city. Broadheath and Timperly to the south of the city are intersected by a series of small urban streams and have a long history of localised flooding. Following a 1981 storm when the insufficient capacity of culverts resulted in 80 houses being inundated by up to 1.75m of water in the Brunswick Road area, the then Rivers Division of the North West Water Authority drew up a plan in 1983 to put an end to flooding in the area. The Timperley, Baguley and Sinderland Brook Improvement Scheme involved the use of playing fields as a 5000 m³ flood basin, increasing the capacity of the culverts to cope with a 1:35 year event by inserting a new culvert next to the original 1772 culvert where Timperley Brook passes under the Bridgewater Canal and the Warrington to Stockport railway line, channel straightening, the reinforcement and raising of banks and undertakings by the authorities to control debris and limit illegal tipping (Plates 1, 2 and 3).

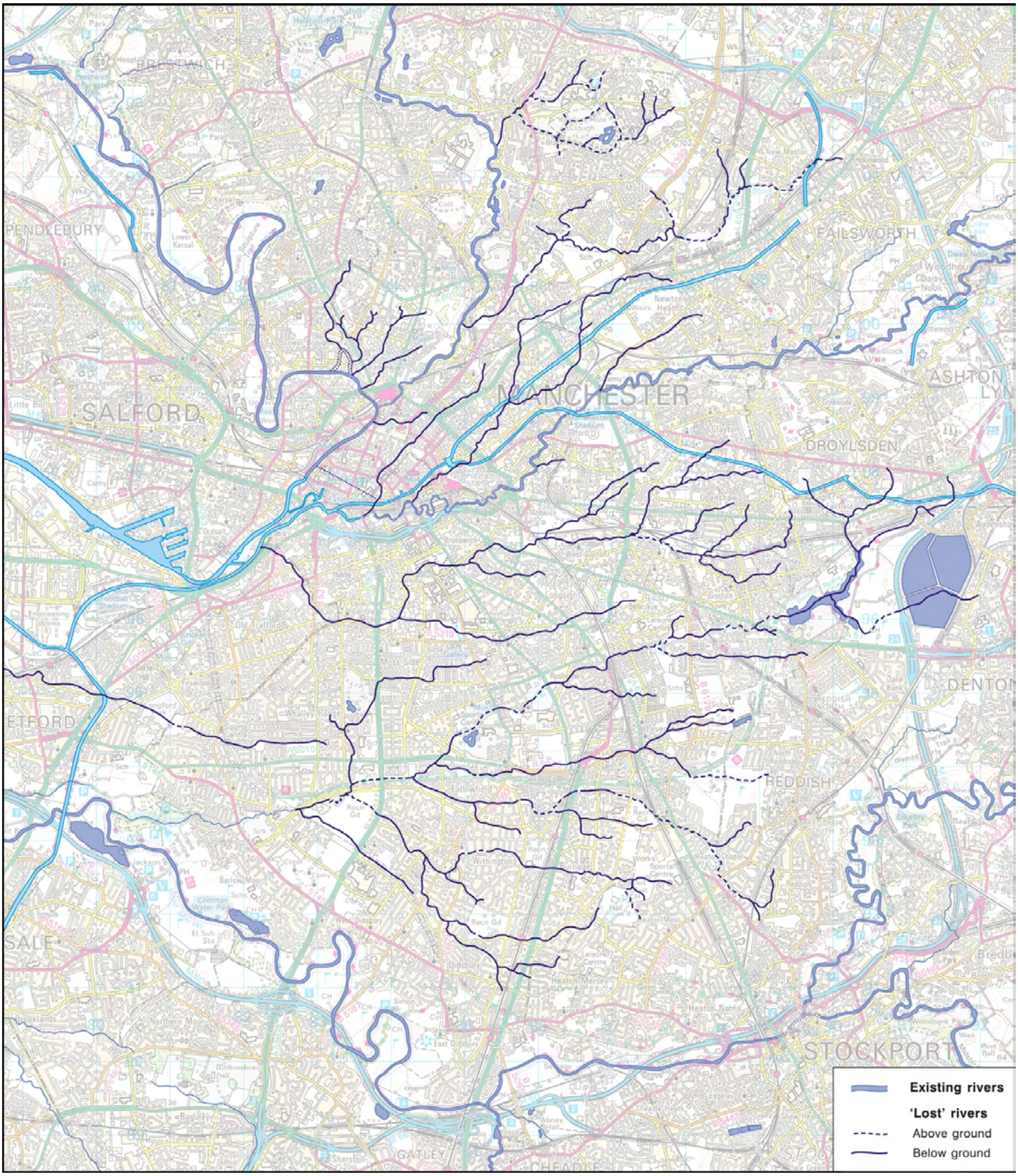

Figure 3: The hidden (culverted) rivers of Greater Manchester (after Ashworth 1987)

However, residents of this area continued to witness regular sewer flooding and a July 2006 storm resulted in a sewer overflow and further flooding in Brunswick Road for the fourth time in two years (Griffen, 2006a), with the utility company undertaking to carry out detailed studies (Griffen, 2006b).

To the north of the city, the Pilsworth Road area of Heywood experienced severe flooding following summer storms in 2004 and 2006. On July 2nd 2006 the rain gauge at Cowm, Whitworth, recorded a total rainfall of 50.4mm in 3.5 hours. The first hour saw 33.2mm of rainfall and the peak rainfall intensity was 17.2mm in 15 minutes. Excessive surface water and back-up of water from an old 1.25m wide combined sewerage system and a now hidden stream in a culvert under the area resulted in 200 properties being inundated with up to 700mm of sewage infected water and 40 homes had to be evacuated (Plate 4). The same area was also hit by a storm on August 3rd 2004 when 37.5mm of rain fell in 1.5 hours. The drainage systems were not designed to cope with such extreme weather events and grids blocked with silt and other debris greatly increased the amount of flood damage incurred. One of the principal causes of flooding in Heywood is old underground culverted watercourses overflowing because their hydraulic capacity is unable to cope with such high intensity rainfall, urban infill induced increases in runoff and debris blockages (Figure 4).

Plate 1: Timperley Brook bank reinforcements.

Plate 2: Timperley Brook culverted under the Warrington to Stockport railway line.

Plate 3: Timperley Brook flood regulator and flood storage basin.

Plate 4: Pilsworth Road, Heywood, July 2nd 2006.

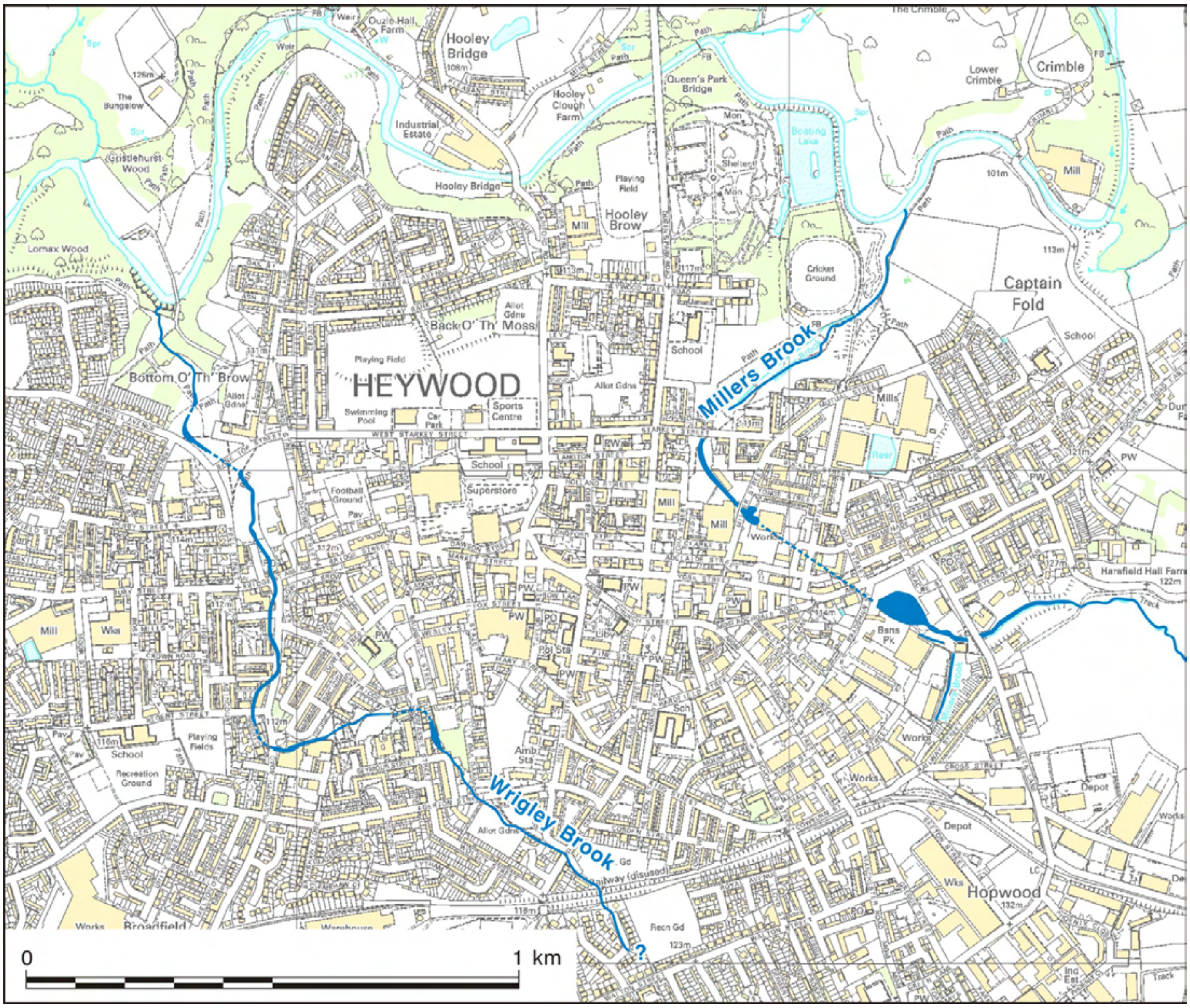

Figure 4: The course of culverted streams under Heywood.

Future flood risk mitigation in Greater Manchester: future challenges

Under existing socio-economic conditions the National Appraisal of Assets at Risk of Flooding suggests that by 2050, with median climate change predictions, average flood damage could exceed £80 million per year in the northwest of England (Holman et. al., 2002). The climate in the North West is set to get warmer and wetter, most recent research by the United Kingdom Climate Impact Programme suggests that winter rainfall over northwest England may increase by between 6% and 14% by the 2050s, weather patterns could become more extreme with increasing risk of storms (Environment Agency, 2006), and both average and extreme rainfall are likely to increase by a factor of 1 to 1.25 in the region by the end of the 21st century (STARDEX, 2005).

The traditional method for managing the risk from flooding is to assess the chance or probability of a particular past event repeating itself and to mitigate against the impact that the event would have if it re-occurred. Appropriate mitigation is the result of prediction based on knowledge of the magnitude, frequency and geography of past events and the effect of changes in climate and in infrastructure since they last occurred. Severe events such as those that occurred in the 1880s, 1946, 1954, 1964 and 1981 trigger responses. In a highly urbanised area such as Manchester it is also important to recognise the legacy of rapid industrial expansion and constant redevelopment on the drainage systems and how this affects both the causation and the magnitude of these past events. Over the years, flood alleviation works throughout Greater Manchester such as the 1975 Mersey flood storage basins in Didsbury and Sale and the 2005 Irwell basin at Littleton Road, bypass channels, channel adjustments, bank reinforcements, storm-water storage tanks and increased drainage and sewerage capacities have been required to compensate for the growth in urban development and are also needed in response to climate change.

The Environment Agency gives its highest priority to the development of a flood risk management strategy for the Lower Irwell by 2010 and it is clear that this remains the area most at risk from riverine flooding in Greater Manchester with much flood alleviation work still required. Because several different agencies are responsible for the provision and maintenance of urban drainage systems in the UK many small events go unrecorded and a comprehensive analysis of the scale and consequences of sewer and culvert flooding in Manchester is not possible, but it is noticeable that this type of urban flood has become more prevalent since the 1980s (Table 1). In addition to climate related predictions, increased urban infilling and intrusions into natural floodplains mean that the hydraulic capacity of the now largely antiquated drainage systems in Greater Manchester requires urgent amelioration. Without co-ordinated widespread participation in flood mitigation by all stakeholders ranging from individual home owners to utility providers and governmental organisations, riverine flooding in the Lower Irwell Valley and localised drainage related flooding in Manchester will continue to be a problem.

Providing sustainable solutions to ongoing flood problems in the city, not least within the context of anticipated climate change, clearly requires a holistic approach to flood risk management (White & Howe, 2004). In considering the development of specific adaptation solutions, consideration of local processes is of course important but the role of city-scale and catchment wide strategies cannot be underestimated. For example, approaches that consider the inherent blue and green networks of the city, natural land-cover and land-use configurations and soil infiltration characteristics (see for example estimated run-off characteristics Figure 5). Through taking a city-wide view and working with coherent land-cover parcels which are able to represent functional landscape units, more internally consistent strategies can potentially be developed (Gill et al 2007).

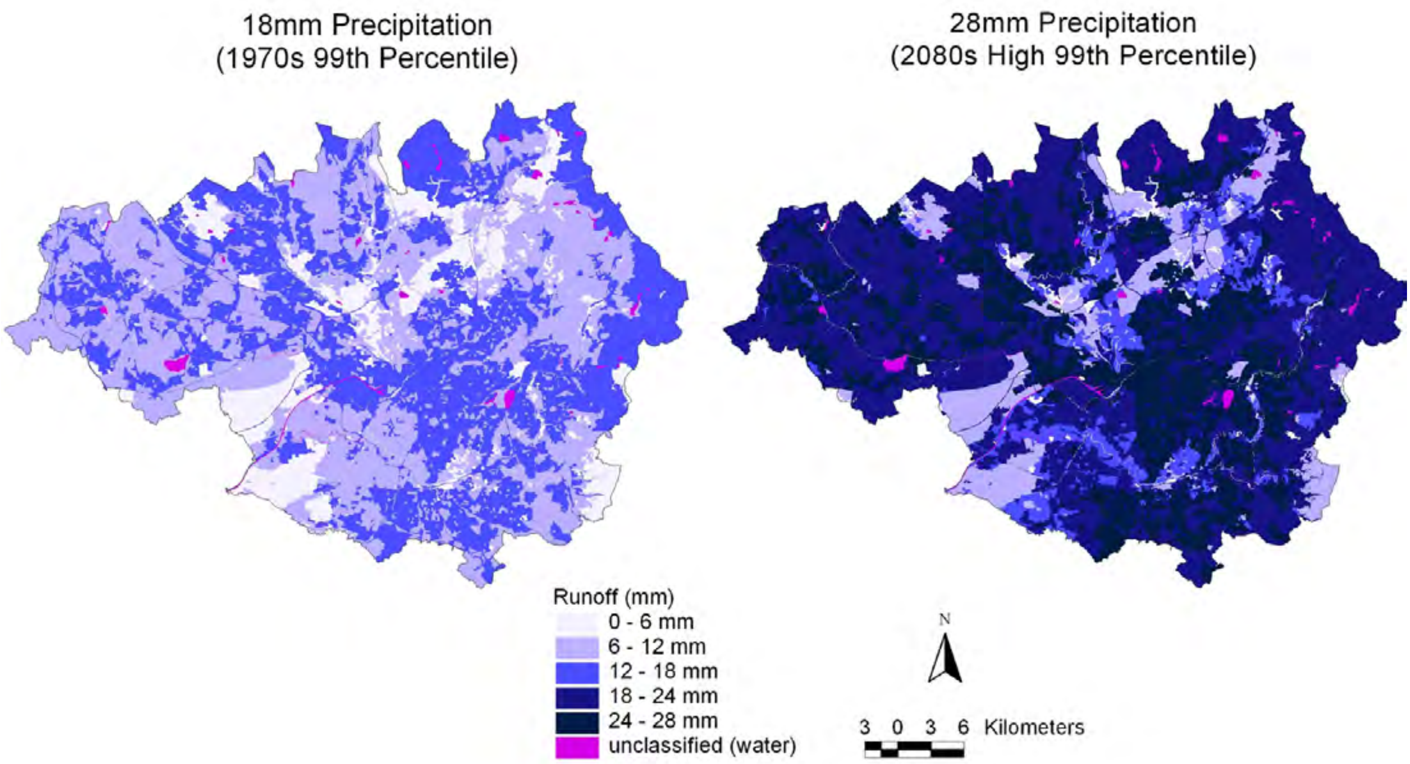

Figure 5: Estimated surface runoff over Greater Manchester for a once per winter daily precipitation event (Gill et al, 2007; Handley et al 2007) of 18 mm (current) and 28mm (2080s High scenario).

Perhaps the prime constraints to sustainable flood risk management at both city-wide and local scales is the conflict caused by the fact that flooding, and the consequent impacts of flooding, are the responsibility of several different agencies.

- The Environment Agency is responsible for riverine flooding in designated main rivers and soon to be critical ordinary watercourses, i.e. rivers and high density streams.
- Local Authorities (LA) are responsible for surface water (runoff) and ordinary water courses, i.e. brooks and small watercourses. LAs are also the sole agencies responsible for granting planning permission for all new developments. However, LAs are reluctant to incorporate Sustainable Urban Drainage Systems (SUDS) such as swales in new developments because of their ongoing maintenance responsibility. [A swale is a long narrow channel on flat ground that drains water evenly off impermeable areas; it acts as a temporary water storage basin for the relief of local flooding.] Flooding is a low priority for many urban LAs faced with social deprivation.
- The utility company is responsible for the sewage system but is not a statutory consultee to the planning process, and this should be rectified. However, capital investment in drainage capacity by utility companies is invariably constrained by the regulator, OFWAT, which has a duty to the customer to monitor charges levied by the utility. OFWAT therefore operates an *at risk register* to flooding and will only sanction capital investment, and thus increased charges by the utility company, where the risk of flooding is worse than 1:20 years. Homeowners are encouraged to report flooding to the utility company so that they can be included on the register but are often reluctant to do so because a property known to be at risk to flooding is likely to depreciate in value.
- Riparian landowners are responsible for culverted watercourses underneath their buildings.
- The insurance industry is responsible for covering insured home owners against loss. However, repeated claims invariably result in increased premiums, increased excesses and even refusal to insure.
- The home-owner clearly also has a responsibility to mitigate against flooding wherever possible.

An illustration of these problems is provided by a housing development, built in 1989 on former school premises in Greater Manchester, which suffers from regular sewer flooding. Whilst one of the properties is on the *at risk register* and the utility company accepts responsibility, prioritisation inhibits them unlocking relatively modest funds to provide a holding tank which would solve the problem. The Local Authority disclaims any liability despite being the agency which granted planning permission for this unfortunate development. It is estimated that the totality of the insurance claims paid out to residents possibly exceeds the cost of installing the holding tank and the residents are left with the problem unsolved and potentially un-saleable properties.

An additional area for concern is the flood maps issued on the internet by the Environment Agency. These maps are published by the Agency to increase awareness among the public, local authorities and other organisations of the likelihood of flooding, and to encourage people living and working in areas prone to flooding to find out more and take appropriate action. The EA is responsible only for riverine and coastal flooding and its maps are modelled to show flood plains as being at risk and the influence of flood defences is ignored. However, because the emphasis is on the risk element, i.e. a 0.5% -1.3% (1 in 200 years to 1 in 75 years) chance of flooding, some areas may experience flooding from rarer events than those intimated by the model, while others may have no recorded history of a flooding. For example, residents of parts of Heywood experienced significant flooding in 2004 and 2006 in areas not indicated on the map (see case study above), while parts of Fallowfield that are shown as being at flood risk, have not had a flood in living memory. Misinterpretation may arise because people fail to study and fully appreciate all the data available on the EA's web site. For example, only by clicking on the link to "learn more" will they find the explanation:

> "Our maps only cover flooding from rivers and the sea. Flooding can occur at any time and in any place from sources such as rising ground water levels, burst water mains, road drains, run-off from hillsides, sewer overflows etc."

There is now considerable anecdotal evidence that flooding from sewers and other non-river sources is as prevalent as flooding from rivers and the sea. This lack of clarity on the likelihood of such flooding has been known to have severe effects on property transactions.

Risks from subsidence in Manchester

The creation of voids and human induced changes to the hydrological regime have the potential to cause subsidence and over the years Manchester has suffered its fair share. Old sewer systems deteriorating when subjected to increased flows have long been a cause of subsidence in urban areas and Manchester still has approximately 950 km of pre-1880 sewers which have been described in engineering terms as *"primitive"* and prone to collapse (Read, 1986). Sewers are generally located under roads; collapses cause major disruption, and renewal is difficult.

The North West of England, including Greater Manchester, has a legacy of mining, and mine voids continue to be a source of subsidence. The exact location of many abandoned mine shafts is unknown, old workings filled with mine spoil become unstable, voids fill with water and subsequent ground-water depletion as a result of changing climatic conditions can further reduce their stability. Although data resources describing surface characteristics of towns and cities are ever expanding, this is considerably less true for complementary resources detailing sub-surface characteristics.

Mining-induced subsidence in Greater Manchester comes in many forms and with many outcomes. These include examples of large areas now filled with surface water such as the 57ha Pennington Flash, holes large enough to accommodate a railway engine suddenly opening up in Abram, damage to the M62 motorway, cracked water mains, severe structural damage to buildings, and damaged road surfaces. Coal mining took place in urbanised Manchester with both Agecroft Colliery and Bradford Colliery very close to the city centre. Whilst Agecroft remained active until 1991, Bradford Colliery closed in 1968 even though there were still substantial reserves of coal. The underground workings from the colliery were causing a great deal of subsidence and in particular large areas of Bradford village and Miles Platting were affected. Houses and factories alike were reporting structural damage and even one of the large gasholders at Bradford Gas Works was affected by subsidence. The expansion plans for Bradford Colliery at the time included working seams below Collyhurst, Cheetham and Ancoats, but with the attendant risk of still more subsidence the NCB had no alternative but to close the colliery. The location and depth of the Bradford Colliery Four-Foot workings are shown in Figure 6. Figure 6 also shows the wider spatial extent of former Coal Board workings in Greater Manchester but does not include information about all historical workings or the many private mines that also lay under the conurbation.

The amount of serious subsidence events in Manchester is considerable (Table 3; Plates 5 and 6). In addition to the examples described in Table 3, local and national newspapers and Manchester City Council's photogaphic archives (www.images.manchester.gov.uk) have recorded a further 28 severe subsidence incidents and numerous small incidents causing disruption to traffic and services.

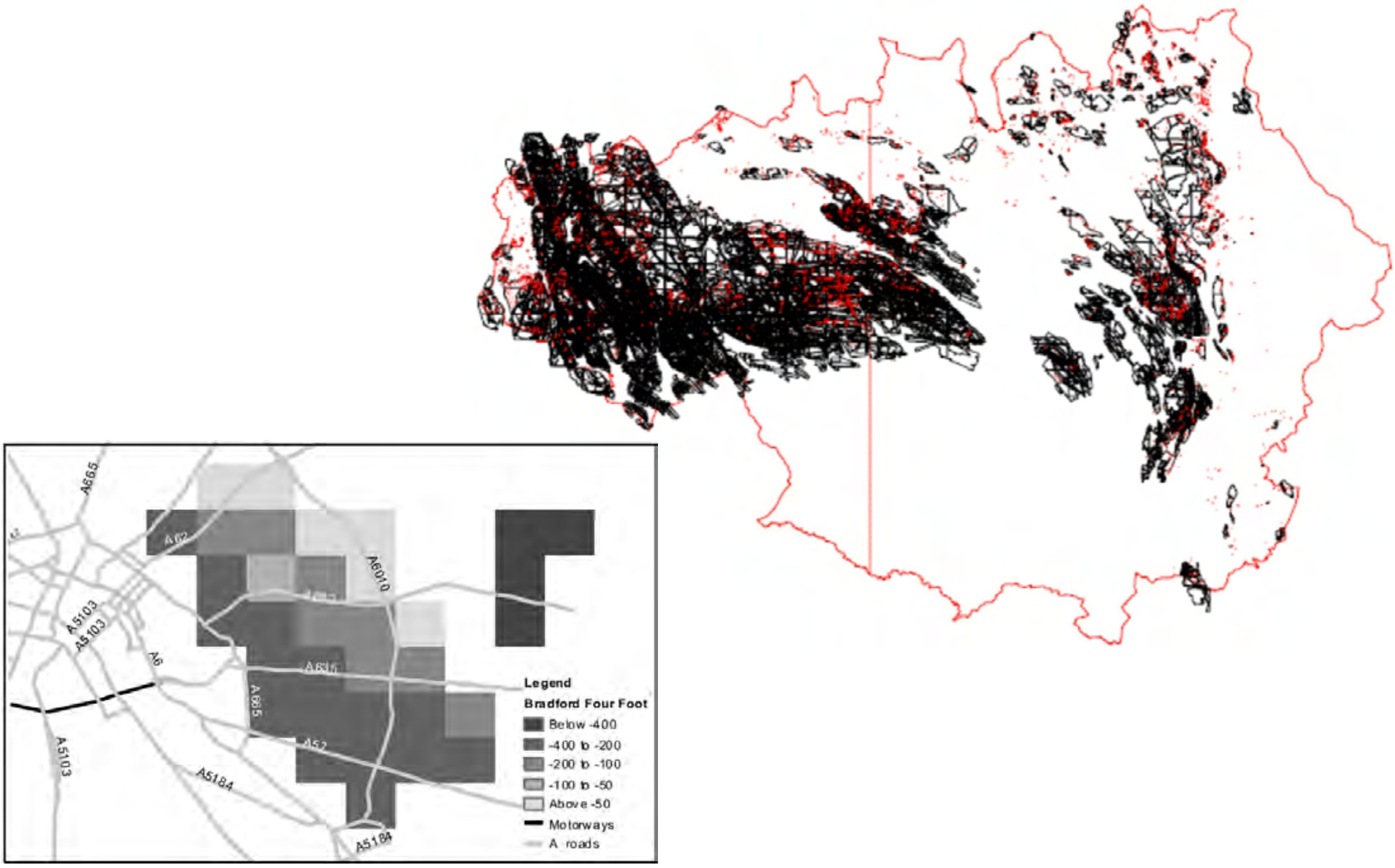

Figure 6: Former coal workings in Greater Manchester with the insert showing the Bradford Four Foot workings. Depths are shown relative to Ordnance Survey datum in metres. Scale: Grid squares are 500x500m. (Source: Coal Authority.)

Table 3: Major subsidence events in Greater Manchester.

Year	Location	Cause	Effect	Reference
2006	Darcy Lever (Bolton)	Collapse of mine shaft, last used in 1902 and capped in 1978, potentially caused by new house building within 10 metres of the shaft.	Tractor fell in to a 27m deep crater above a hole believed to be 300m deep.	Britton, 2006
1992	Clifton Country Park	Cessation of water pumping at recently closed Agecroft Colliery	Infill material collapsed, mine shafts exposed and capped. Several lower risk shafts left untreated and still fenced in 2005.	Waghorn, 2005
1975 and 2003	Store Street / Great Ancoats Street (Plate 6)	Sewer collapse due to sheer failure of an inadequate drop shaft servicing an earlier higher level sewer.	Adjacent property demolished. Need to excavate to 21m-severe disruption for several months. Also further collapse in 2003 in/near same location.	Read, 1986; Ottewell, 2003
1973-74	M62 west of Manchester	Mining subsidence	Reactivation of the Twenty Acre fault in the Lancashire coalfield. Structural damage to M62 and buildings	Donnelly, 2000
1964	Farnworth	Shaft collapse at disused coal mine	Bungalow fell in to the resultant crater over a 300m shaft	The Guardian 17/1/1964
1962	Miles Platting	Mining subsidence (Bradford Colliery)	11 council houses in Thomas and Lewis St. damaged and demolished.	The Guardian, 10/8/1962.
1957	Flyde Street Farnworth (Plate 5)	Sewer running parallel to old water course in rain weakened glacial deposits collapsed.	40m long, 6m wide and 4m deep crater and ground movement over a radius of 75m. 17 houses damaged beyond repair, 120 houses evacuated.	Douglas, 1985.
1945	Abram	Old plugged mine shaft opened.	Mine train disappeared down the hole.	Douglas, 1985
1936	Manchester Bolton & Bury Canal near Nob End.	Subsidence caused by Ladyshore Colliery (?)	Canal breached, two boats swept down in to river below, canal damaged beyond repair.	www.penninewaterways.co.uk accessed 28/09/2006

Plate 5: Fylde St., Farnworth, September 1957.

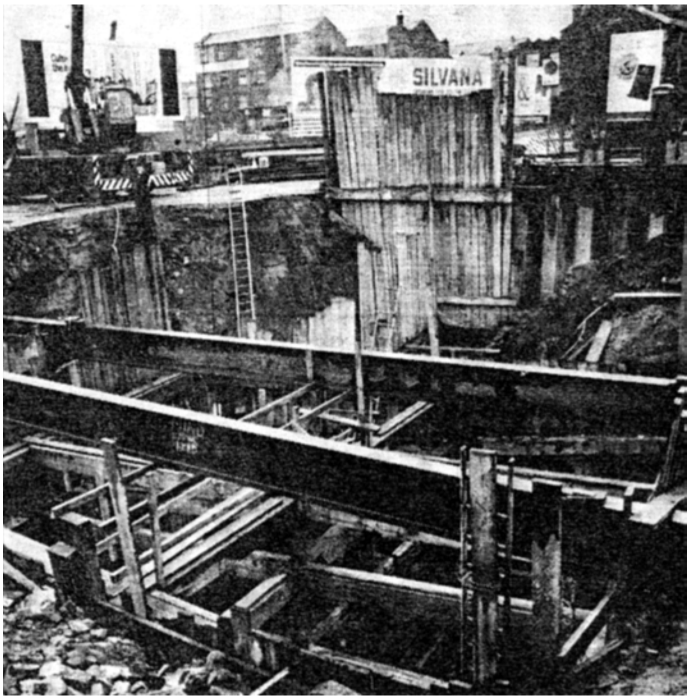

Plate 6: Store Street/Great Ancoats Street, 1975.

All voids under a city face some degree of risk from climate induced subsidence. The Quaternary Tills (Boulder Clay) deposits which form a large part of Manchester's drift geology contain a high proportion of quartz and rock-flour from the glacial erosion of the bedrock and are not generally considered to be particularly susceptible to shrink-swell (Talbot, 2005). However, much of Manchester is covered with lodgement till overlain by supraglacial tills and fluvio-glacial deposits (Douglas, 1985) which are inherently unstable and intrusion can induce changes in their hydro-geological regime which could trigger increased instability. Manchester has not only been excavated to make way for coal mines, sewers and services but also has a series of other lesser known underground voids (Table 4).

Well-recorded underground hydraulic structures other than culverted rivers in Manchester include the Haweswater, Thirlmere and Longendale aqueducts; several canal tunnels under Castlefield; a tunnel running south from the River Medlock and a small tunnel leading off the River Medlock into Chorlton Mills next to Hulme Street (Hilton, 2003). However, underground haulage in mines by water was in vogue ever since the Duke of Bridgewater adopted the practice in his Worsley Pit in 1761 and it is reasonable to assume that many unrecorded former pit canals still exist. Doubtless other now unrecorded and unmapped tunnels and/or underground structures exist in a city with a history such as Manchester and all have the potential to increase the risk to infrastructure.

Table 4: Underground Manchester: other principal known voids.

Location	Description	Reference
Back George Street.; Lockton Close, Ardwick; Salford.	The Guardian Underground Telephone Exchange, built 1954 to withstand a Hiroshima size atom bomb. 34m underground, main shaft 300m x 7m plus 1.6km tunnel running west to Salford and 700m tunnel to Ardwick. Contains own artesian well. Also contains an access shaft to Rutherford telephone exchange in George St. Still in use by BT as an underground cable route.	Campbell, 1983; www.cybertrn.demon.co.uk
Greystoke, West Didsbury	Manchester Corporation Main Control Centre. Cold war bunker built in 1954; now derelict.	www.subbrit.org.uk
Alexandra Hospital, Cheadle	Cheadle-Manchester Regional War Room. Built 1952, operational as Greater Manchester Emergency Centre until 1991, demolition planned.	www.subbrit.org.uk
Great Bridgewater Street to Water Street	Manchester and Salford Junction Canal. Opened 1839, abandoned in 1936, used as an air-raid shelter during WWII, subsequently partly filled in but the main tunnel remains intact under Granada TV studios and the former Great Northern Warehouse.	Hilton , 2003; www.subbrit.org.uk
The Catacombs	Tunnel or series of tunnels running under Victoria Station to River Irk used as an air-raid shelter in WWII and believed to be extant.	Hilton, 2003
Deansgate and Mosley Street	Private tunnels linking branches of Kendals (Deansgate) and Royal Bank of Scotland (Mosley Street)	Hilton, 2003
Belle Vue	Underground railway line to Belle Vue Goal, disused by 1889	Hilton, 2003
Worsley Delph	Around 75km of underground canals were constructed in the Duke of Bridgewater's Worsley Pit in the 1760s. A 1997 inspection found them in excellent condition.	www.penninewaterways.co.uk; www.d.lane.btinternet.co.uk
Alkrington	Colliery canals under the old Alkrington Colliery, 2 x 1,25m wide parallel tunnels about 1000m in length at a depth of about 100m built in the 1770s. The colliery was closed in 1841. They were of concern to Oldham Council in 1960.	Beckett, 1960

Conclusions

Data on historic events can help provide a useful narrative for understanding risks in the urban environment. In many cases the analysis of past events nicely illustrates the complex processes and conditions underpinning the realisation of risk. Inevitably, it is this complexity which makes mitigating and managing risks a difficult task. Given their utility, a strong argument can be made for ensuring that records of events are maintained and even extended to provide a consistent and comparable dataset for the future.

The risk of serious subsidence has been reducing in Greater Manchester over recent times, primarily due to the cessation of underground coal mining some 20 years ago and ongoing sewer renewal programmes. It is therefore a reasonable expectation that under current climatic conditions the most at risk areas with sufficiently vulnerable conditions have already been affected. However, climate change impacts could easily alter this pattern.

Evidence from climate impact studies suggests that the future risk of flooding generally, and in urban environments in particular, is likely to increase substantially. Mitigating against this increased flood risk is currently complicated by the number of actors and agencies involved in management and a lack of clarity regarding roles and responsibilities. A case could be made for further delineation of roles within a holistic management framework. For example, this might involve local authorities giving greater focus to issues associated with the intrusion of development on to flood plains, infill, runoff and urban green-space. Utility companies, given their data resources and wider interests, roles and responsibilities, might be statutory consultees in the planning process and have more local control over investment in infrastructure.

More reliable data on instances of flooding are certainly required but the collation of such records would need to take account of the sensitivity of information and not jeopardise home owners in affected areas. Whereas the Environment Agency possesses the expertise to be more proactive in controlling flooding, it does not, at present, have adequate resources to cover all aspects of the problem and is unable to collate comprehensive records of all types of flood events. One solution could be the establishment of a single, locally controlled, but centrally subsidised, agency able to accept responsibility for all aspects of flooding and the risk to individuals from climate induced changes to urban infrastructure.

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